Towards Wearable Physiological Monitoring on a Mobile Phone

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Towards Wearable Physiological Monitoring on a Mobile Phone

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Abstract ***In this chapter, we present our experience in using mobile phones as a platform for real-time physiological monitoring and analysis. In particular, we describe in detail the TripleBeat system, a research prototype that assists runners in achieving predefined exercise goals via musical feedback, a glanceable interface for increased personal awareness and a virtual competition. We believe that systems like TripleBeat will play an important role in assisting users towards healthier and more active lifestyles.***

Index Terms

Adaptive Mobile Devices, Exercise Enhancement, Jogging, Competition, Experimentation, Persuasive Interfaces, Social Pressure, Wearable Physiological Monitoring.

Introduction

Wearable health monitoring devices have attracted increasing interest in recent years, both in research and industry. The ability to continuously monitor physiological signals is of particular importance for the world's increasingly aging and sedentary population, whose health has to be assessed regularly or monitored continuously.

It has been estimated that a third or more of the 78 million baby boomers and 34 million of their parents may be at risk for the development of devastating diseases including cardiovascular disease, stroke and cancer. Fortunately, presymptomatic testing could save millions of these lives –and dollars– in the coming decades, according to experts. Wearable physiological monitoring devices are a critical component in preventive medicine where they will play an increasingly important role in the years to come.

In addition, a sedentary lifestyle is a major underlying cause of death, disease, and disability. Unfortunately, levels of inactivity are high –and keep increasing– in virtually all developed and developing countries. The World Health Organization (WHO)[1] has estimated that 60 to 85% of all adults are sedentary or nearly so. Physical inactivity is the cause of approximately 2 million deaths every year. All causes of mortality are increased by physical inactivity. In particular, it doubles the risk of cardiovascular disease, type II diabetes, and obesity [Booth et al., 2002], [Flegal et al., 1998]. It also increases the risks of colon and breast cancer, high blood pressure, lipid disorders, osteoporosis, depression and anxiety. Chronic diseases are now the leading causes of death in the entire world, with the exception of sub-Saharan Africa. The WHO has estimated that the greatest public health problem in most countries in the world are unhealthy diets, caloric excess, inactivity, obesity and associated chronic diseases.

Fortunately, technology can play a very important role to address the reality of an aging, sedentary population. Wearable health monitoring devices will be at the core of this role, since they have the potential to: (1) support the practice of preventive medicine by enabling the detection of early signs of health deterioration; (2) allow daily, casual monitoring, which would lead to finding correlations between lifestyle and health [Oliver and Flores-Mangas, 2007]; (3) notify health care providers in critical situations; (4) enhance the sense of connectedness with loved ones by sharing real-time raw or interpreted physiological data; (5) promote and support an active lifestyle, *i.e.* a lifestyle that incorporates physical activities, sports and healthy life choices [Andrew et al., 2007], [cdc, 2005], [Oliver and Flores-Mangas, 2006a]; (6) bring sports conditioning into a new dimension, by providing detailed information about physiological signals under various exercise conditions; (7) bring healthcare to remote locations and developing countries, where cellular phones are pervasive and in some cases the only available communications device; and ultimately (8) transform health care by providing doctors with multi-sourced, real-time physiological data.

However, there are still technical, legal and societal obstacles that need to be tackled before these wearable devices are ready for general use. For example, these devices need to be non-intrusive, easy to use, comfortable to wear, efficient in power consumption, privacy compliant, with very low failure rates and high accuracy in triggering alarms, especially if used for diagnostic purposes.

In this chapter, we describe our experience in developing wearable real-time health monitoring systems on mobile phones. In particular, we have developed two prototypes that explore the impact of real-time physiological monitoring in the daily life of users: (1) HealthGear to monitor users while they are sleeping and automatically

†The work presented in this chapter was carried out while all authors worked at Microsoft Research in Redmond, WA.
[1] `http://www.who.int`.

detect sleep apnea events; and (2) MPTrain/TripleBeat, a mobile phone-based system that encourages users to achieve specific exercise goals.

The HealthGear prototype has been described in detail elsewhere [Oliver and Flores-Mangas, 2007]. Hence, the focus of this chapter will be the MPTrain/TripleBeat[2] prototype. TripleBeat allows users to establish healthy cardiovascular goals from high-level desires (*e.g.* lose fat); it provides real-time musical feedback that guides users during their workout; it creates a virtual competition to further motivate users, and it displays relevant information and recommendations for action in an easy-to-understand glanceable interface. Note that this chapter is based on research presented elsewhere [Oliver and Flores-Mangas, 2006a], [Oliver and Flores-Mangas, 2006b], [de Oliveira and Oliver, 2008]. The focus of the chapter is to provide a comprehensive description of the TripleBeat prototype, to present our results in two user studies and to illustrate with an example the impact that systems like TripleBeat will have in supporting more active and healthier lifestyles.

The chapter is structured as follows: First, we review the most relevant previous work in the area of wearable physiological monitoring. Then, we describe the software and hardware architectures of the TripleBeat system, followed by TripleBeat's signal processing algorithms. TripleBeat's music selection algorithms, competition and glanceable interface are presented in the next three Sections, followed by the two runner studies that we carried out to validate the system. Finally, we describe future trends in the area of wearable physiological monitoring, present our conclusions and outline our future directions of research.

Related Work

A. Wearable Physiological Monitoring

Consumer health monitoring devices have become increasingly popular in recent years. In particular, a significant portion of these devices have been developed for the sports conditioning and weight management areas. Some examples include sophisticated watches[3] that provide real-time heart-rate information and let users store and analyze their data on their home PCs, or an armband with multiple sensors by Bodymedia [Harrison, 2005] to continuously collect physiological data for a few days at a time. The Bodymedia PC software allows users to compute "Lifestyle" information, such as energy expenditure, duration of physical activity, number of steps, etc. their historic sensed data.

In the medical domain, there are numerous projects for telemonitoring physiological data [Scannell et al., 1995]. Holter monitors are probably the most common personal medical monitoring system. However, they have traditionally been used only to collect data for off-line processing. In addition, multi-sensor systems for physical monitoring and/or rehabilitation typically feature many wires between the electrodes and the monitoring system. These wires may limit a patient's activity and level of comfort, thus potentially affecting the reliability of the measured results. Therefore, there has been an increasing interest in health monitoring in the wearable computing community. In particular, we shall highlight three lines of research in this domain that we believe are of importance: real-time analysis of physiological information; wireless, non-intrusive physiological monitoring and user-centric systems that are tested on real users.

There has been recent work in the area of health monitoring where the devices provide real-time feedback to the patient [Martin et al., 2000], [Cheng et al., 2004] and/or are active nodes of a Personal Area Network (PAN) or Body Area Network (BAN) [Park and Jayaraman, 2003], [fos, 2003], [Paradiso, 2003], [Husemann et al., 2004], [Jovanov et al., 2005]. However, most of the research prototypes in this area have not been validated in user studies with real users.

We shall highlight two exemplary projects in the area of wireless sensor networks: the MobiHealth European project [van Halteren et al., 2004] and CodeBlue [Malan et al., 2004]. MobiHealth aims to provide continuous monitoring of patients outside the hospital environment by developing the concept of a 3G-enabled BAN. CodeBlue is a wireless infrastructure intended for deployment in emergency medical care, integrating low-power wireless vital sign sensors, PDAs and PCs. Their research interests include wireless ad-hoc routing protocols, adaptive resource management and the integration of medical sensors with low-power wireless networks.

One of the most remarkable research prototypes in the field of wearable physiological monitoring devices is the AMON prototype [Anliker et al., 2004]. It consists of a wearable (wrist-worn) medical monitoring and alert system targeting high-risk cardiac/respiratory patients. The system includes continuous collection and evaluation of multiple vital signs (blood pressure, SpO_2, one lead ECG and two-axis accelerometer), multiparameter medical emergency detection (via a rule-based approach with some heuristics) and cellular connection to a medical center. Unlike other research prototypes, the AMON prototype was tested in a medical trial with 33 patients. Even though the trial highlighted some problems with the prototype, it also validated the feasibility of the concepts and solutions adopted by the project.

Finally, our work with the HealthGear prototype [Oliver and Flores-Mangas, 2007] was aimed at addressing some of the limitations of previous systems. In particular, HealthGear's main contributions include: (a) A real-time, light-weight wearable health monitoring architecture to wirelessly send physiological data to a mobile

[2]MPTrain was the first version of the TripleBeat prototype. In the following we shall refer to both systems as TripleBeat, adding a V1 or V2 suffix when necessary.

[3]See products from Polar (`http://www.polarusa.com`) and Suunto (`http://www.suunto.com`).

phone; (b) the ability to store, visualize and analyze in real-time physiological data on a mobile phone; and (c) the implementation of two algorithms for automatically detecting in sleep apnea events from blood oximetry. In addition, we validated the complete system (hardware and software) in a user study with 20 participants.

B. Physiology and Motivation

Health monitoring systems typically assist users in changing their behavior to maintain or improve their health. Therefore, motivation is a key element in these systems. Unfortunately, regular physical activity is part of the lifestyle of a small percentage of the adult population worldwide. Therefore, we believe that a motivational tool to support and encourage active lifestyles would be of great value to a large portion of the population.

According to Fogg, *persuasive technologies* are computer-based tools that persuade people to change their behavior [Fogg, 2002]. Some strategies to successfully implement persuasive systems include self-monitoring, computer-originated recommendations and tailoring.

Researchers in the area of wearable physiological monitoring systems have proposed an array of techniques to motivate users to follow a desired workout routine. In particular, we would like to highlight four distinct methods for persuading users:

1) Enjoyable Interaction: Systems that are fun to interact with are not only more attractive to users, but they also engage the user for longer periods of time. Therefore, it is no surprise to find exercise support systems that exploit the benefits of music on exercise [Reddy and Mascia, 2006], [Oliver and Flores-Mangas, 2006a], [Biehl et al., 2006], include appealing 3D virtual trainers [Buttussi et al., 2006] or bring indoor exercises to virtual environments [Mokka et al., 2003].

2) Social Factors: Social factors are a strong motivating factor. Previous research has supported the value of providing real-time information about the performance of other users who are engaged or have been engaged in the same activity [Vorderer et al., 2003]. Social pressure is so relevant as an external motivational factor that users lose their interest in a competition that is easy to cheat [Sohn and Lee, 2007]. Maitland *et al.* [Maitland et al., 2006] proposed using a mobile phone as a health promotion tool. Their prototype application tracks the daily exercise activities of people carrying phones –using fluctuation in signal strength. They have validated their system with a short-term user study where participants shared activity information amongst groups of friends, and found that awareness encouraged reflection on, and increased motivation for, daily activity. Brien and Mueller concluded in [O'Brien and Mueller, 2007] that a jogging experience supporting a conversation between remote partners during the workout was desirable and motivating. Other systems support interaction with a group of friends or peers via instant messaging after a workout session [Sohn and Lee, 2007].

3) Awareness of Physiological State: Several research prototypes and commercial products, such as the Nike+iPod[4] and the Polar watches[5] have been developed that improve the jogging experience with information about the user's performance and workout goals. In such systems, current physiological and activity data collected on-the-fly using accelerometers, heart-rate monitors, GPS sensors, *etc.* is captured and presented to the user in a general purpose system [Asselin et al., 2005], or targeted to specific groups, such as children [Hartnett et al., 2006] or women [Toscos et al., 2006], [Consolvo et al., 2006], [Gockley et al., 2006].

4) Unobtrusive and Intuitive Interaction: A big challenge in wearable exercise and activity monitoring systems is the need to provide users with relevant information without interrupting or disturbing their workout or current activity. One example of unobstrusive notification is the use of sound spatialization to make it easier to identify the position of the partner while jogging apart [Mueller et al., 2007].

