EVERY SIGN OF LIFE

by
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ABSTRACT

Every Sign of Life introduces an approach to and motivational schema for personal health monitoring. It is an exploration of how to make information collected by personal health-monitoring devices fun and engaging, and consequently more useful to the non-specialist. In contrast to the common methodology of adding game elements to established biofeedback systems, the *Every Sign of Life* approach is to design and build games that use biosensor information to effect the game environment. This work tests the hypothesis that fun (the joy of learning, achieving, competing, etc.) is a way to achieve the goal of self-efficacy; to induce people to take care of their own health by altering their habits and lifestyles.

One result is a basic architecture for personal health-monitoring systems that has led to an approach to the design of sensor peripherals and wearable computer components called "Extremity Computing." This approach is used to redefine biosensor monitoring from periodic to continuous (ultimately saving data over a lifetime). Another result is an approach to adding implicit biofeedback to computer games. This has led to a new genre of games called "Bio-Analytical Games" that straddles the boundary between sports and computer games. A series of studies of how to present health information to children and adults have demonstrated the ability of consumers to use bioinformatics without involving professionals.

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Introduction

When we think about doing something fun, checking our heart rate or body temperature is not usually the first thing that comes to mind. This thesis, *Every Sign of Life*, challenges this assumption about how we might think and feel about personal health monitoring. The hypothesis is that a new approach to wearable sensor design combined with a new approach to game design will lead to a multiplicity of scenarios where feedback about physiological profiles is engaging. Experiments suggest that increased awareness of basic health indicators may make us more attentive to what is normal for us, enable more informed lifestyle decisions, and provide an early alert to health problems.

This work started with the *Hand-held Doctor for Children* project, which focused specifically on devices and software that interest children in how their bodies work. That work focused on a Constructionist or learn-through-doing approach to engage children in a learning activity. The computer serves as a tool to visualize, analyze, and explain the processes going on inside our bodies and suggests ways we can change these processes.

One interface is a child's-size motorcycle helmet that digitizes biosensor signals and sends data to a PC or toy. For younger children, the helmet can be used to send physiological signals that control a computer-based animation character: the heart and chest of the character enlarge and contract with the rhythm of a child's pulse and breathing; the skin sensor on the arm measures body heat, which is reflected in the color of the character changing from blue to red.

Older children used this system to build their own robots and write their own visualization programs. One high-school student built a LEGO toy castle in which a flag waves in response to each breath, castle guards march with each heart-beat, and a drawbridge moves up and down as with changes in body temperature.

Every Sign of Life is geared towards adults. A PDA-sized health monitor, which can be carried on your belt or in your pocket, both saves its information on a CompactFlash memory card for future analysis and transmits it to a PC in real time. This allows you not only to monitor your physiological parameters in real time, but also to track stress levels over specific time periods (days, weeks, months), and overlay your calendar to correlate specific periods of stress to particular daily events.

But making health data accessible only addresses part of the challenge to increase health awareness. The expression of these data in fun and engaging activities that trigger both personal and community introspection completes the picture. "Bio-Analytical Games," which straddle the boundary between sports and computer games, were developed to make health-monitoring fun. For example, in a new game I have developed called Heartball, the team of players who most dramatically lower their pulse rates while in possession of a ball scores the most points.

Thus the focus of this thesis is the exploration of how to make information collected by personal health monitoring devices fun and engaging, and consequently increase the likelihood that non-specialists will be more introspective about their health. The target audience is generally healthy people who may be interested in health maintenance or preventing the onset of health problems, although many of the results may be applicable to people with an existing condition or disease. The approach is to design and build computer games and scenarios based on biosensor information. The ultimate goal is to implicitly make people take care of their own health by altering their habits and by health-aware planning of their life.

My hypothesis is that people can better understand and use the health information if it is presented in an entertaining and engaging form. To check this hypothesis I explore how to make the health information fun by designing hardware, software, and activities that make observing and learning from the health information as engaging and entertaining as playing a computer game. These explorations lay the ground for longitudinal studies that would demonstrate the efficacy of this new approach to consumer bio-informatics.

The questions explored in this thesis include what parameters to capture, how to capture them, and how to process and present these data, so that people can adequately interpret and respond to the health information. The work has lead to several results. It includes an exploration of basic architecture for personal health monitoring systems. An "Extremity Computing" approach, which allows for rapid prototyping and effectively resolves user-interface issues for data collection devices, has been defined and applied to a wide variety of health-monitoring scenarios. Another result is a series of demonstrations of how to present health information to children to help them learn basic facts about their health. Finally, scenarios based on personal health monitoring were designed and tested with adults.

In *Every Sign of Life*, I have developed:

(1) a new approach to design of sensor peripherals and wearable computer components called Extremity Computing;
(2) a redefinition of biosensor monitoring from periodic to continuous (ultimately saving all the data over a lifetime);
(3) a new approach of adding implicit biofeedback to computer games;
(4) a new genre of games that straddles the boundary between sports and computer games called Bio-Analytical Games;
(5) a set of design principles for these games;
(6) a new approach to bio-informatics, geared towards the consumer; and
(7) a series of experiments and studies that demonstrate the efficacy of this approach.

The remainder of this document provides the motivation and background for my thesis, with particular emphasis on my choice of games as the medium for engagement. I present several case studies from various instantiations of *Hand-held Doctor for Children* and *Every Sign of Life*. I follow up with a description of the hardware and software architectures that I developed, as well as the design principles used to develop the applications. The experiments are then documented. I conclude with a review of the claims.

Chapter 1
Background

Learning is hard fun. — Seymour Papert

Every Sign of Life challenges assumptions about how we might think and feel about personal health monitoring. The hypothesis is that a new approach to wearable sensor design combined with a new approach to game design will lead to a multiplicity of scenarios where feedback about physiological profiles is engaging. In this chapter, I present the groundwork upon which my hypothesis is built: (1) wearable data-acquisition and the motivation for the Extremity Computing approach to incorporating sensor peripherals into wearable systems; (2) biosensor design, with an emphasis on those sensor technologies relevant to consumer health monitoring; (3) personal health monitoring within the context of normal life experiences; (4) fun (and games) as a mechanism for engagement and reinforcement; and (5) Bio-Analytical Games within the context of game design.

1.1 Extremity Computing

Technological innovation in data recording has a history that long pre-dates the digital revolution, or even the harnessing of electricity. For example, the ratcheting high-tide lines on the ocean shore that people see daily gave way to chart recorders that could record decades of data. The early 1970s saw the emergence of data-acquisition systems that were separate from, but interfaced with, minicomputers. A modular approach remains an attractive alternative to designing field equipment. Examples include one-of-a-kind systems, such as the Australian Long Baseline Array telescope facility, and commercially available systems such as PowerLab™ from ADInstruments Pty Ltd. [1].

As special-purpose wearable technology, such as early telemetry systems, gave way to wearable computers, more general-purpose architectures have become the prevailing paradigm [87]. The wearable-computer concept has evolved to include a wearable substitution of all conventional computer components: display, keyboard, mouse, central processing unit, storage, and communication interfaces. However, although wearable computer development has been concurrent with the computer/Internet boom of the 1990s, wearables have not become a mass phenomenon. A possible reason for this is a poor usability of the wearable human-interface components: wearable displays are bulky and are disappointing in their optical properties. Although the displays may get smaller, their optical properties may never get as good as that of larger displays [15]. The wearable keyboard and mouse substitutes are non-trivial to use. Facile voice I/O remains elusive [122].

A broad research effort has revealed many potentially interesting applications of wearable computers, but it is still hard to point to important reasons to use these computers. One of the problems is that many applications may work just as well on laptop computers or personal digital assistants (PDAs). Working with a computer usually requires the complete attention of the user. In these circumstances, it may not matter whether the computer is worn, held, or sitting on a lap or desk. However, a wearable computer may perform useful tasks impossible for a conventional computer when wearers do not pay any attention to it. Such tasks include gathering data about the wearers and their surroundings.

There are some exceptions. Systems such as the "body network" created for a scientific expedition to Mt. Everest in 1998 showed that small, special-purpose computers allow easy creation of inexpensive systems for high-quality measurement of biometrics in mobile applications. The system consisted of an I^2C network of Microchip PIC microcontrollers. Each of these nodes was attached to a sensor or communication radio in order to transmit information about a climber to a data-acquisition system. The body network is a useful and inexpensive example of small, interacting, programmable devices. The entire system was built in less than six months. The interaction between the devices represented the most of the design complexity.

Extremity Computing [50], described in Chapter 4, is a modular follow-on system to the body network that focuses on data acquisition and aggregation as an architecturally simplifying way of creating ubiquitous computing interfaces. We define a class of devices, which we refer to as extremity-computing devices, and scenarios for these devices, suggesting that wearing a device or attaching a device to an object is both meaningful and appealing.

1.1.1 Personal electronic monitoring and assistive devices

There are two classes of commercially-successful electronic wearable devices neither of which is a multipurpose programmable computer: (1) Personal electronic assistive devices with a significant user interface, e.g., watches, camcorders, or photo cameras; and (2) Personal electronic monitoring devices with little or no user interface, e.g., pacemakers, Holter and event monitors, industrial data acquisition and monitoring systems, sensors that can be surgically installed, or thermometers with transmitters that are able to be swallowed.

The assistive devices do not normally perform other useful tasks while the user interface is not engaged. The monitoring devices constantly perform meaningful tasks, but never actively engage in user interaction. There is an emerging class of devices that is somewhere in-between these two categories. These devices usually look like a watch, but can display and collect some additional information such as pulse rate or bicycle speed. Devices in this intermediary category are specialized for a narrow set of tasks in a limited set of scenarios.

Devices of both categories rely on autonomous user interface and function independently of a general-purpose computer. Even though some of the devices such as digital cameras have to be regularly interfaced to a computer in order to save information, they rarely use the possibility of user interaction through the computer. For example, it may be much easier and faster to see, set, and fine-tune camera parameters using a computer program instead of a set of buttons on the camera. One of the exceptions is Timex Data Link™ watch [131] that has no usable input interface, but can download schedule, phone book, and other pieces of information from a host computer. Another example of such interaction is synchronization interfaces of PDAs. Although synchronization works both ways; i.e., data goes from the computer to the PDA and from the PDA to the computer, its purpose in many cases is to resolve the user interface deficiency of the PDA by letting the user input and modify information using a regular computer.

There is also a class of experimental devices such as the IBM Linux watch [82], the Seiko Ruputer™ watch [120], or most recently wristwatches developed for Microsoft SmartPersonal Objects Technology (SPOT) [90]. These devices are conceived to prove that it is technically possible to run an operating system on a watch. However, they offer very little insight into why a general-purpose operating system may justify the increase in the complexity and cost of a watch. Neither of these watches contributes significant ideas to the user interface design or to applications for very small computers.

1.1.2 Interfacing computers with human bodies

The sensory organs of living creatures can often move independently of the body and are capable of reaching out, touching, and feeling their surroundings. Computers, on the other hand, have a very limited set of sensors (if any), confined to fixed positions within the case. Data-acquisition hardware may expand the sensory capabilities and extend the reach of the sensors by a wire length, but still does not offer much mobility to the sensors. Using the biological sensory-extremity metaphor we decided to define a new class of sensor peripheral devices for computers called extremity-computing devices.

The extremity-computing research expands and generalizes the data-acquisition category of wearable devices. First, we make the data-acquisition devices more general or capable of measuring a broad set of signals from a variety of plug-in sensors. Second, we make it easy to transfer real-time and long-term information from those devices to computers. We developed an assortment of research projects that employ devices capable of taking measurement from different sets of sensors and sending this information to computers or other devices for processing and presentation.

Although computers have substantially advanced in their ability to store and process large amounts of data, the design of hardware to gather sensor information is ad hoc. Data-acquisition devices, although more compact and efficient, remain highly specialized and not programmable. The hardware is usually designed as an add-on board or adapter, may require extensive wiring, and is often expensive and hard to customize. Data-acquisition software is likewise non-standard.

Many research tasks require some sensor data collection and analysis. Projects related to human interaction, health, environment, physics, and many other areas could be done faster and more easily if there were a standard way of developing and attaching sensors to a computer and a standard application-development environment. Education is another area where data collection and analysis is important [118].

In the following section, I review biosensor technology within the context of the extremity-computing approach; in particular how it expedites prototyping by allowing researchers to unify hardware design and improves user experience by adding sensor capabilities to various objects—or to the body—and by substituting potentially poor proprietary user interfaces implemented on small devices with the well-evolved rich user interface of a conventional computer.

1.2 Biosensor technology

Biosensor technology is an integral part of modern medicine. It is invaluable in diagnostics and patient monitoring. Biosensors measure electrical, optical, chemical, magnetic, and other physical signals produced by various biological activities.

Biosensors can be classified by the type of physical property they measure or by the type of biological function they are designed to monitor. For example, a finger photo-plethysmograph is an optical sensor used as a heart monitor. Physically it measures changes in optical reflective characteristics of skin due to changes in amount of blood in the skin blood vessels at different phases of heartbeat. Logically it provides information about pulse rate.

Many biological parameters can be measured in several ways. For example, the body temperature can be measured directly with a thermistor or other temperature sensitive device placed in direct contact with a part of our body or indirectly using an infrared optical sensor placed close to an eardrum. Pulse rate can be measured by detecting electrical, optical, acoustic, or tangible impulses.

Biosensors used in medicine are usually a part of proprietary equipment built for one highly specialized task. Such equipment is hard to use without special training, hard to modify, and hard to interconnect with any other systems, which makes it unfit for the goals of my research. To rapidly prototype health monitoring scenarios and demonstrations I applied the *Extremity Computing* approach to build a set of sensors that can be used in any combination for quick prototyping of health monitoring scenarios and demonstrations.

Since the emphasis of *Every Sign of Life* is on healthy people, I focused on heartbeat, breathing, temperature, and skin conductance. These are well-explored parameters and are the basis of health information for a generally healthy person. There are other signals that could be included in the personal health monitor, e.g., blood glucose level and blood pressure. These specialized sensors are necessary for comprehensive health monitoring of people with specific health problems such as diabetes and hypertension, but these sensors are more invasive and require more specialized electromechanical hardware.

Since the target audience of *Every Sign of Life* is the active consumer, the design preferences were to make the system small and minimally invasive. The feature set that I targeted includes: robustness, ease of use, non-intrusiveness, portability, stability during rest and motion, durability, low- or no-power consumption, and continuous vs. periodic sampling.

1.2.1 Monitoring heart activity

One of the most common classes of biosensors is a heart monitor. Non-invasive visualization techniques such as MRI can be used to obtain the most comprehensive analysis of heart activity. However, in most cases this method is neither feasible nor necessary. Pulse rate monitoring is usually sufficient for hospital patients without a specific heart-failure risk. Electrocardiogram (abbreviated as either EKG or ECG) is a broadly used technique to obtain information ranging from a simple pulse to a very detailed description of heart activity. EKG is obtained by recording changes in weak electrical potential coming from the heart to the skin surface. Essentially, EKG records an electrical side effect of heart activity.

The discovery of the fact that electrical activity of the heart can be measured without exposing the heart is attributed to Augustus Waller [20] who was also the first to record the electrical activity of human heart in 1887. Einthoven [20], who developed a basic theory of EKG, introduced the term electrocardiogram. In 1901 he also developed a more sensitive instrument to record EKG.

The potential is measured between electrodes placed on the skin. Depending on where the electrodes are, the changes in potential reflect depolarization and repolarization of the heart muscle along different axes. A certain electrode placement is called a lead. For example, a placement of two electrodes on two arms to measure difference in potential is called Lead I; a placement on the right arm and the left leg is called Lead II; etc. Changes in the potential in time have a characteristic repeating pattern [Figure 1]. The five visible spikes on the graph are called P, Q, R, S, and T waves. The most prominent feature of EKG graph is the tallest spike called R-wave. The top of the R-wave corresponds to the beginning of systole or ventricle contraction when blood is pumped into arteries. Heart rate is usually derived from the time difference between consecutive R-waves.

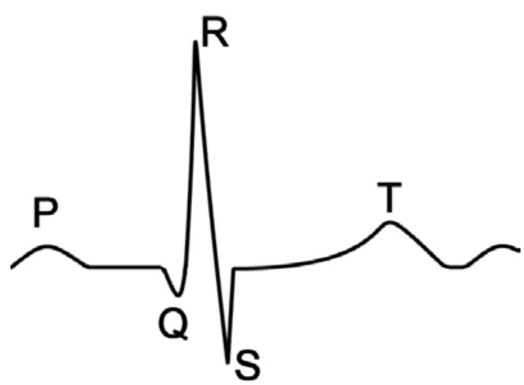

Figure 1 Typical EKG Lead II; P, Q, R, S, T waves

Both theoretical basis and hardware for EKG are very well developed. Electrocardiographs are widely used by doctors to diagnose heart problems and to monitor patients. In addition to electrocardiographs used in ambulances, hospitals, and other medical environments there is a class of devices called Holter or event monitors [63]. Doctors give these devices to patients who may have rare or irregular episodes of a suspected heart problem. The patient can wear such a device in everyday life to record EKG over extended periods of time. The event monitors also allow the patient to press a button to mark different activities or an onset of symptoms. All such devices normally deliver data to the doctor and are limited to recording only EKG.

A typical modern Holter monitor records a 3-lead EKG either on a magnetic tape or a memory card. Digital Holter monitors sample data 100–1000 times per second and are capable of recording from a few hours to a couple of days of data. Many event monitors record only periods when an event button is pressed to record an episode of interest.

Photoplethysmography is another way of monitoring heart activity. This method is based on measuring changes in the amount of light backscattered by the skin depending on the volume of blood in the blood vessels [6],[17]. Photoplethysmography has significantly advanced since the early 1980s and successfully applied in a variety of diagnostic and monitoring procedures [29],[19]. Hospitals now often use finger photoplethysmographs to monitor pulse of their patients. Another frequently used optical device called a pulse oximeter that not only detects pulse, but also can measure the amount of oxygen in blood is a combination of two photoplethysmographs measuring skin reflectance at two different wavelengths of light [39].

In the *Hand-held Doctor for Children* project I made my own photoplethysmograph to investigate the basic design principles of this kind of devices. I compared the output of my photoplethysmograph to that of a ProComp+™ photoplethysmograph and ProComp+ EKG sensor; the output of both photoplethysmographs matched well. However, both devices were highly sensitive to motion, making heart-rate monitoring of an actively moving person difficult. High motion sensitivity is one of the main problems of photoplethysmography [17].

Although motion artifacts were present at the ProComp+ EKG sensor output, the quality of the signal was not as adversely affected as with optical sensors. An output of a photoplethysmograph also lacks the details of heart activity visible on an electrocardiogram [Figure 1]. Both photoplethysmography and EKG require a probe or a set of electrodes in direct contact with the skin. Although a photoplethysmograph is usually easier to put on and requires fewer wires, it is harder to adjust and usually requires some interactive process to make sure it picks up a heart-rate signal. EKG sensors are usually more robust and more accurate [51] for heart rate measurement. These factors defined my decision to use an EKG sensor instead of photoplethysmograph in the *Every Sign of Life* health monitor.

1.2.2 Monitoring breathing

Breathing monitors are less common than heart monitors. The most accurate sensor system to indirectly monitor breathing is respiratory inductance plethysmograph. This technology is based on measuring inductance of a conductive loop placed around the chest. The area encircled by the conductor changes with the breathing, affecting the inductance of the loop. Other technologies for monitoring respiration are less developed and not as reliable. For example, other respiration monitors have either a chest band (such as ProComp+ breathing sensor) with an electro-mechanical component that measures the mechanical band tension or a probe placed near the nose or mouth that measures humidity or temperature.

For the *Hand-held Doctor for Children* project I developed a thermistor-based respiration sensor. This sensor allowed the system to obtain a basic breathing pattern. Unfortunately, as with any respiratory sensor that relies on difference in temperature or humidity of inhaled and exhaled air, the sensor had to be near the nose, making it intrusive and inconvenient to use.

An alternative method of measuring a breathing pattern is EKG analysis. Breathing slightly alters the electrical conductivity of tissues between the electrodes and the heart (transthoracic impedance), changing the electrical axis of EKG and the amplitude of the EKG signal [98]. It is possible to derive a breathing pattern from changes of the signal pattern of even a single-lead EKG [97]. Since I decided to build an EKG sensor for the

Every Sign of Life health monitor, I chose not to add a specialized breathing sensor. I was able to exclude both a chest strap and a nose probe from the design.

Before building the *Every Sign of Life* health monitor I tried to detect breathing by measuring electrical conductance between pairs of EKG electrodes placed on different parts of the chest. However, I could not find a combination of electrode placement and amplification schematic that would produce a consistent breathing signal. Therefore, I decided not to pursue the development of conductance-based or other respiration sensors; I used the EKG signal analysis instead.

1.2.3 Monitoring body temperature

Body temperature is one of the most common parameters used in diagnostics. Increased body temperature or fever usually suggests that we are sick. There are well known basic guidelines on how to measure temperature and what to consider a fever [136]. However, our body cannot keep its temperature perfectly constant even when we are perfectly healthy. “Exercising, wearing too many clothes, taking a hot bath, or being out in hot weather can cause an increase in your temperature.” [136]

Different parts of our body may also have different temperature at the same time. This makes it impossible to absolutely define what temperature is too high and is associated with a disease rather than with another factor. For example, the authors of Marathon Man project at the MIT Media Lab [117] encountered unexpected significant fluctuations of the body temperature even though they used a wireless Body Core Temperature Monitor (by Personal Electronic Devices Inc) swallowed by the participants. Apparently drinking cold or hot liquid immediately affects the temperature monitor even inside the stomach.

Changes in core body temperature are not only related to external factors, a progress of an infectious disease or an action of a medication, but also are linked to sleep cycles [72]. It is also established that changing body temperature externally or with a medication may affect when a person falls asleep. Medical body thermometers measure temperature at discrete moments of time. If the temperature is not measured at least several times each hour it is impossible to establish an exact body temperature dynamics. A personal health monitor, on the other hand, can help to keep track of body temperature dynamics. When such a monitor interacts with a personal computer or an alarm clock the person can not only be awakened at an optimal moment, but also informed when is the best time to go to bed.

A typical temperature sensor consists of a thermistor and a Whetstone bridge connected to an amplifier. In both the *Hand-held Doctor for Children* and *Every Sign of Life* projects I used a precision temperature-sensor chip connected to an operational amplifier. In the *Every Sign of Life* health monitor I epoxied the temperature sensor inside the ground snap-on EKG electrode, so that the person who uses the monitor does not have to put on an additional component. The ground electrode was attached to the left shoulder in the area usually covered by clothing. This location allows the system to measure temperature of the unexposed skin. This temperature measurement is usually lower than the core body temperature, but correlates with it well enough to detect fever and to observe slow rhythmic fluctuations.

1.2.4 Monitoring skin conductance

The level of skin conductance or its reciprocal, skin resistance, depends on environmental or emotional events. For example, changes in temperature or humidity may significantly affect skin conductance. Emotional events may cause a sharp increase in skin conductance that may last 10 – 30 seconds. These temporary changes in skin conductance are generally called Galvanic Skin Responses or GSRs. Skin conductance is usually measured across the palm of one of the hands. Two skin conductance electrodes are placed on either the palm side of two fingers or on the palm of one of the hands.

Edelberg developed the generally accepted theory of skin conductance and GSR [34],[35]. When the skin sweat ducts fill with sweat in response to a stimulus, the skin conductance increases. As the sweat evaporates or gets reabsorbed by the skin, the skin conductance decreases. Skin conductance is not always a good indicator of sympathetic arousal. For example, if skin is fully hydrated or very dry sympathetic sweat discharge has little effect on the moisture on the palm and produce very small response.