The TripleBeat prototype presented in this chapter is a real-time and mobile heart-rate and acceleration monitoring system. TripleBeat stores, analyzes and presents heart-rate and pace information to its users in real-time. In addition, it utilizes an array of persuasive techniques, including: (1) *personal awareness* by allowing users to monitor their heart-rate and pace in real-time, (2) *computer-generated recommendations* by providing real-time feedback on what needs to be done to achieve specific workout goals, (3) *tailoring* by learning from past interactions to provide a personalized experience, (4) *social pressure* by establishing a virtual competition with other runners, (5) *enjoyable interaction* via musical feedback and (6) *unobtrusive notifications* via a glanceable interface.

SYSTEM DESCRIPTION

TripleBeat implements three main features to help users achieve their personal workout goals: (1) An automatic music selection algorithm that takes advantage of the music's *tempo* to influence the user's pace, (2) a glanceable interface that provides visual feedback during an exercise session based on physiological information obtained from the user's *heartbeat*, and (3) a virtual competition that persuades the user to *perform better* than his/her opponents in a healthy manner. Next, we describe TripleBeat's architecture and introduce its music selection algorithm (the glanceable interface and competition are described in later sections).

[4] http://www.apple.com/ipod/nike.
[5] http://www.polarusa.com.

TripleBeat's architecture is composed of two main components: the *Sensing Module* and the *Mobile Computing Module*. The Sensing Module, represented on the left side of Figure 1, includes a set of physiological and environmental sensors, a processing board to receive and digitize the raw sensor signals, and a Bluetooth transmitter to wirelessly send the processed data to a mobile computing device (*e.g.*, smartphone, PDA, *etc.*). The right side of the Figure depicts the Mobile Computing Module, which gets the sensed data via a Bluetooth Receiver and makes it available to TripleBeat's software. TripleBeat's software analyzes the raw sensor data and extracts and logs the user's heart-rate and pace, in addition to other relevant information (*e.g.*, song being played, percentage of time inside the training zone, *etc.*). It also selects and plays songs from the user's Digital Music Library (DML) to help users achieve their workout goals: a song with faster tempo than the current one will be chosen if the user needs to speed up, with similar tempo if the user needs to keep the current pace, and with slower tempo if the user needs to slow down.

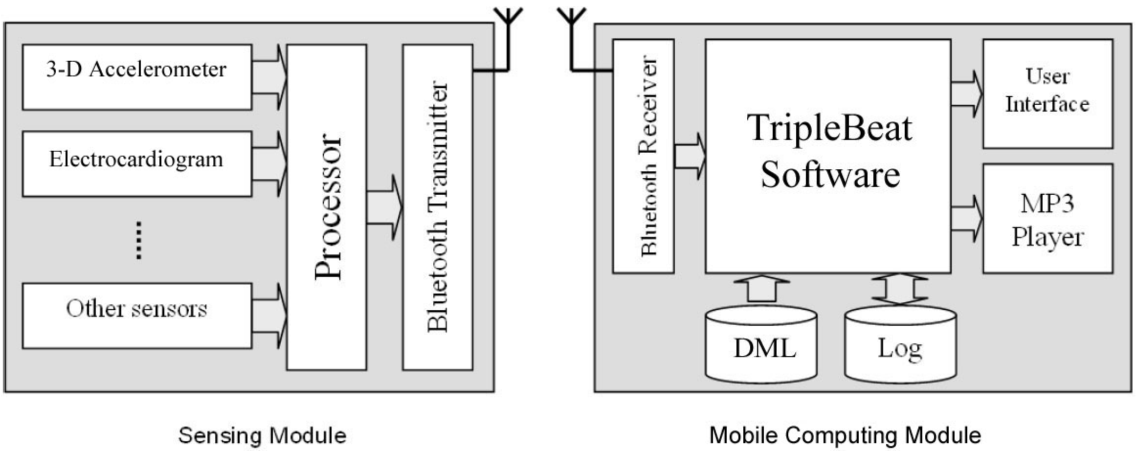

Figure 1. TripleBeat architecture.

Figure 2 depicts TripleBeat's musical feedback data flow. The runner carries a mobile phone while jogging and uses it to listen to music while exercising. Before starting the workout session, the user selects the *desired* workout goals for that session. Once the user starts running, TripleBeat's software monitors and logs the user's heart-rate and running pace. When the song currently being played is about to end –typically with 10s remaining, TripleBeat compares the user's current heart-rate with the desired target heart-rate according to the pre-selected workout. The *Next Action Module* determines if the user needs to speed up, slow down or keep the pace of jogging, based on whether his/her heart-rate needs to increase, decrease or remain the same. This information is used by the *Music Finding Module* to identify the most appropriate song to be played next. As will be described in detail later, the music selection algorithm searches the database for songs that: (1) haven't been recently played, (2) whose tempo –in beats per minute– is similar to the user's current gait plus an amount that is inversely related to the deviation between the user's actual heart-rate and the desired heart-rate.

The user's performance with respect to the desired workout can be checked at any time via auditory and visual feedback. In addition, exercise goals and music tracks may also be changed during the workout session.

Next, we shall describe TripleBeat's hardware and software components in some detail.

HARDWARE

TripleBeat is implemented using off-the-shelf hardware components, as illustrated in Figure 3:

1) **Alivetec**[6] **Alive heart-rate monitor**. Depicted on the right in the Figure. Similar to most wearable heart-rate monitors available in the market, the Alive heart-rate monitor is worn in a chest band. It only weighs 60 g (including the battery), and its low-power consumption allows for 60 hours of continuous operation and wireless transmission. Cardiac activity is sensed using a single channel electrocardiogram (ECG), which provides 300 samples per second with a resolution of 8 bits per sample. Additionally, the unit features a 3-axis accelerometer, digitally sampled 75 times per second with 8 bits per sample resolution. A Secure Digital (SD) card for local data storage is also built in, as well as a Bluetooth class 1 transmitter, which is used to send the sensor data to the mobile phone, via the Serial Port Profile protocol. In summary, this device provides continuous and wireless cardiac and motion monitoring for up to one week.

[6] `http://www.alivetec.com`

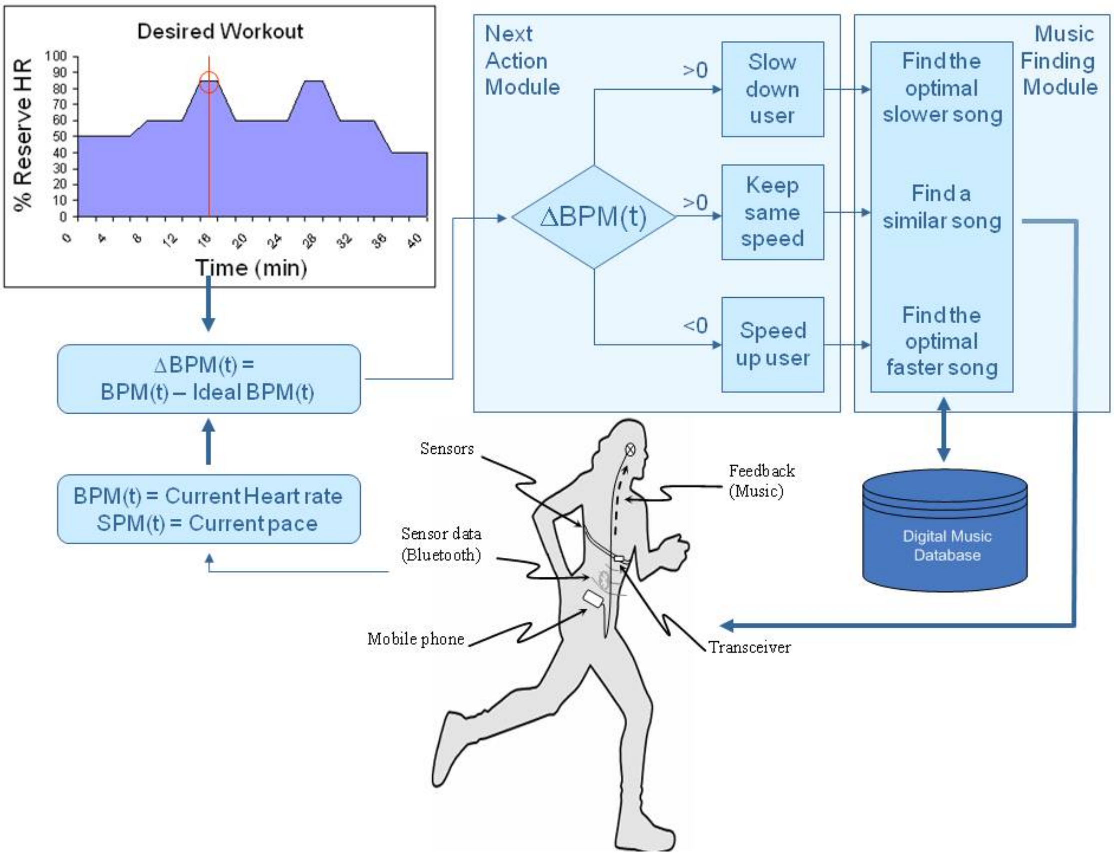

Figure 2. Musical feedback data flow in the TripleBeat system.

2) **Audiovox SMT5600**. The processing unit of TripleBeat is the SMT5600 (or Cingular 2125) GSM mobile phone (depicted on the left in the Figure), which features Microsoft's Windows Mobile 2003 operating system. The mobile phone includes a built-in Bluetooth interface, 32 MB of RAM, 64 MB of ROM, and a 200 MHz ARM processor which allowed TripleBeat to run in real-time. The SMT5600's battery lasts for about 5 days on stand-by mode.

Figure 3. TripleBeat's Hardware. Left: Audiovox SMT5600 mobile phone. Right: Alivetec Alive heart monitor.

Note that the TripleBeat prototype runs in real-time for about 6 hours uninterruptedly (playing music, updating and displaying the user interface, receiving and storing data), before the mobile phone's battery runs out. We have experimentally identified the music playing module as the component that drains the most power in the system.

SIGNAL PROCESSING

In order to compute in real-time the user's heart rate (in beats per minute) and running gait (in steps per minute), TripleBeat's processing unit (*i.e.* the mobile phone) must continuously receive and analyze raw ECG and acceleration data, wirelessly provided by the sensing module.

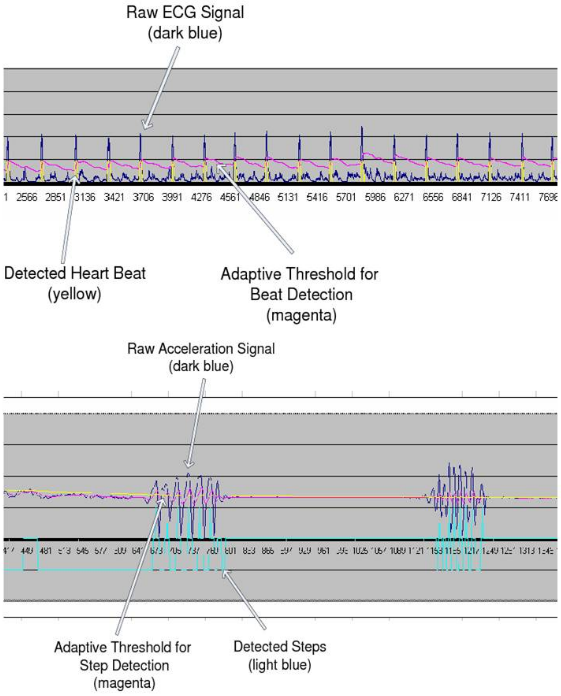

Figure 4. Top: Beat detection (yellow) from a raw ECG signal (blue). Bottom: Gait detection (light blue) from raw Y-acceleration (dark blue).

C. Heart-rate Computation from ECG

An ECG is a record of the electrical activity of the heart over time. This common, non-invasive measurement is typically obtained by positioning electrical sensing leads (electrodes) on the thorax area of the person to be monitored. In our experiments, we used a 2-lead ECG positioned either via a chest band or with 2 adhesive electrodes. The algorithm with which TripleBeat determines the user's heart-rate from raw ECG data is described below.

The top part of Figure 4 illustrates a typical ECG signal (dark blue). Overlaid, the results of the heart beat detection algorithm can also be observed. The main steps of the algorithm are as follows:

1) Apply a low pass filter to the raw ECG signal to obtain *ECGLowPass*.
2) Extract the high-frequency component, named *ECGHighfreq*, by subtracting *ECGLowPass* from the original ECG signal.
3) Compute a high-frequency envelope, named *ECGHighFreqEnv*, by low-pass filtering the *ECGHighFreq*.
4) Compute a dynamic threshold, named *ECGThreshold* (on magenta in the Figure), by low-pass filtering from *ECGHighFreqEnv* using a very low frequency. A heart beat is detected when the high frequency component (ECGHighfreq) is greater than the dynamic threshold (ECGThreshold), provided that no heart beats were detected during the last quarter of a second.
5) Compute the user's instantaneous heart-rate (in yellow on the same graph) as the inverse of the time period between beats and then multiply by 60 to obtain beats per minute (BPM):

$$HR_i = 60 \times \frac{1}{TimeBetweenBeats} \quad (1)$$

Heart-rate samples beyond the range $30 < HR_i < 300\ BPM$ are considered spurious and therefore are discarded.
6) Finally, apply a median-filter to HR_i to obtain the heart-rate HR. Median filtering increases robustness and preserves the edges of the input signal, effectively removing impulses and outliers [Pitas and Venetsanopoulos, 1990].

D. Pedometry from 3-Axis Accelerometry

Pedometry is the count of strides that a subject takes. As previously described, TripleBeat's current hardware features a 3-axis (X,Y and Z) accelerometer. However, the step detection algorithm requires information about vertical (Y axis) acceleration only. Therefore, data from the other two axes is disregarded by the algorithm. The bottom part of Figure 4 shows both standing (flat signal) and walking (oscillating signal) stages of typical, raw, Y-acceleration data (in dark blue), as well as the detected steps by TripleBeat's algorithm (as positive peaks on the cyan signal).

The algorithm used by TripleBeat operates in the time domain and is similar in nature to the heart rate detection algorithm. The raw Y-acceleration signal is first low-pass filtered to obtain *AccelYLowPass*. Another low-pass filter is applied to the original raw Y-acceleration signal using a much lower pass frequency to obtain an adaptive threshold *AccelYThreshold* (in magenta in the Figure). A step is detected when the filtered signal (AccelYLowPass) is larger than the adaptive threshold (AccelYThreshold). A new step is detected only after the filtered signal has gone below the threshold. The instantaneous number of steps per minute is given by the inverse of the time period between detected steps, which is then multiplied by 60 to obtain steps per minute:

$$SPM_i = 60 \times \frac{1}{TimeBetweenSteps} \quad (2)$$

A median filter is also applied to SPM_i to obtain the final number of steps per minute, SPM.

To validate the accuracy of the proposed heart-rate and pace detection algorithms, we ran a set of experiments comparing the output of our algorithms with that of commercial systems, including the popular Polar heart rate monitor and other standard acceleration-based pedometers [Melanson et al., 2004]. We found no performance differences.

Before presenting TripleBeat's music selection algorithms, we first present some background information on cardiovascular training.

HEART-RATE TARGET ZONES

Heart-rate is perhaps the best indicator of the intensity level at which a subject is exercising, as it adapts to the subject's changes in oxygen requirements. In the sports science community, training zones are the most popular tools to characterize the correlation between the type of exercise with its level of cardiac stress (and in turn with its specific fitness benefits). One of the most effective methods to define training target zones is via the *Heart Rate Reserve*, $HR_{reserve}$, formula, which is defined as the difference between the subject's maximum heart-rate (HR_{max}), and his/her resting heart-rate (HR_{rest}). Both maximum and resting heart-rates can be either empirically measured or approximated. Miller's equation [Miller et al., 1993] is, for instance, a commonly accepted approximation for HR_{max}. It is given by the expression: $HR_{max} = 217 - (0.85 \times age)$. TripleBeat uses Karvonen's formula

$$PHR_{reserve} = (HR_{max} - HR_{res}) \times P + HR_{res} \quad (3)$$

to define user-specific training zones based on the percentage (P) of the user heart-rate's reserve.

Clearly, user-specific heart-rate zones must be defined using his/her maximum and resting heart-rates. Additionally, note that variations on a user's heart-rate are relatively slow, requiring seconds or minutes to adjust to a specific range of values.

Using $HR_{reserve}$ as a reference point, different zones have been defined using 10% increments. Each zone can then be related to the fitness benefits that will be achieved during a workout [Edwards, 1999]. Table I summarizes exercise types and fitness benefits when exercising at each training zone.

Based on the user's personal information and high-level goals, TripleBeat will automatically select the ideal training zone for the user.

MUSIC LIBRARY AND MUSIC SELECTION ALGORITHMS

Auditory feedback is used by TripleBeat to encourage the user to accelerate, decelerate or maintain a running pace, acting as a personal trainer. A key observation is that music improves gait regularity due to its beat, which motivates individuals to maintain a specific pace [Staum, 1983]. When both music and motion are rhythmically similar, they are believed to combine and synchronize.

E. Digital Music Library

TripleBeat's Digital Music Library (DML) is stored in the mobile phone's memory. In our experiments, the DML consisted of 70 MP3 songs, with durations that vary from just over two minutes to almost six. Tempi ranged from 65 to 180 beats per minute, and the collection spanned a variety of genres including pop, techno, soul and hip-hop, with both instrumental and vocal songs. For each song, TripleBeat stored additional information, such as the song's tempo[7] and energy, both in 20s window intervals and for the entire song. The music selection algorithm described in this Section takes into account the song's duration and tempo. Figures 5 and 6 show three histograms of the average tempo, duration and genres (and subgenres) of the songs in the DML.

[7]Determined automatically or manually.

TABLE I.
TRAINING ZONES AND THEIR RESPECTIVE EXERCISE TYPES AND BENEFITS

Zone	Exercise Type and Fintess Benefits
Healthy ($50-60\% HR_{reserve}$)	Walk: Decrease body fat, blood pressure and cholesterol.
Temperate ($60-70\% HR_{reserve}$)	Slow jog: Same benefits as healthy zone, but burns more calories.
Aerobic ($70-80\% HR_{reserve}$)	Steady jog: Improves cardiovascular/ respiratory system and increases heart's size/strength.
Anaerobic ($80-90\% HR_{reserve}$)	"Burning" run: Same benefits as aerobic, but burns more calories (less fat).
Maximal/Red Zone ($90-100\% HR_{reserve}$)	Full out run: Used in interval training.

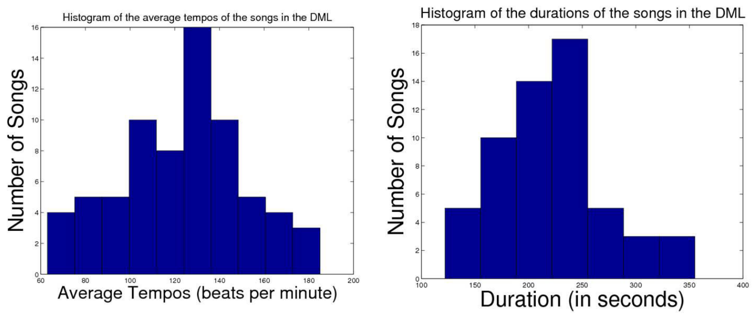

Figure 5. Histograms, from left to right, of the average tempo and duration of the songs in the DML

F. Music Selection Algorithms

Audible feedback is provided to the user by TripleBeat in either of two ways: (1) with a metronome or (2) with music.

A *metronome* is a device that produces regular clicking or beeping sounds with a steady tempo. TripleBeat contains a library of metronome tracks with tempi ranging from 100 to 200 beats per minute. Each track is 2 minutes long and a constant tempo is kept throughout the whole track. Two distinct beating sounds can be heard on these tracks. The first sound keeps the tempo. The second sound complements tempo and also indicates rhythm (number of beats per measure). A 4 beat rhythm is used, which means that the second sound is heard after three repetitions of the first one, *e.g. tic tic tic toc tic tic tic toc, etc*. The motivation for using a *metronome* in TripleBeat is to isolate *tempo* from all other musical features that could have an impact in the user's response, such as *perceived* tempo, the music's average energy and its variance, and even emotional factors. Therefore, the metronome mode would provide a better understanding of the impact of tempo in the runner's pace.

Figure 7 shows a typical example of TripleBeat's music selection algorithm with real data. The top graph shows the user's heart-rate in red and the target heart-rate is in blue. This graph also highlights 4 heart-rate zones, namely, from bottom to top: (a) temperate, (b) aerobic, (c) anaerobic and (d) maximal [Edwards, 1999]. The workout shown includes sections that fall within the temperate, aerobic and anaerobic regions. TripleBeat keeps runners from reaching the over-exertion region. The bottom graph shows the runner's actual pace (in green) and the metronome or song's tempo (in magenta). The highlighted regions in this graph correspond to running paces, from walking to sprinting.

During a workout, TripleBeat keeps playing the current track[8] until one of the following three conditions is true.

1. The current track is about to end (*e.g.* 10s before the actual end): In this case, TripleBeat determines whether the user needs to increase, decrease or keep the actual running pace. This decision is made based on

[8]In the following, we will use the term *track* to indistinctively refer to a song from the DML or a metronome of a particular tempo.

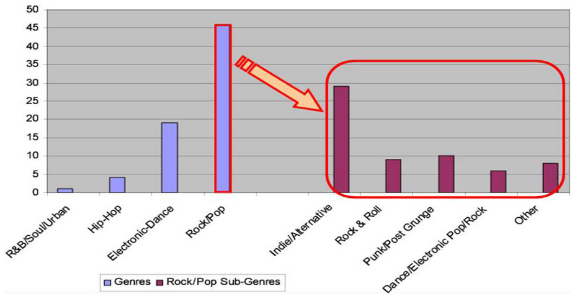

Figure 6. Histogram of the genres and subgenres of the songs in the DML

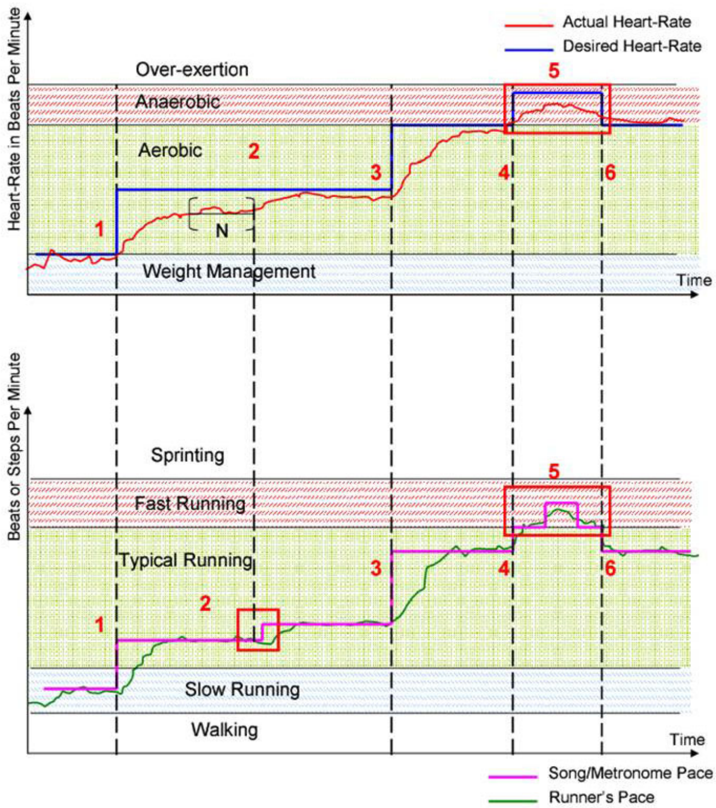

Figure 7. TripleBeat's music selection behavior.

the difference between the user's *average heart-rate*, during the last N seconds (where N is typically 25) and the *target heart-rate* given by the workout. Once it has determined the action to take, the DML is searched for the optimal track to play.