GSR correlates with strong emotions, stress, and anxiety and is broadly used in psychophysiological research [108], [107], [119], [40], [60], [59], [127], [103]. Skin conductance is also one of the most important parameters measured in the polygraph test ("lie detection") [111].

A skin-conductance sensor is easy to implement. In the *Every Sign of Life* health monitor two skin electrodes made of metal foil are held onto two fingers with narrow Velcro bands. The electrodes are connected to one of the sides of a Whetstone bridge connected to an operational amplifier.

In the *Hand-held Doctor for Children* project I made the electrodes out of dimes (10-cent coins) and used the same Whetstone Bridge with an operational amplifier. In addition to conducting tests with electrodes attached to the fingers, I also tried to use a configuration where electrodes were placed on the forehead. In that configuration the skin conductance sensor did not consistently produce GSR spikes. The skin on the forehead requires a more thorough preparation to remove grease and it exhibits weaker GSR changes than the skin on the palms of the hands. The sweat glands on the forehead have stronger reaction to thermal changes than to psychological changes that cause GSR.

1.2.5 Other sensors

Blood pressure is an important parameter used in diagnostics and polygraph testing. Dependence of blood pressure on stress [3] may be particularly important in personal stress monitoring. Unfortunately, devices that measure blood pressure require a complicated mechanical and signal-processing setup that includes an inflatable cuff on an extremity or finger that restricts blood flow, a pulse detector, and an air-pressure sensor. Measuring blood pressure involves inflating the cuff above systolic pressure and deflating it with a simultaneous monitoring of the arterial pulse. The systolic and diastolic blood pressure corresponds to the highest and lowest pressure where the pulse is detected [18]. The pulse can be monitored either acoustically by detecting the pulse noise or with an ultrasonic Doppler detector.

In addition to biosensors, a personal health monitor can include motion sensors and sensors that capture some environmental parameters such as food intake, lighting conditions, noise levels, or external temperatures. Such sensors are a necessary part of a complete health monitor. Because of the scale and specific focus of my project, I did not include them in the design.

Motion sensors in combination with a heart-rate monitor can provide an accurate free-living measure of exertion [128],[129]. The heart rate alone is not an accurate indicator of physical activity because it can be affected by other factors such as emotional stress [96]. The role of the motion sensors is to distinguish whether a heart-rate change is caused by physical activity or some other factor. There is evidence that in some cases, stress and anxiety can be isolated by analysis of skin conductance, breathing, and heart rate without motion sensors [60],[59].

Novel sensor technologies are being developed to do a rapid chemical analysis of blood and saliva [81] either optically or electromechanically. In the future, such sensors may expand the range of parameters for a personal health monitor.

1.3 Personal health monitoring

With little effort we can be well informed about what is going on around us. We can easily get information about events on the opposite side of the globe or intimate details about celebrities. Yet getting even basic information about our own health requires a significant effort. Such information might help us to predict and prevent diseases, as often our body sends us a clear signal about need for treatment only when it is too late to work on prevention.

For centuries the doctor has been serving as an intermediary between the patient and medical information. The doctor also accesses means of diagnosing and treating diseases that are unavailable to the patient. This form of medical practice has made many impressive achievements in treating diseases and prolonging lives. But the legacy of intermediation, such as coding medical literature in Latin (intentionally or not) has raised a barrier to information access for the patient.

In today's public health system in the US (and many other countries) the patient is in large part dependent upon the doctor. While preventive medicine efforts target large groups of people trying to prevent the most dangerous diseases by vaccination, water treatment, health screening, or public advertisement campaigns, at an individual level doctors are more likely to treat sick patients than protect healthy patients from getting sick. A multitude of economical and social reasons discourage doctors from addressing preventive issues with healthy patients individually. For example, the reward system for doctors in the United States is procedure-based—doctors are paid for doing something to a patient rather than spending time thinking about or discussing health problems.

1.3.1 Biofeedback exercises

Health-monitoring devices can be used to reveal information about various physiological parameters such as heart rate, blood pressure, or skin conductance that are not normally visible or consciously controlled. This information can help a person to interactively learn how to affect these parameters consciously. An activity of this kind is called a biofeedback exercise.

There is evidence that biofeedback exercises can have effects beneficial for health. For example, Respiratory Sinus Arrhythmia (RSA) biofeedback [79], [80] was successfully applied to treat asthma, hypertension, and neurotic disorders.

Organizations and companies such as Institute of Medical and Biological Cybernetics, Thought Technology, HeartMath, Elixa, Futurehealth, and Media Laboratory Europe develop biofeedback software. Some of the software developed by these organizations have entertainment elements to make biofeedback less monotonous. Examples of such software are discussed in Section 1.5.3 of this chapter.

1.3.2 Direct access to personal health data

Increased demand on the system due to an aging population also limits the resources available for individual patients. Brent A. Lowensohn, Ph.D., of Kaiser Permanente, America's largest not-for-profit health maintenance organization, observes that "two issues, a rapid increase in the over 65 age group which generates at least six times the average demand and advances in health care that increase both longevity and chronic-care consumption, taken together suggest a demand for services in the next few years, particularly in chronic care management, which will outstrip our ability to provide them, using current methodologies. Even an aggressive campaign to recruit and train new caregivers will not be able to keep up with the anticipated increase in demand for health care." In such an environment we may be compelled to take an increased share of the health care burden into our own hands and exert more control over health information we receive and share with our doctors (See Figure 2). Internet access and computer databases do make it easier for us to locate relevant health-related information and as a population we are generally more educated. Doctors report that the average patient is coming into the office much more informed than in the past [84] although there remains a degree of skepticism about the merits of health information in the hands of the non-professional.

Pragmatically each individual can dedicate more time and interest in observing and correcting his or her health than a doctor. This may benefit not only people with chronic conditions [141],[64], but also generally healthy people who traditionally stay below the healthcare system radar. However, the most sophisticated medical device most healthy people have at home is a body thermometer. Compared to all other equipment used at home, e.g., entertainment systems, kitchen appliances, computation and communication devices, etc., personal health-monitoring technology is underutilized and underdeveloped.

Biosensor monitoring technology is used over short periods of time in a limited variety of situations. EKG, temperature, blood pressure, and other parameters are usually measured only during checkups or when people have a specific medical condition. Even in case of the Holter and event monitors the patients normally collect the information for a limited time to detect specific symptoms. The studies conducted as a part of *Every Sign of Life* suggest that *continuous* health monitoring can be practical and beneficial. Ultimately both patients and doctors may be interested in collecting and analyzing biosensor data over the whole lifetime period.

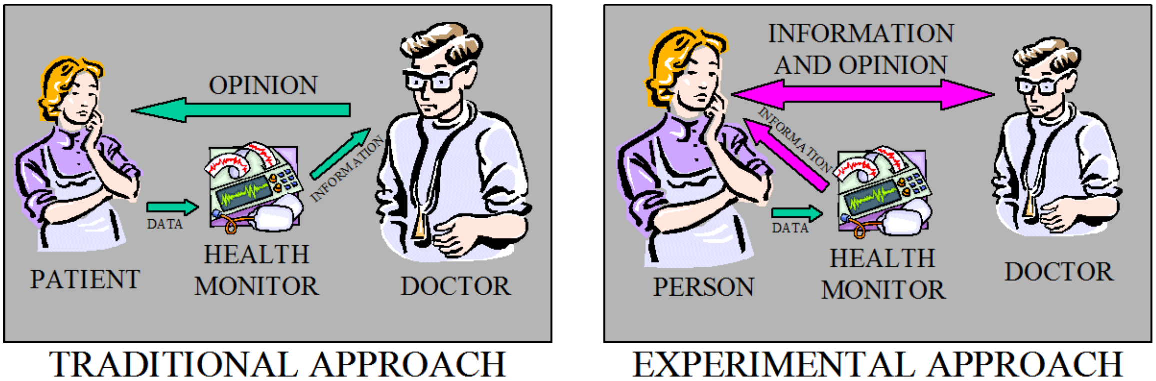

Figure 2 Health information can flow directly to the doctor or via the patient in the form of a discourse.

1.3.3 Feedback and reflection

Based on the disability-adjusted life-years reports, "it is estimated that 80% of medical problems stem from counterproductive behaviors." [93] A health-monitor feedback system that reinforces healthy behavior and medical compliance and promotes self-knowledge has a potential to significantly reduce this trend. In the future people may get daily updates about their own health from their personal health monitors as easily as they get daily news updates today. The information may help people to understand the effects of their own behavior on their health and detect early signs of some diseases. That, consequently, may encourage people to plan their lifestyle to improve their health and make their interaction with the doctors more efficient. For example, seeing an immediate impact of drinking coffee or alcohol on heart activity may help people to understand the healthy limits of such activities; monitoring circadian rhythms (based on body temperature [72]) may help to find an optimal time to go to sleep or to wake up; arrhythmias recorded and detected by the device can alert the person about a possible heart problem and help the doctor to diagnose and treat the condition.

Hirzel, in his master's thesis project [62], prototyped a system that suggested that long-term health monitoring may be important. He used the health monitors designed for the *Every Sign of Life* project to record EKG and his own software to calculate and visualize heart rate. He added a button to the health monitor to allow users to mark events. His study demonstrated that feedback of all-day heart-rate monitoring might change beliefs about exercising and help people lead more active lifestyle. He used visualizations of heart rate correlated with logs of daily activities to promote the elimination of the common tendency to seek the path of least resistance in one's daily routine.

My hypothesis goes beyond Hirzel's study by arguing that people can better understand and use the health information if it is presented *in vivo* in an entertaining and engaging form. I explored how to make the health information *fun* by designing hardware, software, and activities that make observing and learning from the health information as engaging and entertaining as playing a computer game.

The Heartball and Breathing Pac-Man studies described in Chapter 6 show that people are capable of quickly learning facts about their health from interaction with personal health-monitoring technology. On a broader scale, this could lead to improvement in public health in general.

The questions explored in this thesis include what parameters to capture, how to capture them, and how to process and present the data, so that people can adequately interpret and respond to the health information, and that they are motivated to do so. In the next section, I argue that fun and play are likely mechanisms for engaging people in reflection about these personal health data.

1.4 Fun

Fun is usually associated with positive emotions, primarily joy. It is something that people are willing to do without a material reward, enjoy doing, and find amusing. Formal definitions of fun usually link fun to joy, amusement, recreation, but seem incomplete. I think we understand fun intuitively better than formally. When something is fun the question about whether the activity is necessary, important, or useless goes to the background.

Play is a form of having fun. While there is no science of fun, there is science of play; ludic psychology is the study of behavior related to play [16]. Berlyne, who uses this term, also gives the following definition of play: "play 1) is an end in itself; 2) is spontaneous; 3) is an activity for pleasure; 4) has a relative lack of organization; 5) is free from conflics; 6) is overmotivated." Berlyne's definition of play does not encompass sports very well, which is often an organized conflict. Play is often used as an antithesis of work, thus non-productive. Work, however, can also be fun. Both work and play have been associated with learning and reflection. There is no universal recipe for fun. Different people prefer different forms of recreation. However, all types of fun lead to joy and satisfaction that make them attractive or even addictive.

Nearly all social species engage into playful activities that seem like fun to us, but do not have an immediate, clear purpose. Development of a similar behavior pattern in a broad range of different animals is unlikely to be coincidental [7]. Fun and play may, in fact, serve several developmental needs [104],[13] stimulating mental and physical development. For all species physically active play helps to exercise and get physically strong. Social game activities help to explore and learn the basic rules and forms of social behavior. Some researchers [13] also hypothesize that play prepares animals for the unexpected.