TripleBeat analyzes several factors to appropriately choose the next track. Depending on the current situation, it will search for a track whose beat is similar, higher or lower than that of the one currently being played, according to the difference between the actual and desired heart-rates. In the event that the workout target is about to change (*e.g.* within the next 20 seconds), TripleBeat selects a track appropriate to the *next* workout target.

Region 2 in Figure 7 illustrates this behavior. As can be seen in the graph, the user's average heart-rate (in red) has been lower than the target heart-rate (in blue) during the last N seconds. Because the user is maintaining a running pace close to the current track's tempo (as can be observed in region 2 of the bottom graph), TripleBeat selects a track with a higher tempo than that of the track currently being played. The increase in the track's tempo is proportional to the difference between the target and actual heart-rates. Additionally, TripleBeat acknowledges the user's physical limitations and avoids tempo increments larger than a certain threshold (*e.g.* $5-10\%$). Notice how as the tracks's tempo increases (right part of Region 2 in the bottom graph), the runner's pace follows, and in turn his heart-rate increases as well (same region, top graph). Therefore, the target heart-rate is closely followed by the subject's heart-rate.

Training workouts should have paces within the *typical running* region (*e.g.* 140 to 170 steps per minute). TripleBeat treats paces that are outside the typical running region differently. Tracks with slower or faster tempi will be selected only if (1) the user's heart-rate must be decreased or increased and (2) the user has been closely following the current track's tempo for the past N seconds (where N is typically 10). Region 5 of Figure 7 is a good example of this behavior. In this case, the user's heart-rate is below the target heart-rate and in consequence, TripleBeat tries to speed up the user by selecting a track whose tempo is at the upper limit of the *typical running* region (first part of region 5, bottom graph). After this change, the user's heart-rate is still lower than the target, but because he/she still keeps up with the current song's tempo, TripleBeat now plays an even faster track (middle part of Region 5), which takes the subject into the *fast running* region. Now, the user's heart-rate increases accordingly, but he is no longer capable of following the track's tempo since it is too fast to keep up. In consequence, the next track (last segment of Region 5) will be chosen with a slower tempo, hoping that the user may synchronize back to it.

The previous analysis leads to a noteworthy phenomenon, which is supported by our experimental data: if a user is running at a significantly different pace than the tempo of the track being played, the system will have difficulty inducing running pace changes to effectively guide the user's heart-rate. However, if the user's pace is within a small range (*e.g.* 5 to 15 bpm) of the track's tempo, he/she will often synchronize his/her motion to the track's beat, allowing for efficient heart rate control.

2. The workout pattern changes, as when moving from warming-up (about 60% of maximum heart-rate reserve[9]) to weight management (about 70% of maximum heart-rate reserve). Regions 1, 3, 4 and 6 of Figure 7 are examples of this situation. In this case, TripleBeat will stop the track currently being played (unless the song has been playing for a short time, *e.g.* 20s, in which case the song has already been selected based on the new target heart-rate) and will search for a song as described in condition (1), taking into account the difference between desired and current heart-rates, and the current runner's pace.

3. The user requests to change the song. In this case, TripleBeat selects the a new song from the DML whose features still satisfy the constraints given the current situation.

The current implementation of TripleBeat makes use of two empirically learned functions, one that maps the influence of the music's beat with the running pace and another one that maps running pace with physical stress (heart-rate). The data used to parameterize these functions was obtained from a varied population of runners which allows TripleBeat to make statistically accurate track selections. We envision further versions of the system that will continuously incorporate user-specific information into these functions in order to increase the accuracy and effectiveness of the track selection algorithm.

VIRTUAL COMPETITION & GLANCEABLE INTERFACE

In this Section, we focus on TripleBeat's two additional persuasive techniques to motivate runners in achieving their exercise goals: (1) a virtual competition with other runners and (2) real-time personal awareness via a glanceable interface.

G. Virtual Competition as a Persuasive Technique

A hypothesis that we wanted to validate with the TripleBeat prototype was that users can be more motivated to achieve their predefined workout goals when participating in a social competition. Therefore, TripleBeat was designed to create challenges between the user and other runners, including fictional runners, real runners that have previously run with the system, or the actual user on past runs. The main feature of TripleBeat's competition approach is that it does not reward runners who run faster, burn more calories or arrive earlier to a particular landmark. The competition is instead defined by how well users achieve their predefined goals, thus encouraging users to workout in a *healthy* manner (*i.e.* maintaining their heart-rate as close as possible to the suggested target heart-rate). In the following, we describe how TripleBeat evaluates competitors during the workout and how it selects appropriate opponents according to the user's profile.

1) Performance Score Function: A well-designed competition defines an unbiased *score function* that summarizes how well users achieve their predefined exercise goals. This score function should ensure the user's success in achieving the predefined workout goal while feeling appropriately challenged. Users typically lose interest in competitions that others could easily cheat on, or that require a skill level significantly lower or higher than their own. In addition, if the score function persuades runners to go beyond their physical limits, consequences could be dangerous. Therefore, we designed a score function that is safe, fair and easy to understand.

[9]As given by Equation 3.

The score function consists of the linear combination of two components. The first component, *ZoneAccur* guarantees that the partial computed score is always proportional to the amount of time spent by a certain runner inside the proposed training zone. Equation 4 presents a cumulative measure for this score:

$$ZoneAccur(x) = \frac{SecondsInZone}{x} \tag{4}$$

where x is the duration (in seconds) of the workout.

As can be noticed, the score given by Equation 4 always has a value in the interval between zero and one. The closer the value to 1, the closer the user's performance to his/her desired high-level goals –*i.e* heart-rate remains inside the proposed *training zone* more often.

The ZoneAccur function captures correctly the runner's performance according to the competition criterion. However, it still lacks information on how accurate the runner's heart-rate is in relation to the target heart-rate. In other words, if two runners spend the same amount of time inside their target zones, ZoneAccur will not identify which one is doing better than the other, *i.e.* whose heart-rate is on average closer to the target heart-rate. Therefore, we added a second component to the score function named *Heart-Rate Accuracy* (HR_{Accur}), and given by Equation 5.

$$HR_{Accur}(x) = \frac{|fac(x) - lowest|}{|HR_{target} - lowest|} \tag{5}$$

where

$$fac(HR) = HR_{target} + \tag{6}$$

$$\frac{1.5^{-\frac{|HR_{target}-HR|}{\sqrt{2\times HR_{target}}}} - 1.5^{\frac{|HR_{target}-HR|}{\sqrt{2\times HR_{target}}}}}{2}, \tag{7}$$

$$lowest = min(fac(HR_{rest}), fac(HR_{max})) \tag{8}$$

where HR_{target} is the target heart-rate and HR is the current heart-rate.

Note that the Heart-Rate Accuracy function reaches its highest value on the HR_{target} and falls as a hyperbolic function, reaching zero when $HR = HR_{rest}$. The hyperbolic function was chosen to benefit runners that maintain their heart-rate closer to the HR_{target}, and penalize those that deviate from it.

TripleBeat computes the final score as a linear combination of HR_{Accur} and $ZoneAccur$, given by:

$$Score(x) = 0.5 \times HR_{Accur}(x) + 0.5 \times ZoneAccur(x) \tag{9}$$

Figure 8 illustrates the behavior of the score function computed for a hypothetical runner.

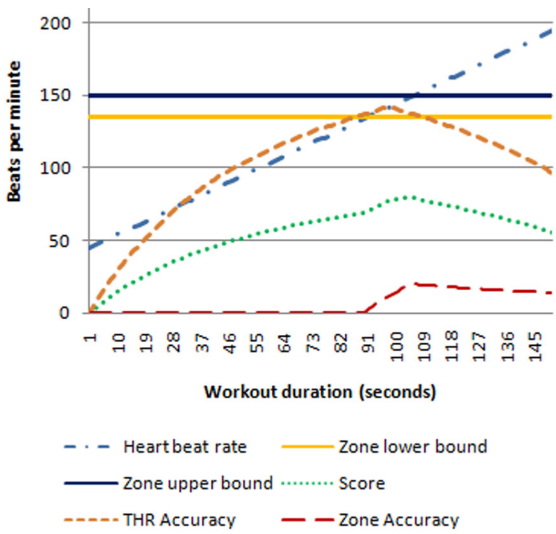

Figure 8. Example of the score function computed for a hypothetical runner with constant heart-rate acceleration of 1 beat/second, resting heart-rate of 45 BPM and maximum heart- rate of 195 BPM. The cumulative score increases as the runner's heart-rate approaches the target heart-rate band (*Zone Lower Bound:* 136 BPM) and decreases as the heart-rate leaves the target heart-rate band (*Zone Upper Bound:* 150 BPM). Note that *Zone Accuracy* and *THR Accuracy* are normalized by the runner's target heart-rate of 143 BPM to ease visualization.

TripleBeat computes the score function given by Equation 9 every second to determine the positions of every runner in the competition. Another attribute computed during workout is the score *difference* between opponents in a $0 - 100$ scale for feedback purposes.

2) Real-time Competition and Opponents Selection: In addition to ensuring a fair score function, an engaging and motivating competition needs to provide opponents of similar skill level when compared to the user. In order to do this, TripleBeat stores information about all the runners and their performances. Before starting a workout, the user is given the option to select his/her competitors manually or automatically. TripleBeat's automatic opponent selection algorithm uses a variation of the k-nearest neighbor algorithm to choose registered users whose scores are the closest to that of the current user. In addition, TripleBeat always selects *at least one* opponent with slightly better performance than the user.

H. A Glanceable Interface as a Persuasive Technique

TripleBeat provides real-time feedback about the runner's physiological responses, both auditory –via the selected music– and visual –by means of its graphical interface. A major constraint in designing a user interface for a mobile phone is its reduced screen. In addition, mobile users add the challenge of having to interact with the device while in motion. The information displayed on the mobile phone, when appropriately presented, should enhance and support the runner's decision making process during the workout. Therefore, we developed a *glanceable* interface for the TripleBeat system that would enable quick intake of visual information with low cognitive effort.

Figure 9 displays two exemplary screenshots of TripleBeat's glanceable interface. The screenshot on the left of the Figure illustrates the visual feedback when the the runner needs to *take an action* to move inside the proposed training zone. TripleBeat displays a red background and other visual clues (*i.e.* plus/minus signals, heart-rate difference) to indicate that the runner needs to increase or decrease the running pace. On the other hand, the screen turns green when the user's heart-rate enters the training zone, as shown on the right screenshot.

Accurate real-time information (obtained every second) is critical to increase the runner's personal awareness during the monitored workout. Moreover, TripleBeat's interface presents information about the competition, such as the runner's current position and the difference in score to the next and previous opponents. Finally, the bottom part of the interface displays the total number of calories burned, the workout elapsed time and the name of the song being played.

Figure 9. TripleBeat's V2 glanceable interface. The screen on the left uses red color semantics to inform the user that his/her current heart-rate is outside the suggested training zone. The plus sign indicates the need to speed up the heart-rate by 6 BPM. The screen on the right illustrates the case where the user's heart-rate is inside the target zone –hence the green background color. In this case, TripleBeat displays the actual heart-rate, as there is no need to increase or decrease the heart-rate. The user's position in the competition is shown on the right side of the interface. Right below, there are the names and distance in score to the opponents. The lower part of the interface displays, from left to right, the total number of calories burned and the total time of workout. Finally, the name of the song currently being played is shown at the very bottom together with a progress bar underneath.

Musical Feedback User Study

To validate the TripleBeat prototype, we conducted two user studies. The goal of the first user study was to validate TripleBeat's musical feedback as a persuasive technique. The second user study was designed to evaluate TripleBeat's two other persuasive techniques: its glanceable interface and virtual competition.

This Section is devoted to describing the first user study, while the next Section will present the results of the second user study. The first user study expanded for a period of 9 weeks. Participants were amateur runners who ran with the TripleBeat system for up to 4 running sessions of 42 minutes long each.

Note that the TripleBeat system that runners used in the first user study was the *first* version of the system, named MPTrain or TripleBeat V1. TripleBeat V1 did not have a glanceable interface nor a virtual competition feature. Its only persuasive technique was the musical feedback. Figure 10 depicts TripleBeat's V1 user interface. As shown in the Figure, this user interface significantly differs from TripleBeat's V2 glanceable interface, depicted in Figure 9.

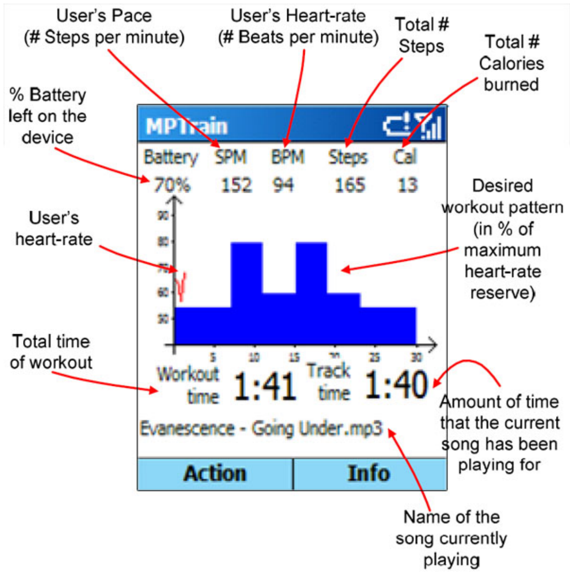

Figure 10. TripleBeat's V1 main user interface.

I. Hypotheses

The main hypotheses for this first user study were:

1) Runners listening to music or metronome as selected by TripleBeat are able to achieve their predefined workout goal *better* than when running without any music or with randomly selected music;
2) Runners listening to TripleBeat's music *enjoy* their workout more than when running without music or with randomly selected music;
3) Runners listening to TripleBeat's auditory feedback *perceive* their run as more effective towards reaching their workout goal than when running in silent or random modes.

J. Measures

In order to investigate the validity of the hypotheses previously presented, we quantitatively measured the following variables:

a) Task Performance: Task performance was measured by the % of time that the user spent running inside the training zones associated to the proposed workout pattern. In practice, this was computed as the % of time that the user's % heart-rate reserve (see Equation 3) was within a $[-5, +5]\%$ range of the target percentage of heart-rate reserve, as commonly defined in the exercise physiology literature [Edwards, 1999];

b) Enjoyment: A subjective quantitative measure about the runner's enjoyment of the workout. We obtained this measure via a post-run questionnaire in which participants had to: (1) rate their run on a scale from 1 to 10 in terms of enjoyment and (2) compare it to previous runs with and without the system;

c) Perceived Usefulness: A subjective quantitative measure about the runner's perception about the exercise effectiveness towards achieving the workout goal. We obtained this measure via a post-run questionnaire in which participants had to: (1) rate the run's effectiveness on a scale from 1 to 10 and (2) compare it to previous runs with and without the system.

K. Design

We designed four running sessions to evaluate the impact of TripleBeat's musical feedback. Each session corresponded to one of the following running conditions:

1) *Mute condition:* Participants had to run and follow the proposed workout without any audio feedback;
2) *Random condition:* Participants had to run and follow the proposed workout listening to random music;
3) *Metronome condition:* Participants had to run and follow the proposed workout listening to a metronome controlled by TripleBeat;
4) *TripleBeat condition:* Participants had to run and follow the proposed workout listening to songs selected by TripleBeat.

All participants first ran in the *mute* condition, which was useful to give them a certain level of expertise with the system's hardware and software. In addition, we could also obtain good estimates of each participant's

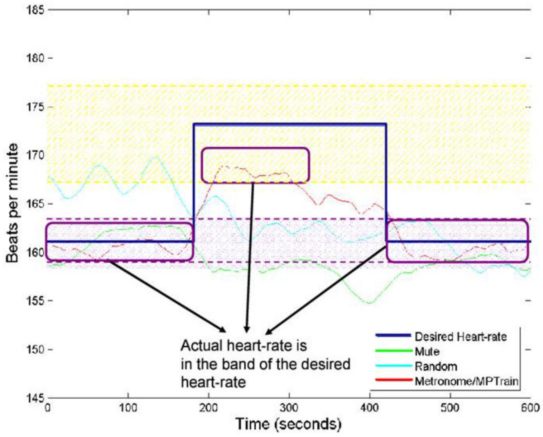

Figure 11. Detail of the heart-rate zones defined for 2 of the workout regions. The Figure highlights the areas where the runner's heart-rate is within the band for each of the running conditions.

resting and maximum heart-rates. The order for the rest of the running conditions was randomly assigned to participants to avoid bias. We carried out a statistical analysis of the participants' data by means of a factorial within-subject design with one independent variable, named *condition* (referred to each of the running sessions).

In the remaining of the discussion we will refer to the runs with auditory feedback as *TripleBeat/Metronome*, without distinguishing between them. We shall present quantitative and qualitative differences between them in Section -P.1.

L. System Setup

All participants used the same hardware and software. As described in Section -B.4, we used an AliveTec ECG and acceleration monitor attached to either a leather chest-band that contained the 2-lead ECG sensors or to 2 adhesive ECG electrodes. The sensors were wirelessly connected to an Audiovox SMT5600 mobile phone running the TripleBeat's software. The same Digital Music Library was used for all runners to ensure consistency among running sessions (see Section -D). In addition, we offered an armband pouch to carry the mobile phone during sessions. Interestingly, the pouch was used by 50% of the runners. The other 50% of runners preferred to track their performance visually and therefore chose to carry the phone in their hand.

M. Participants

Participants were recruited by email advertisement within a big corporation. Twenty participants[10] (13 men and 7 women) ran at least once with the system. The average age was 36 years, ranging from 24 to 63, and all participants were regular runners of various levels of expertise and fitness (4 runs of 52 minutes per week on average).

From the 20 participants, 13 (9 men and 4 women) completed at least three runs with the system and 7 finished only one or two runs due to traveling, injury (not related to the user study) or sickness. About 35% typically ran with partners (7 participants), 60% had worn a heart rate monitor while running (12 participants), but only 40% wore one regularly (8 participants). With respect to their music listening habits, 12 participants regularly listened to music while exercising. The two main reported reasons for listening to music were because music *"helped pass time faster"* (11 participants) and *"helped them maintain a certain pace"* (10 participants). In the group of runners who did not enjoy running with music (8 participants), the most commonly cited reason was that *"the music device was too cumbersome"* (5 participants).

N. Task

Each running session consisted of a 42 minute workout in which participants had to follow the training pattern displayed on the phone (see Figure 12). The workout included a warm up of 5 minutes (65% of heart-rate reserve), three jogging periods of 8 minutes (75% of heart-rate reserve), two running periods of 4 minutes (85% of heart-rate reserve), and a cool down phase of 5 minutes (65% of heart-rate reserve).

Moreover, all participants were asked to run on the *same* trail for all of the runs in the study, and preferably on a *flat* surface. Note that the current version of TripleBeat does not account for incline on the terrain. Therefore, all changes in the runner's heart-rate are assumed to have been caused by changes in the runner's pace.

[10] Initially, we had a pool of 36 registered participants.

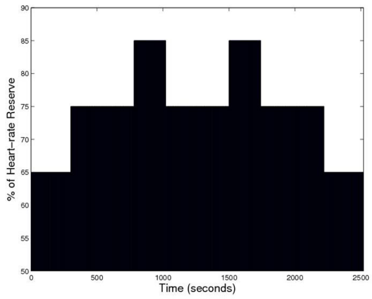

Figure 12. Workout pattern used in the musical feedback runner study.

TABLE II.
PERFORMANCE UNDER EACH OF THE RUNNING CONDITIONS

	Running Condition		
	Mute	**Random**	**TripleBeat/Metronome**
Mean % Time HR in Range	42.6	41.7	**54.0**
Mean HR Error (% of reserve)	5.1	4.1	**2.5**
Mean % Time SPM in Range	N/A	7.0	**33.1**
Best Mode (%)	30.8	7.7	**61.5**
Best SPM (%)	N/A	11.1	**88.9**

O. Procedure

Participants took part in up to 4 running sessions on 4 separate days. Each session corresponded to a running condition: (1) *mute* or without music; (2) *random* or with randomly selected music; (3) *metronome* or with a metronome as selected by TripleBeat; and (4) *TripleBeat* or with music as selected by TripleBeat.

Before their first session, participants filled out an online questionnaire to record personal data and attributes, including their exercise and running experience.

The first running session started with instructions and a demonstration on how to use the TripleBeat prototype. Next, they were asked to put on the system to verify that the hardware was properly working and to compute their resting heart-rate. Finally, they were shown how to use TripleBeat's user interface. The goal of the study was emphasized during this set-up period: participants were supposed to achieve the workout pattern that appeared on the phone's interface and is depicted in Figure 12. Once they were confident with how to use the system (typically after 5 or 10 minutes), they were sent off for a 42 minute run in *mute* mode (*e.g.* without any music).

After the run on *mute* mode was finished, they returned the system to us and were asked to fill out an online post-run questionnaire for the *mute* condition.

The running conditions for the rest of the sessions were randomized. After each session, they were asked to fill out the corresponding online post-run questionnaire.

To further motivate the runners to achieve the workout goals, we offered a 50$ gift certificate to the runner whose heart-rate best tracked the desired workout heart-rate in *any* of the running conditions.

P. Data Analysis

Table II summarizes the quantitative analysis of the data. Note that the Table contains the average results for the *TripleBeat* and *Metronome* modes, in order to better understand the impact of providing auditory feedback to the user versus not. The differences between the *TripleBeat* and *Metronome* modes appear in Table III. Finally, the highlighted cell on each row corresponds to the *best* condition.

The first row of Table II contains the mean percentage of time that the runner's percentage of heart-rate reserve was within a $[-5+5]\%$ band of the desired percentage of heart-rate reserve. The second row contains the mean error in the runner's heart-rate when compared to the desired heart-rate (in percentage of heart-rate reserve). The mean percentage of time that the runner's pace (in steps per minute or SPM) was within a $[-5+5]\%$ band of the desired tempo (in beats per minute) appears in the third row. The percentage of time that each mode was the *best* mode – as measured by how well it helped the runner achieve the workout goal – is summarized in the fourth row. Finally, the last row contains the percentage of time that the runner's pace *best* matched the desired tempo, for each of the running conditions.

As can be seen on the Table, the *TripleBeat/Metronome* condition was the *best* in all cases, *i.e.* it caused runners to spend more time in the target heart-rate zone and with the target pace.

TABLE III.
PERFORMANCE OF THE TRIPLEBEAT VERSUS METRONOME CONDITION

	Running Condition	
	TripleBeat	**Metronome**
Mean % Time of HR in Range	45.7	**62.3**
Mean HR Error (% of reserve)	3.2	**1.8**
Mean % Time SPM in Range	25.6	**40.6**
Best Mode (%)	23.1	**38.5**
Best SPM (%)	33.3	**55.6**

1) TripleBeat's Music vs Metronome: Our study revealed significant quantitative and qualitative differences between the *TripleBeat* and *Metronome* modes[11]. Table III summarizes the quantitative measures for the *TripleBeat* vs *Metronome* conditions. As can be seen on the Table, the *Metronome* mode was superior to *TripleBeat* in all quantitative measures.