Fun may cause a wide range of emotions that are not necessarily pleasant. For example, many people enjoy extreme sports or horror movies that cause fear. However, no matter what the immediate emotions are, people expect to feel good (joy) afterwards. Since individual health is a sensitive personal topic, people would not likely be willing to play with negative emotions in that domain. Besides, negative emotions may aggravate some health problems. For example, a study at the University of North Carolina revealed that people who are most prone to anger are nearly three times as likely as the non-angry subjects to have a heart attack in six years [2],[142]. Therefore, in my studies, I based fun activities around health information on predominantly positive emotions. Fun approach to health may have a positive effect just by improving the emotional balance.

1.4.1 Fun, games, and learning

Breaks, especially ones that involve play, during the school day increase attention of children to cognitive tasks [104]. Aside from helping children to concentrate on regular curriculum fun may support learning more directly. Fun games can make children attend to the subject of the game; better attention and higher interest lead to faster and better learning [71]. Therefore, games with a learning agenda can be a more efficient form of teaching than formal instruction.

When I played the early adventure games by Sierra and other companies, I experienced this phenomenon personally. The games had some animation and static pictures, but mostly relied on text input and output. My great interest in playing the games made me substantially improve my knowledge of English in just a few days. In fact, my knowledge of English vocabulary expanded far beyond the normal curriculum of my high school. Unfortunately, the games did not have any speech output. It took me a few years afterward to connect pronunciation with the spelling and meaning of the words I had learned. Even though connecting a foreign or native language to practically any game that has a story line is easy and many children have interest in playing such games, this is rarely (if ever) exploited in language learning. Most modern adventure games no longer have text input or output completely relying on animation and point-and-click interface.

1.4.2 Fun, games, and reinforcement

Reinforcement is one of the basic psychological concepts that help to understand how to keep people interested in an activity. Research, [41], [116] indicates that variable reinforcement schedules lead to behavior with the longest extinction period. The delay between the behavior and the resulting reinforcement is also important: “the shorter the delay, the quicker will the behavior increase in frequency.” Computer games provide simultaneous multiple schedules of reinforcement. In Pac-Man getting points for eating different objects, getting to a new level, and obtaining the record score are three examples of reinforcement with different schedules.

The schedules are often variable-ratio or variable-interval. The variability of the schedules comes from predetermined or random changes in the game environment as well as from inconsistencies in the player's performance. As the player improves his/her skills, the game increases the complexity to disallow the player to get the reward consistently. This approach in game design is reminiscent to the concept of shaping used in reinforcement learning. Shaping forms a complex behavior by reinforcing a successive approximation of the target behavior. In games with complex strategies such as Caesar™, Pharaoh™, or The Incredible Machine™ by Sierra the player training can be viewed as a form of shaping: the player learns constituents of the behavior necessary to play the game step by step. In most other games that do not have a predetermined strategy, the game system rewards increased performance, but does not clearly defines steps in the learning process. The frequency of reinforcement events in most games is higher at lower levels to encourage beginners while they learn basic skills necessary to play the game. However, the relative amount of reinforcement usually increases substantially at higher levels to reward more skilled players, and to encourage beginners to advance to higher levels.

The emergence of addictive behavior described by Loftus and Loftus in their book *Mind at Play: The Psychology of Video Games* [83] has been confirmed by the evolution of computer games after the book was published. The most popular games provide the most balanced multiple schedules of variable reinforcement. For example, the latest simulation games, shoot-em-up games, and other addictive games all comply with these principles.

In the case of Tetris, reinforcements include removing full lines, giving points for each new piece, advancing to a higher level, and advancing in the best score table at the end of the game. The first level of reinforcement in the game follows the variable-ratio schedule that causes the longest extinction period. It is practically impossible to develop a perfect strategy for playing this game [30], making the first (full lines) and the last (score when the game ends) levels of reinforcement unpredictably variable, but dependent on the player's skills. As the programmer of the first PC version of Tetris I know that the game was not designed with explicit reinforcement principles in mind, but the basic idea of falling pieces and disappearing lines produces an emergent reinforcement system. The original PC version and versions implemented by Nintendo and other companies seem equally attractive despite different scoring systems. Media other than computer games are usually less interactive by design, less capable of tracking real-time user behavior and, therefore, more restricted in the ability to provide a variety of reinforcements.

1.4.3 Fun, games, and affect

Mandler [86] adds another view of the engagement mechanism in his cognitive theory of emotion. In his opinion, emotions and motivations follow a progression of violation of expectation and a subsequent resolution of discrepancy. The violation of expectation of the player, often caused by the player's actions, are common in computer games. The unexpected result can be both desired and undesired. The desired result boosts the confidence of a player. The undesired result often motivates the player to correct a situation. Media other than computer games, such as belletristics or cinematography often violate expectations of the reader or viewer to boost his or her interest in the story line. However, computer games are perhaps the only genre that interactively plays with expectations.

The emotion theory proposed by Lazarus [74] is broader and more general than that proposed by Mandler. It may help to explain the phenomena of computer game popularity and addiction. Although Lazarus never directly discusses any computer-related issues, he explores the process of deriving personal emotional meaning from a person-environment relationship. His theory provides a context for emotional dynamics. Instead of just viewing stimuli and expected responses, it may be possible to speculate about underlying emotions and understand why people have different reactions to otherwise similar situations. Lazarus describes the emotions he identifies, happiness, joy, pride, relief, hope, anger, etc., in terms of appraisal patterns, action tendencies, and dynamics.

The Lazarus concept of appraisal refers to how a person judges an influence of an event on well-being. When people engage in fun activities they tend to take the context of the activity more seriously than logically necessary. This tendency is one of the distinguishing characteristics of fun. Computer games, as with all forms of fun, have to take into account and make use of the basic human perceptions and reactions to the world.

Lazarus gives some clues on emotion and stress detection by describing physiological attributes of emotions. Stress-detection research can be applied in *Every Sign of Life* to personal stress monitoring. Lazarus also discusses the effects of emotions on health and mechanisms of coping with unfavorable conditions [73],[75] analyzing possible use of his theory in evaluation, treatment, and prevention of diseases. For example, he has shown that people recover from a surgery better and faster if they believe that no serious medical problem exists or they believe that the problem is not as severe as it actually is. This is a positive effect of false beliefs.

The emotions a player experiences in the course of a game have a complex dependence on the game situation and influence on the player's actions. One of my hypotheses is that the game appeal is determined by emotional progression. The Lazarus theory may serve as a key to understanding of the emotional context of games in general and computer games specifically.

1.4.4 Fun, games, and self-efficacy

The theoretical basis of Hirzel's [62] project was Bandura's theory of self-efficacy [10]. Bandura defined self-efficacy as "the belief in one's capabilities to organize and execute the sources of action required to manage prospective situations." Self-efficacy is a human behavior model that can be used to understand how various environmental factors or social system influence human beliefs and behavior.

What is the relation of fun to self-efficacy? Fun defines a person's attitude towards the situation. It affects a person's feelings, thinking, motivation, and behavior. According to Bandura [9], similar diverse effects are produced by self-efficacy beliefs throughout four major processes: cognitive, motivational, affective, and selection. Fun also depends on these four processes. Fun and self-efficacy may be involved in two different and parallel motivation models. If self-efficacy is defined as people's beliefs in their abilities to manage prospective situations, fun can be defined as people's enjoyment and interest in managing prospective situations independently of their abilities.

Self-efficacy may affect fun. If one's capacity is too great, a situation may be too boring to be fun. If one's capacity or belief in capacity is too little, a situation may be too frustrating (or frightening) to be fun. Fun, on the other hand, may influence self-efficacy: people's beliefs in their abilities can be unusually strong or weak in a fun situation. At the same time, fun may mitigate boredom or frustration.

Since *Every Sign of Life* is designed to reveal as much objective health information to the person as possible, it is important to eventually evaluate whether this can be harmful to seriously ill people. In the context of healthy people an important question is whether health monitoring can shift emotional balance towards positive emotions; in other words, whether the joy of interaction and exploration can outweigh possible negative emotions caused by health concerns revealed by the system. Within the context of this thesis, I make only general observations related to these questions.

1.5 Game design

Computer games represent one of the newest classes of recreation. (It has been argued in recent years that computer games represent a medium on par with print, television, theatre, and film.) Programming flexibility of the computer has allowed researchers to easily alter game parameters to explore what makes the games fun. However, computer games are usually disconnected from the physical and mental worlds—the player controls and observes the world of the game, but does not physically share it. Most interactions are limited to player's eyes and hands. On the positive side, computers may create imaginary worlds that are impossible to implement physically. On the negative side, such a mode of interaction can hardly benefit a player's health.

1.5.1 What is game design?

Game researcher Jon Orwant defines game design as "the systematic analysis of what makes games successful, and the attempt to codify those principles into reusable rules."[100] He goes on to say that game designers make use of "psychology, mathematics, physics, AI, graphics, user interface design, creative writing, art, music, and programming."

Orwant has developed two taxonomies of design principles: obvious design rules and non-obvious design rules (See Table 1). Another game researcher, Noah Falstein, is assembling a list of 400 rules for game design. Glimpses of his reasoning can be found at [44],[45].

Obvious Design Rules
Have more than one way to win
Have more than one way to enjoy
Ensure players know when they're doing the right thing
Hide the details of real life
Balance competing strategies
Don't make your AI too I (oblivious/omniscient)
Cater to the different player archetypes
Create pride through instant replays
Create lore through Easter eggs & cheats
Give players who are knocked out early something to do

Non-obvious Design Rules
Create mood through color temperature
Partition audio spectrum so that frequent sounds are distinguishable by pitch
Create emotional attachment by forcing players to view the backstory
Make goals linear, but subgoals multilinear
Make ranks persistent
Motivate long-term play via team pressure
Perturb/modulate difficulty to keep player guessing
Favor powerups over material swaps
Economic simulations are better than biological simulations

Table 1 Obvious and non-obvious design rules (from Orwant)

In describing what makes a good game, Orwant says, “Players want constraints so they have something to struggle against, and so that they know what they’re supposed to be doing.”

Sid Meier, the creator of the popular game Civilization™, remarks, “I find it dangerous to think in terms of genre first and then topic. Like, say, ‘I want to do a real-time strategy game. OK. What’s a cool topic?’ I think, for me at least, it’s more interesting to say, ‘I want to do a game about railroads. OK, now what’s the most interesting way to bring that to life? Is it in real-time, or is it turn-based, or is it first person…’”

In *Every Sign of Life* I wanted to do computer games about biofeedback or how to consciously control our physiology to be healthier. And my choice of the most interesting way to bring that to life is combining sports and action games with biosensor monitoring.

1.5.2 Game interfaces

Imaginary worlds in the computer games often include imaginary movement, fighting, interaction with various objects and subjects, but, with an exception of a few arcade games, the player can only see the action and alter it with the mouse, joystick, and keyboard. In fact, most computer game taxonomies only include purely software computer games that require no unusual input devices or gadgets.

Some exceptions worth noting are the arcade games that include hardware to give the player physical feedback. For example, there are game-machines where the player sits on mock-up skis, a motorcycle, water jet, etc., and can feel the motion synchronized with the action on the screen. Another example is Whack-a-Mole™, the arcade game where the player hits plastic moles jumping out of holes with a mallet. Dance Dance Revolution™, a game where players dance to the computer’s lead, is interesting in that spectators routinely play along with the players by also mimicking the steps. (Dance Dance Revolution is being incorporated into some elementary and middle school gym programs as a way to entice the student to exercise.) There are also examples of experimental installations—so called augmented realities—that explore how the computer-generated virtual world and physical real world can mix and interact.

1.5.3 Bio-Analytical Games

Some biofeedback systems include game elements to make biofeedback exercises less monotonous. Examples include biofeedback games developed by the MindGames group at Media Lab Europe, biofeedback visualizations developed at HeartMath Inc., and audio biofeedback developed by B. Gavitz. A common problem of most of these systems is excessive focus on a single biofeedback parameter. It is hard to make an interesting game with a single dimension of control that also has to shift in only one direction. For example, some of those systems focus on continuous relaxation. The difference of my approach from these systems is higher emphasis on the game elements of the system. The goal is to make a fun activity that includes biofeedback rather than augment a biofeedback exercise with game elements.