Some of the reasons that might have contributed to the *Metronome's* superior performance include: (1) In order to minimize the differences between participants, all runners ran with the same music, instead of using their personal music collection. Consequently, some participants were more familiar with the songs than others and some enjoyed the music selection more than others. This fact had an impact on how well they could identify the songs' tempi. Conversely, all runners were able to quite easily identify the metronome's tempi; (2) Some of the songs probably elicited an emotional response in some of the runners. This effect was certainly non-existent with the metronome; (3) About 20% of the runners did not identified the tempo of the songs correctly. Therefore, they synchronyzed their pace to their *perceived* tempo rather than the actual tempo. This phenomenon never occurred with the metronome.

In terms of enjoyment, the *TripleBeat* condition was significantly more enjoyable than the *Metronome*, as explained in Table IV) and Section -Q.

2) Individual Differences: During the study, we observed significant personal differences from participant to participant. Note that TripleBeat is designed to be a highly *personal* and adaptive system. However, in this study, we asked all participants to do the same workout routine and to listen to music from the same DML. Therefore, not all participants responded the same to the workout routine and music selection.

The *task performance* for the 13 participants who completed the runs under the *mute, random* and *TripleBeat and/or Metronome* conditions is depicted in Figure 14. In both graphs, the X-axis corresponds to the participant's number. The Y-axis corresponds to the % of time that the runner's heart-rate was within the target zone (top graph) and the runner's pace was within the target tempo (bottom graph). From the Figure, we can identify 3 groups of individuals, based on their response to TripleBeat's auditory feedback:

1) Almost 50% of the participants responded *very well* to TripleBeat's coaching style via auditory feedback. These runners consistently adjusted their pace with the music. In consequence, their heart-rates tracked significantly better the desired workout than in the conditions without any explicit feedback (*mute* and *random*). Arrow 1 on the Figure points to an exemplary runner belonging to this group.
2) A second group of runners (about 30%) adjusted their pace as needed, but did not achieve a significant improvement with respect to the *mute* and *random* conditions. We believe that runners in this group would perform better with practice. Interestingly, in a few cases runners in this group adjusted their pace *incorrectly*. For example, when the system was cueing them to run faster, they would slow down and vice-versa. We shall address this topic later. Arrow 2 points to an exemplary participant from this group.
3) Finally, about 20% of the runners did *not* change their running pace when cued by the system. These runners seemed to be very accustomed to their running habits and workout. Therefore, they did not deviate from them during the study, even though they knew that they had a specific workout goal to achieve. Arrow 3 illustrates an exemplary runner in this group.

Figures 13 and 15 illustrate the impact of TripleBeat's auditory feedback on two different runners.

An exemplary performance of the same runner under the *mute*, *random* and *TripleBeat/Metronome* conditions is depicted in Figure 13. The runner's actual and desired heart-rates are shown in red and blue respectively. As can be seen in the Figure, the runner's heart-rate nicely tracks the desired heart-rate *only* in the *TripleBeat/Metronome* condition, being unable to do so in any of the other conditions. The impact of the auditory feedback on this runner is very significant.

Finally, Figure 15 shows the performance of a different runner with the *Metronome* condition. This Figure illustrates the impact that the running pace has on the runner's heart-rate. On the top, there is the runner's actual (in red) and desired (in blue) heart-rates. On the bottom, there is the runner's actual pace (in blue) and the metronome's tempo (in green). Note how the runner's pace closely adjusts to the metronome's tempo. This causes his heart-rate to increase or decrease accordingly. In consequence, the runner's heart-rate tracks the desired workout heart-rate very well.

[11]From the thirteen runners that ran on *TripleBeat*, 10 runners also ran with the *Metronome*.

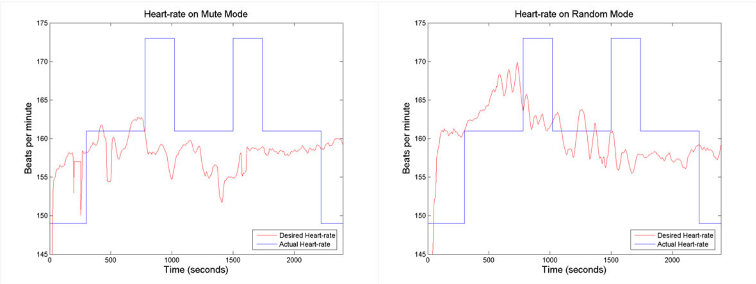

Figure 13. Desired (blue) and actual (red) heart rate for a runner on mute (left), random (middle) and TripleBeat/Metronome mode (right). Note how in the TripleBeat/Metronome condition the runner's heart-rate follows the desired heart-rate.

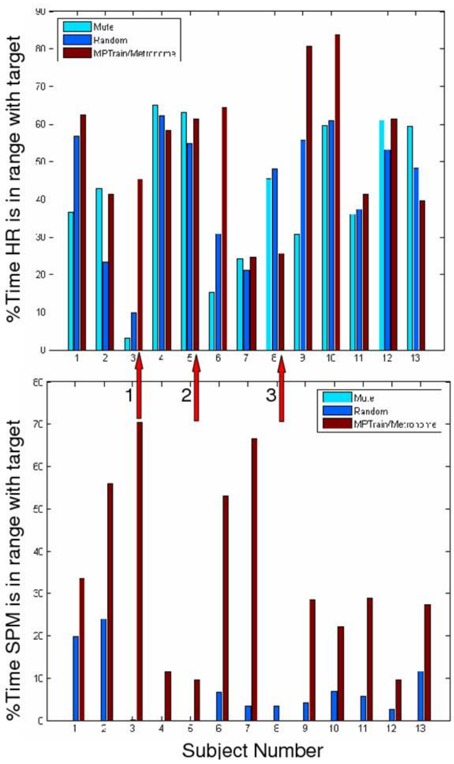

Figure 14. Top Graph: Percentage of time spent within a 5% band of the target heart-rate for 13 runners, where cyan corresponds to *mute* mode, blue to *random* mode and maroon to *TripleBeat/Metronome* mode. Bottom Graph: Percentage of time spent within a 5% band of the target tempo for the same 13 runners, where cyan corresponds to *mute* mode, blue to *random* mode and maroon to *TripleBeat/Metronome* mode.

In order to further understand individual differences, we carried out a small user study. With this study, we wanted to understand the differences between *actual* and *perceived* tempo. In addition, we intended to explore which music features might have an impact on the *perceived* tempo of a song. The main result of this study was that *subdivisions of the major tempo in a song have a substantial impact its perceived speed*. The results of our study also suggest that such a perception is shared between subjects. Therefore, it could be possible to add the user's *perceived* tempo to TripleBeat's song metadata and use that tempo in the music selection algorithm. We plan to do so in the next versions of the system.

Q. Questionnaire Analysis

Table IV summarizes our findings from the post-run questionnaires. The figure in bold highlights the running condition that scored highest for each of the questions.

We shall highlight a few observations that can be drawn from the Table:

1. Under the *TripleBeat/Metronome* condition, runners perceived that they ran for a *longer* distance than in any

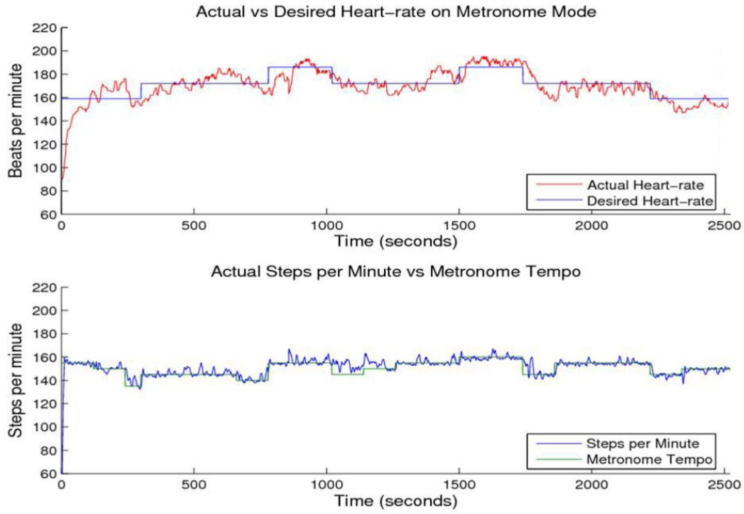

Figure 15. Top Graph: Desired (blue) and actual (red) heart-rate for a user running on Metronome mode. Bottom Graph: Metronome's tempo (green) and user's pace (blue) in steps per minute. Note how well the user is able to track the metronome's tempo with his pace. In consequence, his heart-rate nicely tracks the desired heart-rate.

TABLE IV.
SUMMARY OF QUESTIONNAIRE ANSWERS

	Running Condition			
	Mute	**Random**	**TripleBeat**	**Metron.**
>5 miles (%)	76.4	76.5	**92.3**	81.8
not cumbersome	76.4	64.7	**92.4**	91.0
more energy	76.4	**94.1**	76.9	91.0
more effective	70.7	88.2	84.6	**91.0**
more effective towards workout goals	64.7	64.7	84.6	**91.0**
equally or more enjoyable	52.8	76.5	**76.9**	63.7
more effective within study	N/A	29.4	76.9	**77.8**
worked harder within study	N/A	29.4	23.1	**36.4**
more enjoyable within study	N/A	76.5	**92.3**	54.7
music increased enjoyment	N/A	77.62	**100**	81.8
music **slightly** matched workout goals	N/A	23.5	**46.2**	45.5
music **strongly** matched workout goals	N/A	0.0	**30.8**	27.3
music **slightly** assisted achieving goals	N/A	35.3	**46.2**	45.5
music **strongly** assisted achieving goals	N/A	0.0	**38.5**	36.4

other condition, even though the workout duration was exactly the same for all conditions.

2. The prototype was reported to be *less* cumbersome (second row on Table) when running on *TripleBeat/Metronome* mode.

3. The workout was considered more effective – both than average and within the study – and more enjoyable – both than average and within the study – when running on *TripleBeat/Metronome* mode than on any other mode (rows 4, 5, 7 and rows 6, 9, 10 respectively).

4. Finally, participants found that the music as selected by TripleBeat *strongly* matched the workout goals and assisted them in achieving those goals (rows 11 to 14).

GLANCEABLE INTERFACE & COMPETITION USER STUDY

The first runner study was designed to validate the impact of musical feedback to assist runners in their workout. Therefore, the second user study was dedicated to analyzing the impact of a glanceable interface and a virtual competition. In the following, we shall refer to the TripleBeat system *without* glanceable interface and competition features as TripleBeat V1 or V1. The prototype with full functionality will be referred to as TripleBeat V2 or V2. TripleBeat's V1 and V2 user interfaces are depicted in Figures 10 and 9, respectively. Note that the first version of the TripleBeat system that was used in the first user study (TripleBeat V1) neither included a glanceable interface nor a competition feature.

R. Hypotheses

The goals of the second user study were to: (1) Evaluate TripleBeat's V2 efficacy in assisting runners to achieve a predefined workout when compared to V1; (2) Evaluate TripleBeat's V2 enjoyment of use when compared to V1's and (3) Validate TripleBeat's V2 persuasive techniques. The main hypotheses for this user study were:

1) Runners using TripleBeat V2 are *more effective* in reaching their predefined workout goals than when using TripleBeat V1;
2) Runners using TripleBeat V2 *enjoy* their workout more than when using TripleBeat V1.

S. Measures

Thus, two measures were quantitatively evaluated in the study:

1) *Efficacy:* This measure quantifies how often the runner's heart-rate remains inside the proposed training zone. We captured this measure *objectively*, by computing the percentage of time spent running inside the training zone[12], and *subjectively*, by asking participants about their impressions over the system's efficacy (reported in post-run questionnaires answered after each of the running sessions);
2) *Enjoyment:* This measure evaluates the quality of the user experience, particularly in terms of the enjoyment of their interaction with the prototype. We captured this measure *subjectively* via appropriate post-run questionnaires given to the participants after each of the running sessions.

T. Design

We designed two assays in order to investigate the advantages of the proposed persuasive techniques:

1) *TripleBeat V1 vs TripleBeat V2*: The first assay evaluated efficacy and enjoyment of TripleBeat V1 and V2. This assay investigated the relevance of V2's novel persuasive techniques in the context of personal monitoring systems;
2) *Competition vs No Competition*: The second assay evaluated efficacy and enjoyment of TripleBeat V2 with and without competition. The goal was to investigate the impact of social pressure.

U. Participants

Ten participants[13] (8 men and 2 women) were recruited by email advertisement within a big corporation and completed all the user study requirements, including all running sessions and surveys. Their ages ranged from 25 to 41 years ($\bar{x} = 33$). All participants were in good health and 9 were regular runners. Interestingly, the only participant that was not a regular runner chose the lowest intensity workout that corresponded to a brisk walk.

With respect to the 9 regular runners, they ran an average of 4 times per week with an average of 56 minutes per workout session. Only 3 runners confirmed their experience or interest in running with other partners, mostly to increase their motivation towards finishing the workout. The remaining 6 runners pointed out two advantages for running alone: no need to match schedules (2 participants) and flexibility in coordinating personal workouts (4 participants).

When asked about their experience on carrying a cell phone while running, 9 participants reported not using it for a variety of reasons, including not having a place where to put it, worrying about it getting damaged, not being able to talk and run, avoiding interruptions, and not being able to play music with it. In terms of their habits in listening to music while running, 5 participants reported listening to music with a portable media player during workout. The two main reasons for listening to music were that music was good to (a) make you forget the physical effort (3 participants) and to (b) focus on the workout (2 participants). Those who did not like listening to music while exercising found quiet runs with less distraction to be more enjoyable.

With respect to personal monitoring during workouts, 2 participants frequently wore heart-rate monitors and 6 had a prior experience with it. The main benefits pointed out were the ability to be aware of the training zone and to pace the effort during the run. Conversely, the other runners considered heart-rate monitors to be somewhat inconvenient and of questionable usefulness. Finally, 4 participants were familiar with the TripleBeat V1 system as they had participated in the previous TripleBeat runner study, described in Section -H.

V. Task

Participants took part in 3 to 4 outdoor running sessions, each divided in 3 phases: an initial warm up of 3 minutes, the actual workout of 40 minutes (where physiological and pace data were recorded and analyzed), and finally a cool down of 3 minutes. Each session corresponded to one of the following running conditions:

[12]Note that this is the second component of the score function given by Equation 9. We used the score function to select the opponents and perform the competition, but the efficacy in the study was measured by the more common measure of $ZoneAccur$.

[13]From an initial pool of 20 registered participants.

1) *TripleBeat V1 Baseline:* All participants did their first run with the TripleBeat V1 prototype, because TipleBeat's V2 virtual competition requires a database of previous runs before it can select opponents for any given user. Note that this restriction could prevent fair comparisons between the TripleBeat V1 and V2 systems, as every runner would have had their first run with V1, thus biasing the results. Therefore, we requested an additional run with TripleBeat V1 for some of the runners, and designed the appropriate methodology for unbiased data analysis, as explained below;
2) *TripleBeat V2 (No Competition):* Five participants were randomly chosen to do their second running session with TripleBeat V2 *without* the virtual competition. The following session for this group of runners was a third run with TripleBeat V2 in competition mode. For this session, runners were given the option of choosing their opponents either manually or automatically, based on their best previous run;
3) *TripleBeat V2 (Competition):* Likewise, the remaining five participants did their second running session with TripleBeat V2 in competition mode and their third run without the competition information;
4) *TripleBeat V1 Last Run:* This fourth session was created explicitly to address the bias issue raised by the first session, *TripleBeat V1 Baseline*. We randomly asked five participants to do a last run with TripleBeat V1. Therefore, the data analysis for the first assay could be performed by splitting the sample in two halves: one in which we considered the data from the *first* interaction with the V1 and V2 systems, and another in which we considered the data from the *last* interaction with them. This way, we could ensure a fair comparison on the first assay while still supporting the second assay.

In sum, the four running sessions were conducted considering the sample division in four groups as depicted in Table V. The first assay compared TripleBeat's V1 and V2 interfaces by considering data from the *first* interaction with the prototype on groups 1 and 2 (note that the 3^{rd} run in these groups was ignored to avoid bias, as previously explained), and the *last* interaction for groups 3 and 4 (likewise, the 1^{st} and 2^{nd} runs in these groups were ignored). As for the second assay, all values collected with TripleBeat V2 were used, because five runners started in competition mode (groups 2 and 3) and the remaining five started without it (groups 1 and 4).

TABLE V.
SAMPLE DIVISION IN FOUR GROUPS TO ENABLE COMPARISONS BETWEEN TRIPLEBEAT V1 AND V2 ON THE FIRST ASSAY, AND TRIPLEBEAT V2 WITH AND WITHOUT COMPETITION ON THE SECOND ASSAY.

Group	Subjects	Running Sequence
Group 1	1 and 2	1) TripleBeat V1 2) TripleBeat V2 (no competition) 3) TripleBeat V2 (competition)
Group 2	3, 4 and 5	1) TripleBeat V1 2) TripleBeat V2 (competition) 3) TripleBeat V2 (no competition)
Group 3	6 and 7	1) TripleBeat V1 (just for baseline) 2) TripleBeat V2 (competition) 3) TripleBeat V2 (no competition) 4) TripleBeat V1
Group 4	8, 9 and 10	1) TripleBeat V1 (just for baseline) 2) TripleBeat V2 (no competition) 3) TripleBeat V2 (competition) 4) TripleBeat V1

W. Procedure

Before each running session, we gave participants detailed instructions on how to use the prototype, followed by a demonstration. We also used this setup period to emphasize the goal of the study to the runners: to achieve their predefined workout goal by keeping their heart-rate as close as possible to the desired heart-rate. Participants had the chance to explore the interface before each running session, in order to become more familiar and confident in their use. This process typically took around 10 minutes. Once they were ready, they were sent off for a 46 minute exercise session (40 minutes of workout and an additional 6 minutes of warm up and cool down phases). Note that two system parameters were pre-determined by us for this study: the workout duration and the number of opponents for the virtual competition (two opponents).

With respect to the workout *intensity*, we allowed participants to select their preferred one among 4 options, ranging from an active walk or intensity level 1 (55% of $HR_{reserve}$) to cardio/strength gain or intensity level 4 (85% of $HR_{reserve}$). All levels of intensity were covered in this user study, as each of the intensities ranging 1 through 3 were chosen by 20% of the runners, and intensity 4 was selected by the remaining 40%. Once runners chose an intensity level, they were required to keep the same level for all the running sessions in the study.

Figure 16 presents an example of the typical setup screens shown by TripleBeat V2. Note that the right-most screen in the Figure was only shown during the competition session.

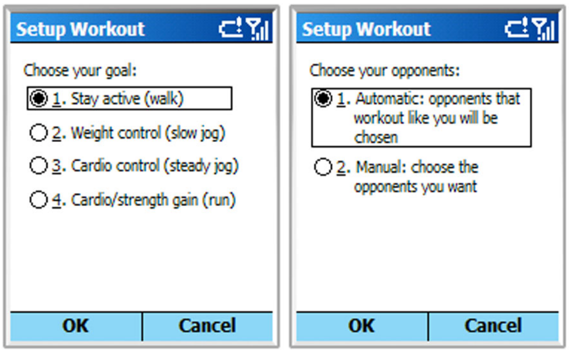

Figure 16. TripleBeat's V2 setup workout interface. The left screenshot captures the user's decision for a walking exercise by selecting the "Stay active" goal. The right screenshot reveals the user's preference for an automatic approach to select his/her opponents.

As soon as the running session was over, participants returned the equipment in person to the experimenter. They typically provided informal, oral feedback, in addition to filling out the corresponding post-run online questionnaire. All runners were asked to select a flat route at their convenience and to use the same route in all their running sessions.

X. Data Analysis

As stated before, we performed two assays (efficacy and enjoyment) with two treatments each. The treatments for the first assay were TripleBeat V1 and TripleBeat V2, and for the second assay, TripleBeat V2 with and without competition. The sample was submitted to all treatments and data analysis was carried out using an analysis of variance (ANOVA). The runners performance variate was transformed using *arcsin* of the square root of the percentages, a standard procedure applied whenever the residues do not follow the normal distribution.

In the following, we present and discuss our results in the evaluation of *efficacy* and *enjoyment* for TripleBeat V1 and V2. Table VI summarizes the results of the objective measures for each of the assays[14].

TABLE VI.
PERCENTAGE OF THE WORKOUT TIME SPENT INSIDE THE PROPOSED TRAINING ZONES FOR ALL SUBJECTS AND THEIR RUNNING SESSIONS.

Subject	TripleBeat V1 (1^{st} run)	TripleBeat V1 (last run)	TripleBeat V2 (no comp.)	TripleBeat V2 (comp.)
1	33.2%	—	49.3%	**99.9%**
2	6.2%	—	**68.3%**	29.6%
3	86.2%	—	100%	100%
4	5.4%	—	19.3%	**50.2%**
5	85.1%	—	100%	100%
6	75.4%	25.5%	61.1%	**86.9%**
7	93.2%	94.2%	**99.6%**	89.5%
8	80.5%	71.0%	83.2%	**99.7%**
9	18.5%	73.7%	94.2%	**100%**
10	69.8%	90.7%	96.4%	**99.7%**

1) First Assay. TripleBeat V1 vs V2: On average, 57.1% and 82.8% of the participants workout time was spent exercising inside the proposed training zone when using TripleBeat V1 and V2 respectively. These averages reveal a significant difference ($p < 0.05$; $n = 10$) between both prototypes. Therefore, we conclude that TripleBeat V2 was *more effective* than TripleBeat V1 in keeping runners inside their desired training zone. Moreover, Table VII shows that 100% of the subjects spent more time inside the proposed training zone when running with TripleBeat V2 than with V1.

In the subjective evaluation of efficacy, we asked participants if their experience with each of the systems was more effective, about the same or less effective than any of the runs they had in the past. TripleBeat V1 was considered more effective by 4 subjects while TripleBeat V2 doubled this preference (8 participants). Such significant difference in the perception of efficacy corroborates the objective performance evaluation results.

Therefore, both objective and subjective evaluations of efficacy lead us to conclude that *TripleBeat V2 was more effective than TripleBeat V1 in assisting runners to achieve their exercise goal.*

[14]Note that this data was analyzed according to the methodology described in section -V).

TABLE VII.
COMPARISON BETWEEN THE PERCENTAGE OF TIME SPENT INSIDE THE TRAINING ZONES WITH TRIPLEBEAT V1 AND V2.

Group	Subjects	TripleBeat V1	TripleBeat V2
1	1	33.2%	**49.3%**
	2	6.2%	**68.3%**
2	3	86.2%	**100%**
	4	5.4%	**50.2%**
	5	85.1%	**100%**
3	6	25.5%	**61.1%**
	7	94.2%	**99.6%**
4	8	71.0%	**99.7%**
	9	73.7%	**100%**
	10	90.7%	**99.7%**
Average*		57.1%	**82.8%**

**Averages diverge significantly for* $p < 0.05$

Participants also revealed the main reasons of efficacy for each of the systems. Musical feedback and the heart-rate graph monitor were considered the most important reasons for efficacy with TripleBeat's V1 interface (5 and 4 subjects respectively). Interestingly, the primary reason for TripleBeat's V2 efficacy was its **glanceable interface** (8 subjects). Figure 17 summarizes these results.

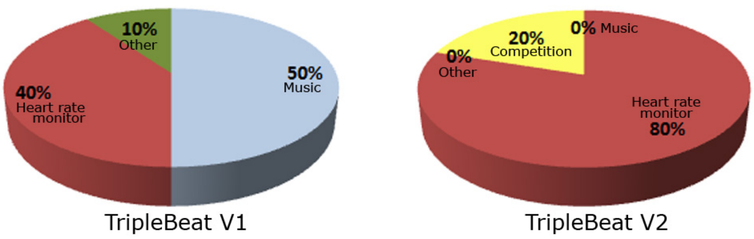

Figure 17. Main reasons for efficacy on TripleBeat V1 and V2 in percentage of subjects.