An interesting example of this approach is a betting game developed by Vikram Kumar in the Media Lab's Human Design group. Children make wagers as to who will best control their blood-sugar levels. The game is an example of how gambling might increase interest in self-monitoring. The difference from my project is that the target group was children with diabetes who already had some interest and urgent need for self-monitoring. My goal is to get healthy people interested in self-monitoring.

Sports are physical activities engaged in for fun or pleasure. The physical activity associated with sports generally has a positive impact on conditioning. Individual sports often have metrics by which performance can be measured, allowing for similar reflection and reinforcement mechanisms as found in computer games. Team sports have the additional benefit that group members can provide feedback to individuals. Group and competitive sports also offer a great opportunity for emotional highs and lows.

The Extremity Computing approach to wearable computing is one way to pull the virtual- and real-world experiences back together. In *Every Sign of Life* I explored a new approach of adding implicit biofeedback to computer games and situate these games in everyday scenarios. A question I investigate is what may work as reinforcement in the context of the health information. Bio-Analytical Games, which combine the data interaction of computer games with the physical world of sports, provide various forms of reward for repetitive use of the monitor, reflecting on health data, and, ideally, improving health.

The most difficult challenge is to establish what people may consider rewarding in the game's context. For example, chess, basketball, Pac-Man™, Tetris™, Quake™, The Sims™, or Myst™ have different environments with different set of rules, player actions, environment responses, and reward systems. The combination of the internal rules makes those games interesting to many people. Most computer games have similar features borrowed from sports such as a scoring system and table of the best results that may be easy to exploit and adjust. Such features serve to increase game appeal by adding an element of competition.

In most sports the activity is designed to produce results that are random, but biased by the skill of the players. This randomness is very important to keep sports dynamic. Without it there would be no unexpected winners. The sports activity itself may not appear sophisticated or interesting, but the score-based competitiveness is engaging or even addictive. The competition may involve broad communities and rise to a high level: from person-to-person to continent-to-continent. The ability of players to increase their skill level by repetitive training is another important feature of sports.

The purpose of sports equipment is to augment, reveal, measure, and contrast particular physical skills of the players. However, classical sports deal with muscle coordination and not with more autonomic physiological characteristics, such as heart rate. Although modern sports arenas are stuffed with electronics to measure results and keep track of events, most people playing sports deal with technologically passive objects to be measured and analyzed by coaches and trainers.

Parameters measured by the biosensors reflect many important internal characteristics of the human body. Many of those parameters are often hard to control even after training. This adds randomness for a sports activity. People can also gain skills in controlling these parameters. And a health monitor could reveal, measure, and contrast these skills. Given a balanced scoring system that depends on the physiological characteristics biomonitoring can be a part of a sports activity called Bio-Analytical Game.

A computer-game visualization is another side of a Bio-Analytical Game. In regular sports the results are evident. In Bio-Analytical Games the computer reveals invisible characteristics and helps to understand the results. The player cannot see the result before the computer shows it. This creates a possibility to manipulate player expectations, generating emotional progression to create a more engaging game.

1.6 Summary

The Extremity Computing approach to wearable sensor design combined with the Bio-Analytical approach to game design may lead to a multiplicity of scenarios where feedback about physiological profiles is engaging. It is this premise that I explore in the remainder of the thesis. In Chapter 2, I give an example of how the *Every Sign of Life* approach to long-term personal health monitoring can be used in educational and entertaining form to help people learn more about stress. In Chapter 3, I describe *Hand-held Doctor for Children*, the precursor to the more general approach I take in my thesis. In Chapter 4, I describe the Extremity Computing in detail. In Chapter 5, I describe the Every Sign of Life approach to personal health monitoring. In Chapter 6, Bio-Analytical Games are presented and I detail the various studies I conducted. I conclude with a summary of my results and a review of my claims.

Chapter 2
Every Sign of Life examples

In this chapter I describe a demonstration of how people can use personal health monitoring over long time periods to learn more about stress and give two other examples of the *Every Sign of Life* approach.

2.1 Stress monitoring

If everything seems to be going well, you obviously overlooked something. — Murphy's Law

Our well-being in part depends on how we feel emotionally. Emotional stress may lead to adverse psychological and physiological changes such as depression or high blood pressure. Lack of stress, on the other hand, may reduce our capacity to cope with unexpected emotional events. An ability to objectively judge the amount and pattern of emotional stress in our life may help us to understand the roots of some of our psychological and physiological problems and to be more informed about how to plan our lives.

For example, if we knew what meetings, appointments, phone calls, or other events consistently cause a lot of stress, we could better schedule our life avoiding long periods of continuous stress. It may become possible to pick a route from home to work based not just on time and distance, but also on the emotional stress patterns that it causes.

At least half of patients with somatic problems – such as chronic fatigue, chronic allergic reactions, muscular and vascular headache, irritable bowel syndrome, primary insomnia, and primary hypertension – seen in primary care do not have identifiable organic disease or psychopathology [138]. According to Ian Wickramasekera many of these problems are manifestations of emotional distress [137] [140] that is not recognized by the patients. To help his patients understand the connection between the body symptoms and feelings he uses a strategy called Trojan Horse Role Induction [138] that includes biofeedback.

The past 12-month period was one of the best in my life for studying extreme emotional stress on myself. This included job interviews, receiving rejections after the interviews, unexpected financial complications, and visa problems. The only drawback is that the high emotional stress often moves the focus off the research. On most job interviews I wore the health monitor to demo my latest projects and recorded EKG, temperature, and on some occasions skin conductance. I made the most extensive set of recordings on a two-day interview at IBM. It includes not only the interview process, but also driving my car to and from the place of the interview and between the hotel and two company locations. In addition to the biosensor recordings I had a detailed two-day meeting schedule that helped me to map the data onto the events of those days.

Based on my observations my heart-rate signal recorded over highly stressful episodes slowly oscillates (3–5 times per minute) between approximately 90 and 140 (See Figure 3). From the power spectrum analysis perspective this means a power density increase in the frequency band below 0.1 Hz. If stress continues over several hours the heart rate may become very high (135+) and steady.

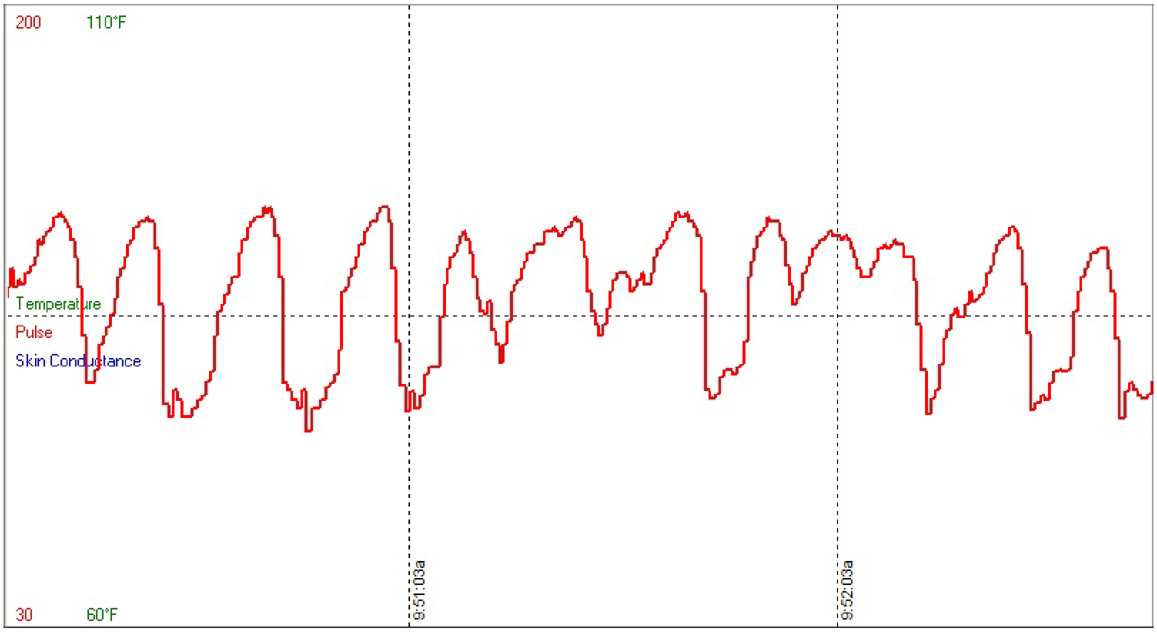

Figure 3 Heart-rate oscillations during high-stress episode: I got lost driving to a job interview

In *Every Sign of Life* I designed a prototype of the system that estimates called "Stress Diary" that could display emotional stress estimation based on physiological parameters recorded by the health monitor and allows the user to overlay the stress information on top of the schedule. The system was designed as an independent application that can extract schedule information from Microsoft Outlook® and obtain stress, weather, and other information from separate databases.

Standardized methods of psychophysiological stress profiling have been developed at Futurehealth Inc. [43], Thought Technology Inc. [130], and other organizations to assess a person's habitual response patterns to stress. However, these methods require an extensive set of sensors and are not designed for continuous monitoring. Ambulatory monitoring protocols have been developed to monitor blood pressure for patients with hypertension [109]. These protocols are designed for either self-monitoring or monitoring with automatic devices that measure blood pressure every 15-30 minutes. The protocols also include assessment of stress based on periodic measurements of blood pressure and heart rate. Thomas Pickering wrote a book for general public that describes how to use self-monitoring to alleviate risks of hypertension [110].

The stress data can be calculated from the personal health monitor EKG recordings using the heart-rate variability analysis algorithm developed in the Affective Computing group at the MIT Media Lab by Prof. Rosalind Picard and Yuan Qi. The algorithm performs a power spectrum density analysis of a heart-rate signal to distinguish patterns characteristic of high stress levels or anger.

Some studies also suggest [89] that a level of stress or strong negative emotions such as anger can be identified by the ratio of power spectrum densities of the heart rate signal in the very low frequency range and the high frequency range. In a test example I applied the analysis similar to the one used in the Breathing Pac-Man study [see section 6.3.3] to estimate the power spectrum density values. I then calculated stress levels for the demonstration as the ratio between the VLF and HF power density for each hour during the day of the interview. The ratios were added into the database so that the demo program can display the stress data overlaid with the schedule information [Figure 4]. Even though the ratio was not proven to be an accurate estimate of stress, the stress pattern during that day was similar to my subjective evaluation. For example, the highest stress level, according to both the calculations and my recollection, was observed in the morning at the time when I got lost driving from hotel to the company location.

This application may not be just a tool to look at the stress levels, but also an entertaining activity for people who like to look at the past events or engage in self-exploration. This application is also an example of how people can benefit from continuous biosensor monitoring. When a person has a recording of biosensor signals over an extended period of time it becomes possible to process and present this information in a useful and entertaining form.

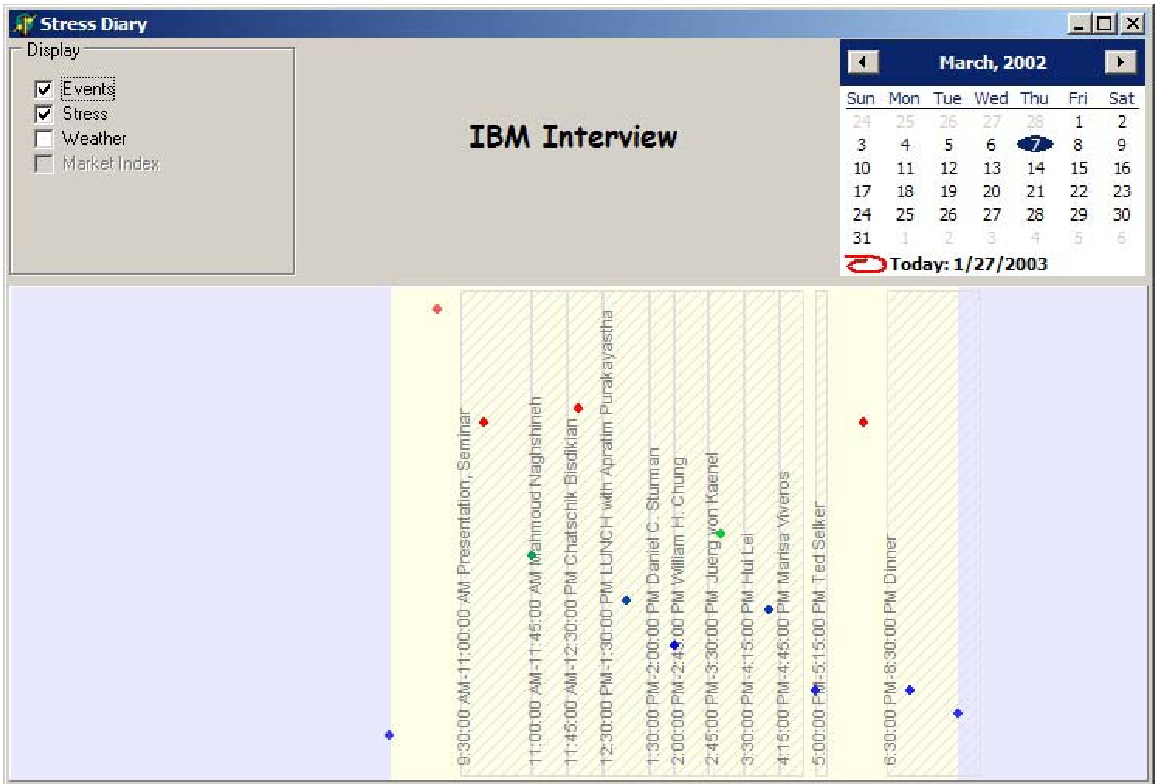

Figure 4 In the Stress Diary demo, circle color and position indicate stress level.

The application has to be further developed to include automatic stress data analysis, improve the user interface, and to process and display more information such as news, e-mail, and other. The stress visualization can also be a useful feature that can be included in the systems that help to remember the past such as the Memory Prosthesis [133] developed by Vemuri at the Electronic Publishing group at the Media Lab MIT.

2.2 Personal health information as news

Many people use computer-scheduling programs to keep track of their meetings, appointments, phone calls, and other events in their lives. Those applications are future-oriented and rarely provide any additional information to help people remember and analyze what happened in the past. However, external information such as news, weather, location, or health data could make a scheduling application a useful tool to remember and analyze events in the past [133]. Based on stress information such a system may even provide recommendations for scheduling future appointments and meetings. For example, it may suggest scheduling potentially stressful events further apart. The question is whether such a system can be fun.

Almost everybody habitually enjoys listening to, reading, or watching news programs. The news is about many topics: weather, traffic, sports, stock market, local and global events, etc. The question is whether information obtained by a personal health monitor can be prepared and presented in such a way that the person enjoys receiving and thinking about it as much as about other news. No doubt, such information is more directly relevant for the individual than typical news programming.

What makes news interesting? One of the factors is the relation to personal well-being. Local news, weather, and market information affect us most. Another factor is relevance to communities the person is involved with. Even if news does not affect the person directly, it may concern the others and may be a potential topic of conversation in a group. A play (or game) factor can contribute to how interesting news is. For example, sports attract attention because players usually have strong community associations and the games are appealing and unpredictable. The quality of news presentation may also greatly influence the reader's interest.

Personal health information is a good candidate for attention-grabbing news. It has personal, and community relevance. The question is how to process and present that information to make it fun. Scenarios include adding personal health reporting to online news, car radio, pagers, etc.

2.3 Communities

Shared health information may enhance relationships in communities. Parents may want to know how their children's health changes. Many children may want to keep track of their elderly parent's health. Knowing how stressful various situations are for members of a community may help to reduce tension and improve understanding. There are numerous other communities, such as senior citizens at a community center, where shared health information may enhance relationships.

The personal health monitor may identify not only health risks and problems associated with individuals, but also the influence of the community context on health. Although the main focus of the research is individuals, it is necessary to account for the effects of community context [124],[58] in the health analysis. The community health-information sharing may, in return, provide a basis for inter-community health competitions, e.g., one neighborhood competing with another on weight loss?

The community support for health monitoring has a role to play in sustaining people's interest in wearing the device and providing a productive environment for exploration of the health issues. In addition to intrinsic reinforcement provided by the monitoring system itself the community may provide the users with an additional level of extrinsic reinforcement necessary to make the health monitoring activities fun [116].

2.4 Summary

In this chapter, I described a demonstration application that presents stress information to people in order to engage them in an (hopefully fun) exploration of past events in their lives. The other two examples demonstrate how to combine health monitoring with news, community participation, and scheduling – areas not traditionally associated with play.

Chapter 3

Hand-held Doctor for Children

Begun in 1998*, Hand-held Doctor for Children* was a project that gradually transformed into the broader exploration of fun and health information described in this thesis. The principal goal of the project was to design health-monitoring devices and software that in combination helped children better understand how their bodies worked and how to design fun activities around these tools. The health-monitoring devices built for the project monitored, analyzed, and recorded pulse, breathing, temperature, and galvanic skin response. A small PIC-based device digitized the sensor signals and sent the data to a PC or a toy. PC programs and LEGO constructions were used to visualize physiological parameters.

One of the questions I explored in *Hand-held Doctor for Children* was how to make health-monitoring hardware that is suitable for rapid prototyping, but also user-friendly and robust. In other words, the hardware had to satisfy the requirements of researchers and children. The sensors and devices I built for the project led me towards defining the Extremity Computing approach. The main idea of this approach was to make a separate small mobile device that could obtain information from a variety of hand-made sensors and deliver the data to a computer wirelessly.

A second question this project addressed was how to make information measured by the sensors both fun and meaningful for children. To answer the question, I built demonstrations and designed scenarios about how children can engage into fun activities that involve viewing and exploring health parameters *in vivo*. In addition to a large number informal demonstrations performed over the course of five years, I conducted several formal case studies to make general observations on how children interact with the built systems, what scenarios are fun and work well for a given age group. The results of the studies were applied to develop new ideas and recommendations on use of fun health monitoring for children.

In this chapter, I first describe the biosensor device I developed that is at the heart of much of the *Hand-held Doctor for Children* work. I then describe a variety of activities I developed for children. I follow this with a discussion of a workshop I did with high-school students. Finally, I conclude with a brief discussion of some follow-up work done by others.

3.1 The Handy board and the biosensor helmet

The device I used to collect and transfer sensor information to the computer was the Handy Board [88]. Although this device had sufficient analog-to-digital conversion and processing capabilities, it was not designed specifically for data collection, which caused several problems. For example, the device was too bulky to wear; it had no wireless-communication capabilities; the on-board memory was very limited; and the serial link required an additional interface board.

Special-purpose integrated computer-sensing systems led to a more stand-alone, miniature device. In 1995, Fred Martin, a researcher in the Epistemology and Learning Group at the Media Lab, worked on a new microcontroller-based robotic-design platform for children called “crickets.” The cricket consists of a small circuit board that fits on the bottom of a plastic 9V battery holder. The crickets seemed like an excellent form factor for the device we needed. I put together a data-collection system consisting of a PIC 16C711 microcontroller, an FM radio-transmitter module, and power supply circuitry with a 9V battery. The microcontroller provided four eight-bit analog-to-digital converter inputs, additional output pins to control optional LEDs or other components, and processing capabilities to assemble and send data packets over the RF link using a serial protocol. The receiver module was connected to the serial port of a PC or other device, and received power from a keyboard, mouse, or proprietary 5V connector. I call this data-acquisition system the HHD device (an acronym for *Hand-Held Doctor*).

With HHD, data were broadcast continuously in packets consisting of a predefined header byte, four samples from each analog input, and a check-sum byte. The receiving computer discarded bad packets, which did not cause serious problems, since communication quality was nearly perfect in practical proximity to the computer.

The HHD device was small, light, and inexpensive enough to be attached to wearable objects or embedded in sports gear and toys. It provided a real-time wireless data feed from up to four sensors (Figure 1).

3.1.1 The biosensor helmet

Given the goal of the project was to help children explore changes in heart rate, breathing, temperature, and skin conductance in different situations [47], I wanted to continuously "feel the forehead" and "keep its finger on the pulse" of a child. The HHD device, in combination with a set of custom-made sensors, allowed me to measure and deliver physiological parameters to a computer in real time.

The sensor set included a precision thermistor temperature sensor, a thermistor-based breathing sensor, an infrared optical pulse sensor, and a skin-conductance sensor. Each sensor had op-amp circuitry powered by the HHD device that filtered, amplified, and shifted the signal to get a desired range and accuracy at the analog-to-digital converter.

In the context of *Hand-held Doctor for Children*, putting on and adjusting biosensors had to be made simple, if not transparent. I sought out objects that would help achieve this design goal. One of such objects is a helmet, since the head is an ideal place to measure many parameters including pulse, breathing, and temperature. A helmet has the advantage that it can be used to position sensors so that they require little or no adjustment. While a helmet is hardly suitable as everyday apparel for most people, children are usually willing to don a helmet and play with it. The same sensors can be mounted inside other toys. For example, some of the sensors may work well in huggable, soft toys. Some subtlety of design would need to be given in order to ensure that children make sufficient contact with the sensors in the course of play.

A few demonstrations and case studies were conducted using a motorcycle helmet with the HHD device attached to its side (See Figure 5). Four sensors were mounted inside the helmet: (1) an optical pulse detector mounted at the left temple; (2) a temperature sensor mounted at the right temple; (3) a breathing sensor attached at the bottom of the face shield; and (4) two skin conductance electrodes attached to the forehead cushion.

The helmet is able to send data to either a personal computer or a robotic toy. As described in the next section, a PC application designed for preschoolers showed an animated cartoon character to visualize pulse, breathing, and temperature in real time. High-school students designed their own robotic toys that responded to the signals received from the helmet. A LEGO castle is an example of such a toy; the castle had three motors inside to move a drawbridge with changes in temperature, a flag with breathing, and guards with heartbeat. A Handy board that had a receiver module plugged into the serial port was used to control the motors.

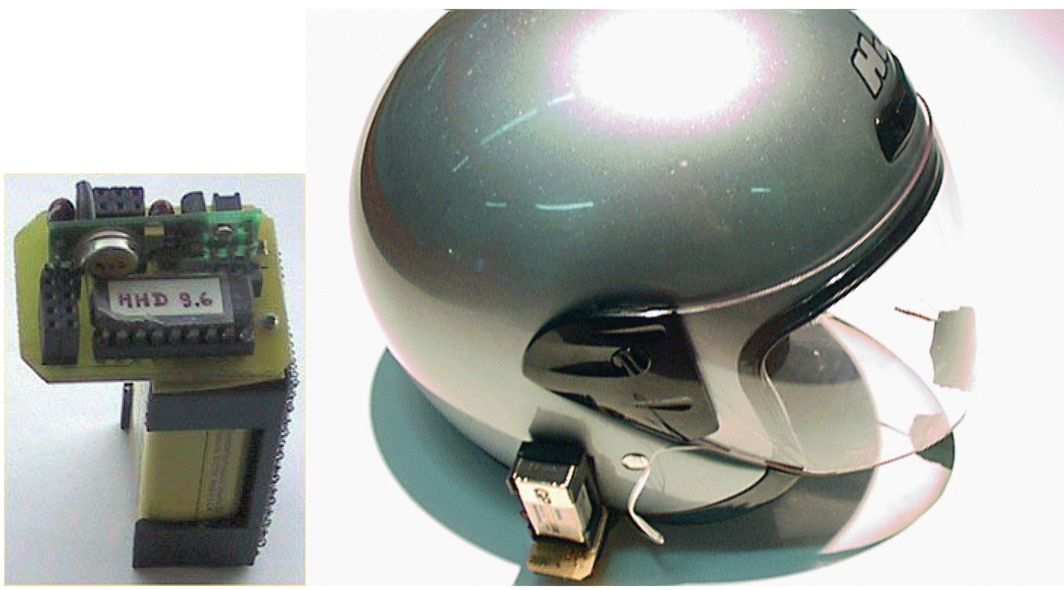

Figure 5 The HHD device and the biosensor helmet. The HHD device is mounted on the side of the helmet while four sensors are mounted inside.