With respect to the subjective evaluation of enjoyment, we asked participants to rate their experience as being more enjoyable, about the same or less enjoyable than any of the runs they had in the past. No significant difference could be observed in this evaluation between TripleBeat V1 and V2: TripleBeat V1 was considered more enjoyable by 5 subjects and V2 by 6. However, when we asked participants to choose between TripleBeat V1 or V2, **all** participants preferred TripleBeat V2 over TripleBeat V1 (see Figure 21).

The main reasons for enjoyment with TripleBeat V1 and V2 were the music (5 subjects) and the competition (5 subjects) respectively.

Finally, Figure 18 summarizes all the reasons pointed out by the subjects for both systems.

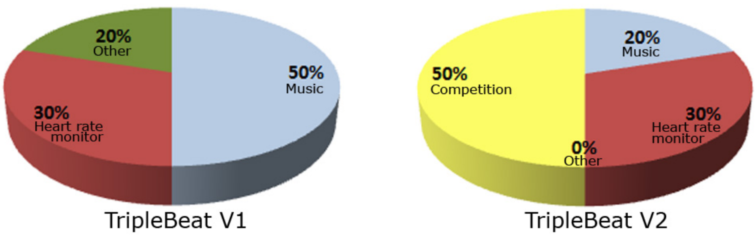

Figure 18. Main reasons for enjoyment on TripleBeat V1 and TripleBeat V2 in percentage of subjects.

2) Second Assay. Competition vs No Competition with TripleBeat V2: In this second assay, our main goal was to evaluate the impact of a competition in motivating runners to achieve their workout goals. In a similar way to the first assay, we also analyzed the *efficacy* and *enjoyment* of the TripleBeat V2 system, without and with competition in this case.

According to Table VIII, 77.1% and 85.5% of the subjects' workout time was spent exercising inside the proposed training zone when using TripleBeat V2 without and with competition respectively. These averages do not diverge significantly ($p > 0.05$; $n = 10$), which might suggest that the efficacy of TripleBeat V2 is *not* due to the competition feature. This assumption is reinforced by the fact that only 2 participants considered competition as being the main efficacy factor in TripleBeat V2 (see Figure 17). Actually, the **glanceable interface** of the heart-rate monitor was considered the most relevant reason for TripleBeat's V2 efficacy, both in competition and no competition modes (see Figure 19)

TABLE VIII.
COMPARISON BETWEEN THE PERCENTAGE OF TIME SPENT INSIDE THE TRAINING ZONES WITH TRIPLEBEAT V2, WITHOUT AND WITH COMPETITION.

Group	Subjects	TripleBeat V2 (no compet.)	TripleBeat V2 (compet.)
1	1	49.3%	**99.9%**
	2	**68.3%**	29.6%
2	3	100%	100%
	4	19.3%	**50.2%**
	5	100%	100%
3	6	61.1%	**86.9%**
	7	**99.6%**	89.5%
4	8	83.2%	**99.7%**
	9	94.2%	**100%**
	10	96.4%	**99.7%**
Average*		77.1%	**85.5%**

**Averages have no significant difference for p* < 0.05

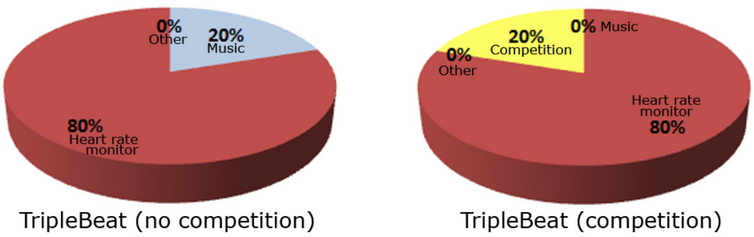

Figure 19. Main reasons for efficacy in TripleBeat V2 (without and with competition) in percentage of subjects.

However, Figure 20 shows that competition was considered the main reason for *enjoyment* with TripleBeat V2 in competition mode (5 participants), whereas music was the most relevant factor in TripleBeat V2 without competition (6 subjects).

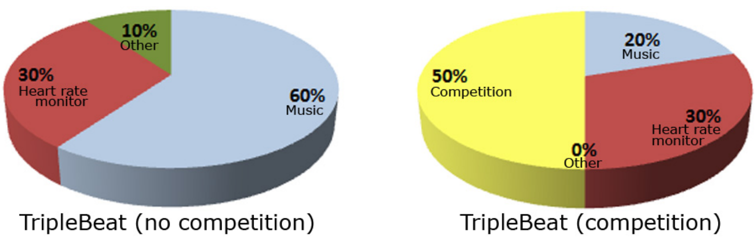

Figure 20. Main reasons for enjoyment in TripleBeat V2 (without and with competition) in percentage of subjects.

As mentioned before, TripleBeat V2 was unanimously preferred over V1 by all participants (see Figure 21). Additionally, 7 subjects considered TripleBeat V2 with competition to be more desirable than without it. This result confirms the importance of *social pressure as a factor for enjoyment in monitored workouts.*

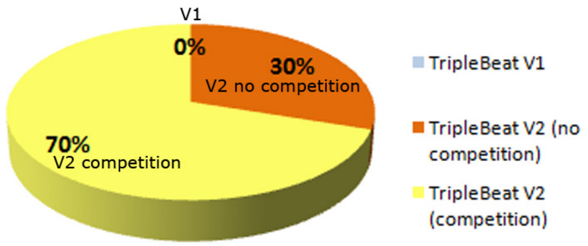

Figure 21. Preferred system in percentage of subjects.

Finally, Figure 22 summarizes the main results obtained with the subjective evaluation.

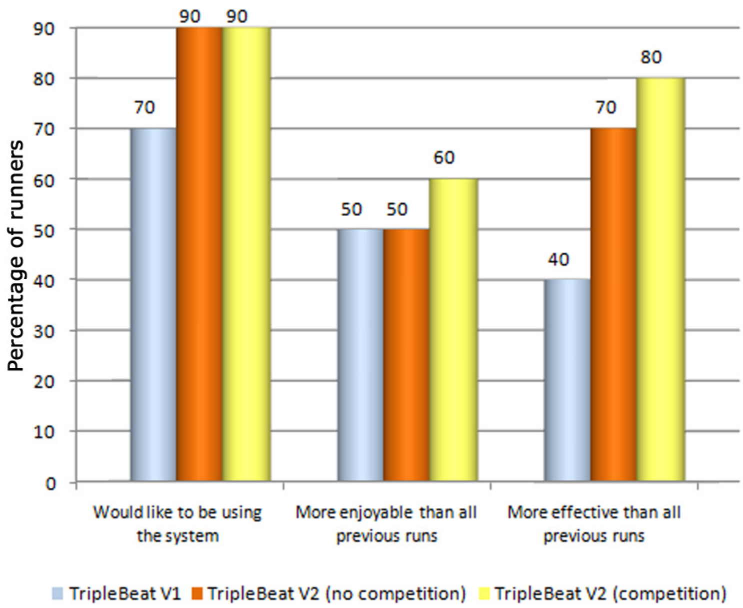

Figure 22. Summary of the subjective evaluation. Runners' perception of TripleBeat V1 and V2 in percentage of runners.

FUTURE TRENDS IN MOBILE PHYSIOLOGICAL MONITORING

Some of the trends associated with the use of mobile devices as the predominant component of personal health monitoring systems include:

1) *Improvement of Personal Information Management (PIM) Systems:* Instead of keeping record of every medical test, doctor's appointment and medicines taken using papers and folders that could be easily lost or damaged, mobile health monitoring systems would provide better tools for maintenance, management and sharing of this information. Additionally, the stored data would also include details on daily exercise and diet, injuries, and other contextual information that would be automatically captured, creating a much more reliable and accurate personal database;
2) *Better access of health information by healthcare professionals:* Digital Information systems might be designed to retrieve relevant information from the subject's personal records and assist specialists in making the right decisions for the patient (*e.g.* avoid potential conflicts with other prescriptions, etc.);

3) *Support for Telemedicine:* Sharing personal, real-time and historic physiological data data with specialists via private and secure network channels would represent a significant step towards reducing the need to travel for medical care;
4) *Physical activity status as a shared feature on social networking:* Sharing personal reports on daily exercise and diet could be of great interest to friends and members of the user's social network (*e.g.* MySpace, Facebook, Orkut, etc.). Social pressure could also act as a strong motivating factor to encourage users to adopt healthier lifestyles;
5) *Reduction of the world's obesity and associated medical problems:* Mobile services and applications that promote healthy lifestyles seem to be an effective strategy towards assisting users in reaching healthier and more active lifestyles. Persuasive interfaces become a critical element for the success of such systems;
6) *Higher demand for powerful mobile devices, faster and more reliable wireless networks and better integration of user interfaces for multiple devices:* By switching from the desktop to the mobile paradigm, the so called "personal computers" are being reinvented with a different perspective, which requires improvements in hardware technologies, network architectures and design methodologies.

CONCLUSIONS AND FUTURE WORK

TripleBeat is a mobile phone based system that includes persuasive techniques for exercise enhancement. We have described in detail the hardware and software components of two versions of the TripleBeat system: TripleBeat V1 and TripleBeat V2. In addition, we have carried out two runner studies to evaluate three of TripleBeat's persuasive techniques: musical feedback, a glanceable interface for increased personal awareness and for providing real-time recommendations, and a virtual competition with other runners.

From our experimental studies, it could be concluded that TripleBeat *significantly* helped runners achieve their workout goals. TripleBeat's higher effectiveness was measured quantitative and qualitatively. Both from a quantitative and qualitative perspective, running with auditory feedback was significantly superior to running on *mute* or on *random* modes. In addition, TripleBeat's V2 glanceable interface increased the effectiveness of the training. Finally, TripleBeat's V2 virtual competition feature was considered to be the most important reason for enjoyment. Most subjects preferred TripleBeat with competition over TripleBeat without competition. Moreover, *all* participants preferred TripleBeat V2 over V1.

In sum, our experimental results support the hypothesis that TripleBeat's persuasive techniques have a positive impact on exercise monitoring systems. We have found the user interface to be the most important element in increasing the efficacy of these systems, while social factors via a competition contribute to a more enjoyable experience. We believe that systems like TripleBeat will have an important role to play in supporting healthier and more active lifestyles.

Next, we shall highlight a few lines of future research that we are planning to pursue:

1) *Real-time telemetry:* Specialized audio feedback via a personal trainer located anywhere to assist the users on the fly might be an important enhancement to increase TripleBeat's efficacy.
2) *Performance Social Network:* TripleBeat's data may be integrated in a social network where users could share their exercise performances and make them available to friends and family. Users could download their friends' data and use TripleBeat to compete against them or just check their friends progress.
3) *Improved score function for multiple target zones:* For the purposes of the TripleBeat V1 vs V2 study (second study presented in this chapter), TripleBeat's proposed workout consisted of a single 46 minute long training zone. Most of the participants (80%) in the study found that TripleBeat chose the right opponents to compete with them. However, the accuracy of the proposed score function could be compromised in the case of interval training or multiple target zones. This is due to the fact that every time there is a change of target heart-rate –*i.e.* each interval during interval training, there is a delay until the human heart can adopt it. Therefore, additional research may need to be carried out to include this factor in the proposed score function.
4) *Motivational training proposal:* TripleBeat should be able to learn from the user's past performances to propose more personalized training schedules. For example, the target heart-rate could be computed considering not only the high-level goal of the workout, but also the user's performance history. Thus, the system would present each runner with a training proposal that would be challenging, but not impossible to achieve.
5) *Additional contextual information:* Additional contextual information would improve the system's decisions to select music, opponents and adequate trainings. Among them, we are planning to include: (1) GPS data to propose routes, connect with other geographically close runners, *etc.*, (2) body and external temperature to detect dehydration, (3) barometric pressure to measure incline, and (4) diet, overall mood and stress levels.

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