An optical pulse sensor (photoplethysmograph) was made specifically for this project. It worked by detecting changes of skin reflectance of infrared light with different phases of heartbeat. The skin reflectance depends on the volume of blood in the blood vessels in and directly below the skin. The sensor consisted of an optical component that touched the skin and an amplifier/filter circuit based on dual operational amplifier chip MAX474. The optical component was an infrared LED and photodiode assembly commonly used in punch-hole readers.

The temperature sensor used a precision thermistor connected to a single operational amplifier circuit that changed the output voltage range to match analog-to-digital converter input range. The sensor was placed at the left temple surrounded by the helmet padding.

The breathing sensor was similar to the temperature sensor, but used much smaller and less precise thermistor to detect temperature difference between inhaled and exhaled air.

The galvanic skin response sensor was a Whetstone bridge connected to a single operational amplifier circuit to increase the gain. One side of the bridge was connected to the skin electrodes. Tests of this sensor indicated that galvanic skin response of the forehead area is substantially different from that of the palm of the hand where normally galvanic skin response electrodes are placed.

3.2 Hand-held Doctor activities

Scenarios designed for *Hand-held Doctor for Children* targeted two age groups of children: younger children 5–7 years old and older children of high-school age. For the younger children I built an application that allowed them to see their pulse, breathing, and body temperature in real time. All three parameters were embodied in a cartoon character. Older children used the device as part of a constructionist activity, using the sensors to control motors.

3.2.1 Cartoon character visualization

The first animated cartoon character that young children played with was a dog (See Figure 6). The chest of the dog expands and contracts with the child's breathing. The red rose in the dog's hand pulsates with the child's heartbeat. And the face, arms and feet of the dog gradually changed the hue from gray-blue to gray-red depending on the temperature measured by the body temperature sensor. The extreme gray-blue hue indicated temperature below normal body temperature range. The extreme gray-red hue indicated high-fever or temperature above normal body temperature range.

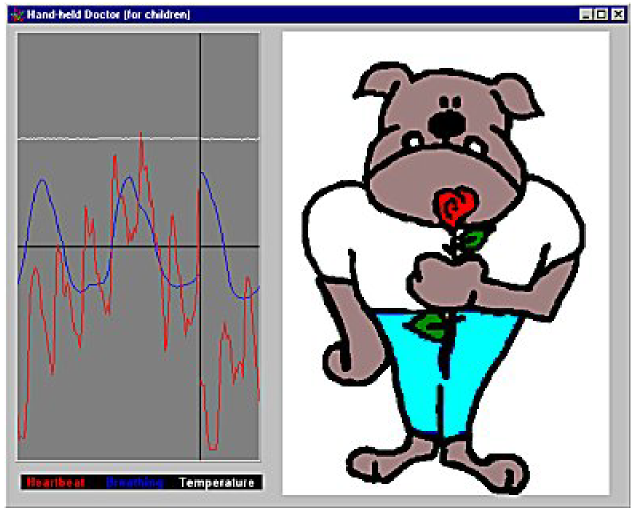

Figure 6 The dog cartoon character

Another cartoon character (See Figure 7) was developed and rendered in the Persistence of Vision™ freeware ray tracer system [114]. The cartoon character has a shape of human figure. A red heart is visible inside the transparent lightly colored torso. This cartoon character is used to visualize the same three physiological parameters as the dog cartoon character: heartbeat, breathing, and body temperature. The size and shape of the heart inside the character changes in accordance with the phases of the heartbeat, as measured by the pulse sensor. The chest expands and contracts with the breathing. And the color of the transparent body changes depending on the temperature measured by the temperature sensor from blue to light brown to red. To create a visibly smooth animation 125 separate frames were rendered to account for all combinations of five phases of heartbeat, five phases of breathing, and five phases of temperature levels. The program continuously determines the phases of heartbeat, breathing, and temperature by analyzing the information received from the sensors and displayed one of the 125 frames to show the current state.

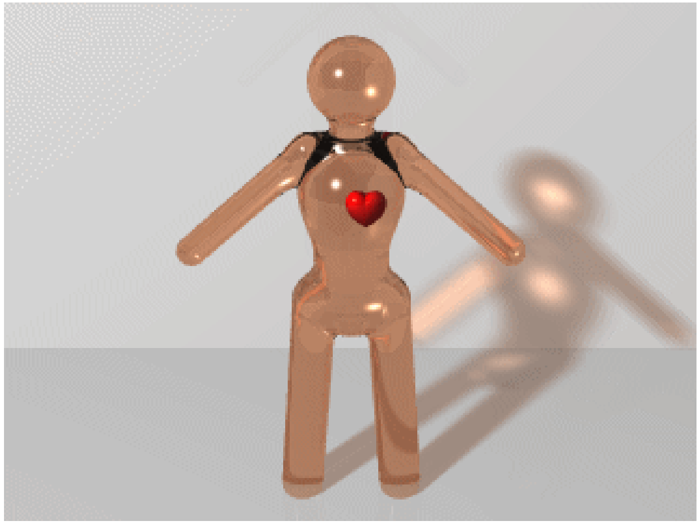

Figure 7 Glass guy cartoon character

Younger children who played with the system were interested in seeing how their breathing and pulse reflected in the cartoon character behavior. After wearing the helmet for a few minutes they usually switched to exploring what else they can do with the sensors. For example, they discovered that touching the pulse sensor makes the heart on the cartoon contract. The children could also remove the sensors and explore them outside of the helmet. On most occasions I also gave the children two cups of water with cold and hot water to dip the temperature and breathing sensors into and see how they work and how the cartoon character changes its color and shape. Children who saw both the dog and the guy usually preferred the latter. A possible explanation for the preference was the quality of animation; the photo-realistic glass figure both looked better and moved smoother.

A cartoon system may be a good medium to explain and demonstrate to younger children what biosensors can do, and to get them interested in further exploration of the relationship between their bodies and the environment.

3.2.2 Robots and toys

High-school children participated in building LEGO constructions activated by the signals from the helmet. An example of such a construction is the castle (See Figure 8) that reacts to the heartbeat, temperature, and breathing. The castle was designed and built by a high school student. She decided to control three features of the castle with three corresponding signals from the helmet: the drawbridge moved up and down as the temperature detected by the body temperature sensor increased and decreased; the flag over the back tower waved when the respiration sensor detected breathing; and the guards on the castle yard made a step forward with each heartbeat.

The Handy Board [88] controlled three motors inside the castle to activate the drawbridge, flag, and guards. The Handy Board was equipped with a radio receiver plugged into the serial port and power bus. The Handy Board received the data packets broadcast by the helmet and activated the motors depending on changes in the signals.

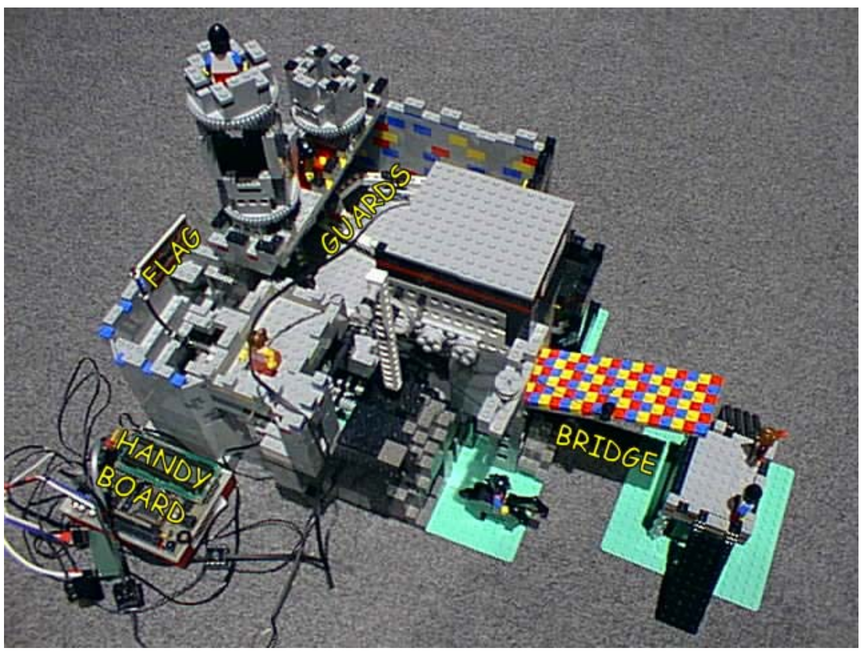

Figure 8 The LEGO castle

Some youth, especially boys, were interested in building moving car-like toys that mapped information from the biosensors onto various parts of the toys. Several toys of this kind were built on different occasions at the Media Lab. An example is shown in Figure 9. The carriage moved forward or backward when temperature increased or decreased. The heartbeat was indicated by the blinking LEDs. The rotating propeller indicated the breathing.

The Media Lab's Life-long Kindergarten group followed up the work with LEGO. A family of biosensors was designed for the LEGO Mindstorms™ "programmable brick," which is LEGO's commercialization of the Handy Board. [91]

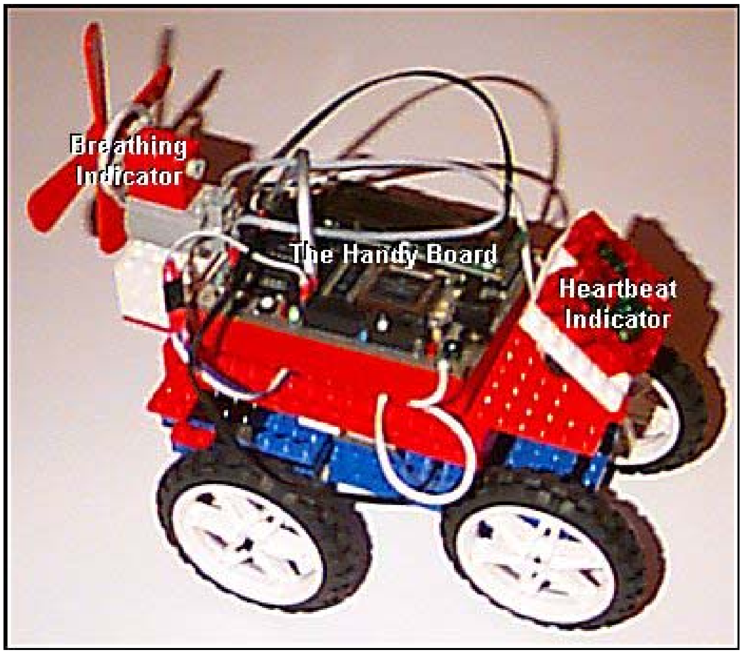

Figure 9 The LEGO carriage robot

3.3 Lie-detection workshop

A lie detector, also called a polygraph, is a biosensor system for trying to discern whether a subject is telling a lie during questioning. Such systems, which typically include a subset of blood pressure, heart rate, respiration, and skin conductance sensors, have been used in police interrogation and investigation since 1924 [37]. A person, the polygraph operator, conducts questioning and determines whether the subject is lying based on the changes in the sensor outputs. Since people usually cannot or do not know how to voluntarily control the measured parameters, individual characteristic patterns of lying can be established by the polygraph operator. However, there is no known physiological response that is unique to deception [67]. The system, therefore, does not detect a lie, but provides patterns of arousal response. The operator has to carefully structure a set questions to establish what patterns may correspond to deception and then infer the subject's truthfulness [67].

Because of the complexity of polygraph testing that depends not only on hardware, but also on individual characteristics of the subject, experience of the operator, and type of questioning [26], reliability of lie detection cannot be guaranteed.

The lie-detection workshop for high school students pursued several goals: to observe whether the activity is fun for the children; to introduce the children to biosensor technology and basics of signal analysis; to demystify the concept of lie detection; and to help the children understand how lie detectors work and why they are not considered reliable.

Four high-school students participated in the study. They used a desktop computer running an application that in real time recorded and displayed the graphs of two signals: heart rate derived from the output of the photoplethysmograph and skin conductance. At any time the previous 20 seconds of data were visible on the graph. The application also made heartbeat sound that corresponded to the heartbeat detected by the photoplethysmograph. One of the youths attached two skin-conductance electrodes and the photoplethysmograph to her fingers with Velcro™ bands. The sensors were connected to the HHD device detached from the helmet. The HDD device digitized and sent the sensor signals wirelessly to the desktop computer.

The high-school students were asked to play a variant of the game 20 Questions, where one subject wearing the sensors picks a random object in the room and the others ask yes/no questions to identify the object. Without lie detection the game only works if the answers are truthful. But with access to the polygraph sensors, they were able to monitor changes in physiological response during question answering and to determine the difference between truths and lies.

The students remained engaged throughout the duration of the workshop, which lasted about 40 minutes. They quickly understood that the way in which they ask their questions makes a difference in the physiological response of the subject answering the questions. If the subject was emotionally engaged with the question, they could see more noticeable changes in heart rate and spikes in skin conductance. To establish a reference physiological response for lies and truthful answers, they came up with a strategy that involved asking personal questions, for which they presumably knew the correct answers. After playing for about 15–20 minutes they had some success in detecting lies—they established that lies most likely correspond to higher increase in pulse rate and stronger change in skin conductance. Physiologically this pattern often corresponds to higher stress or anxiety.

Atypical of lie detection, in the study the subject who answered the questions was able to see the computer screen and observe the progress of the team asking questions. After about 10 minutes the initial success of the team asking questions began to diminish. The subject was able to counteract possible effects of lying by making her physiological patterns noisier and less distinguishable. Although they remarked afterward that they found lie detection interesting—teenagers in general seem to be curious about lie detection—after playing the game several times in differing roles, they abandoned 20 Questions in order to ask each other personal questions.

The youths undoubtedly had fun playing with the lie detection and stayed engaged in the discussion of what changes they were able to see in the signals and how they were able to detect a lie or trick the system. They understood that the sensor system alone couldn't unambiguously detect lies; a carefully selected sequence of questions is needed to keep the subject of questioning emotionally engaged. They also understood that lie detection based on physiological sensors is more of an art than a precise science and may not be reliable.

3.4 HHD hardware design

3.4.1 Overview

The HHD hardware was designed as a universal wireless data acquisition peripheral. In fact, the first application of this device was not in a health monitoring system, but in an instrumented baseball bat. This device helped me to quickly prototype a variety of sensors and sensor-controlled applications. This device looks similar to and was inspired by the Crickets—a family of microcontroller-based computers designed in the Epistemology and Learning Group at the MIT Media Laboratory. This device was different from the Crickets in several aspects. First, it was wireless and could broadcast sampled data from sensors to any computer within its reception range. Second, it was not intended for frequent reprogramming. Instead the same program sampled and transferred signals from any four sensors at the maximum sampling frequency limited by the data transfer rate of the transmitter/receiver. The device could be moved from system to system without a program update. A program on the receiving device had to decide how to interpret the incoming information.

Developing new scenarios and prototyping hardware and software with the HHD device led to the idea of *Extremity Computing.* The idea was further developed and defined later with the Hoarder Board and a set of projects built around it.

3.4.2 Schematics

The circuit for the HHD device (See Figure 10) was made using a minimalist approach. The power was supplied by a 9 V battery connected throughout a power switch and U2—5 V voltage regulator. The power capacitors (one of them is optional) are necessary for the power regulator to eliminate power fluctuations.

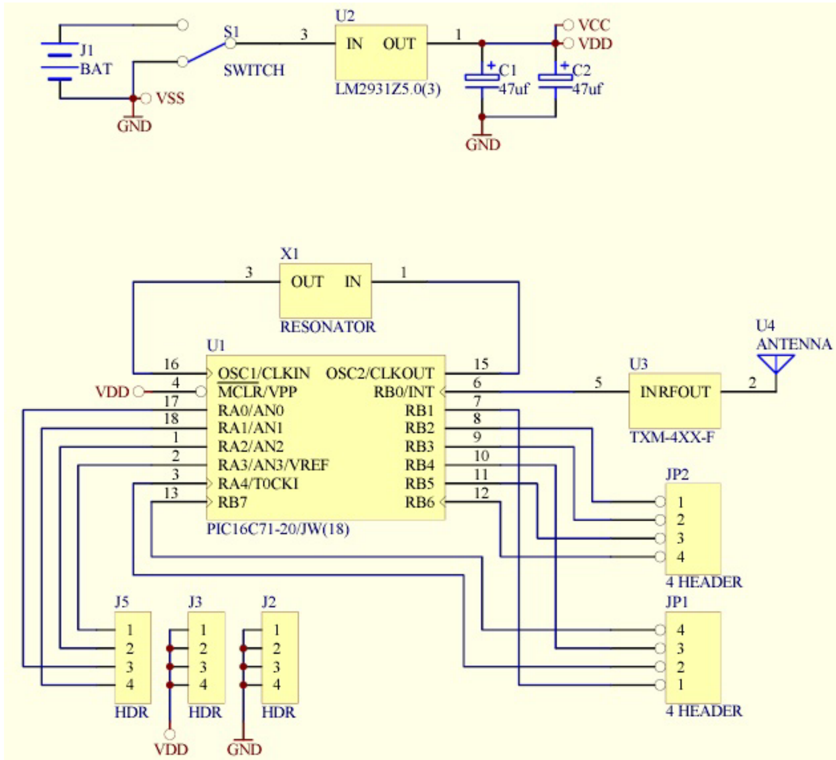

Figure 10 HHD device schematics

The central part of the device is a Microchip PIC® 16C711 microcontroller. The microcontroller had four analog-to-digital converter channels used by the device to sample signals from up to four sensors. The sensors could be plugged into the J5–J3–J2 set of headers that provided input, power, and ground connection. The sensor headers were arranged the same way as on the Handy Board or early versions of the Crickets, so that the sensors could be interchangeable among those devices. JP1 and JP2 headers were put on the board to expose all microcontroller pins unused by the sensor/transmitter circuitry. Those headers could be used, for example, to control LEDs or motors in some of the systems. The RF transmitter U3 connected to an output pin of the microcontroller broadcasted the information. The transmitter was one of the Radiometrix® TXM-4XX-F modules that sent FM radio signal at 418 or 433 MHz.

Radiometrix SILR-4XX-F receivers could be plugged directly into a serial port of a receiving device. The microcontroller sent data encoded as a standard serial protocol sequence of bits. Although the transmitter/receiver manufacturer did recommend using

Manchester encoding [38] to achieve a perfectly balanced ratio of 0s and 1s, a regular serial protocol worked without problems with a continuous data stream. This problem is discussed further in the context of the BIM2 radio modems.

Most of the software I wrote for the HHD board sampled all four analog inputs continuously 160 times per second and sent 160 six-byte data packets at 9600 baud using eight-bit no-parity one-stop bit serial format. Each packet consisted of a header byte, four data bytes (one from each analog input), and a check sum byte. The receiving program usually discarded corrupted packets where the header byte or the check sum was incorrect.

3.5 Batting Belt

From 1996 to 1998, I used the HHD board to rapidly prototype a family of embeddable devices for a baseball bat, the *Swings That Think* project. If an extremity-computing device is inside a baseball bat the baseball bat, becomes a part of the computer, and the computer can sense what the player does with the bat [48].

The goal was to develop a collection of devices that provides real-time motion analysis and audio, tactile, or visual feedback to the user engaged in a task that requires coordination of body movements, and possibly some extra-body affordance, (e.g., a golf club, tennis racket, fishing pole, or baseball bat). The devices performed three functions: sensing, analyzing, and providing feedback to the user. Each device consists of a collection of wearable sensors such as ankle and wrist straps, belts, and hats that sense characteristics of the user's posture and motions as the user engages in various activities.

The focus of the Batting Belt project was to introduce concepts of batting through an in vivo experience. The system helped people to learn how to swing a baseball bat. The first prototype of an instrumented bat was based on the Handy Board. The sensors consisted of a set of accelerometers and gyroscopes placed inside the bat and on the player's body. The Handy Board was placed inside a belt pack and connected to a computer with a cable (See Figure 11). Although this system had adequate data-acquisition support, it was rather heavy, hard to put on, and awkward because of the dangling connection wire. The HHD device allowed us to make a wireless version of the system. Although we had to reduce the number of sensors in the system, we nonetheless were able to obtain enough data to provide meaningful feedback. Ideally, the bat requires three gyroscopes and three accelerometers to estimate six degrees of freedom of motion and produce a realistic 3D model of the bat trajectory [134]. The four inputs of the HHD device were typically used for 3 gyroscopes and one accelerometer, but other configurations were tested as well. The HHD device was placed in an extension to the handle of an aluminum bat, with a wired connection to several sensors and indicator LEDs inside the bat (See Figure 11).

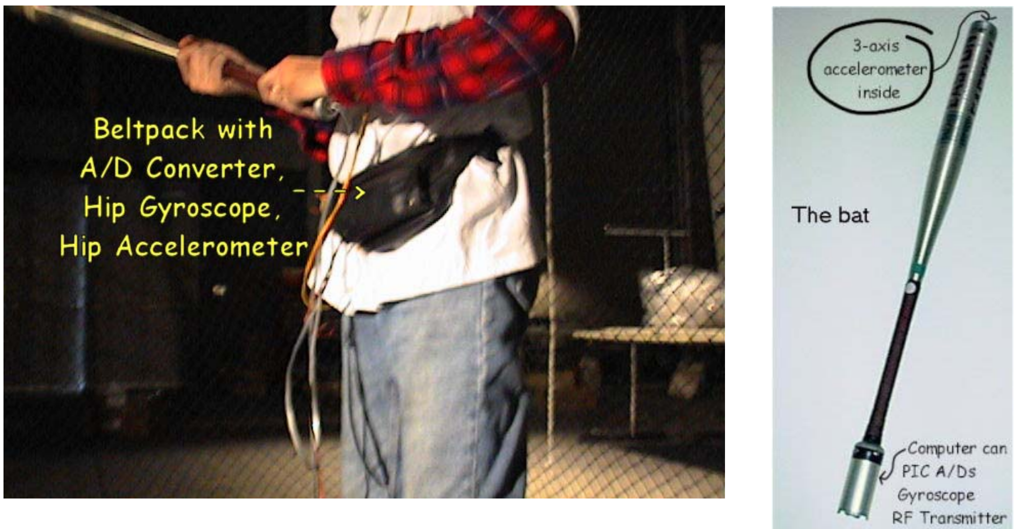

Figure 11 The Batting Belt and the instrumented wireless bat

In this project the HHD device allowed the design of a compact system to acquire and wirelessly deliver information from several sensors to a computer that performed analysis and provided the user with feedback. The light and small wearable component of the system allowed the player to freely move around while the feedback component used a conventional computer to avoid the processing and user-interface shortcomings of smaller computers.

Since the player cannot constantly look at the computer screen during batting practice, most of the feedback was provided with sound. The player could listen to the pitch of the background sound that indicated the real-time speed of the bat as well as a spoken report after each swing that described possible errors and helped to improve the batting technique. A conventional computer had enough processing capabilities and convenient API to implement such a system.

This project demonstrates how extremity computing can help in designing systems that help people to learn physical skills in tasks that require advanced coordination of body movement. The HHD board expedited the creation of the bat prototype. The motion sensors that we used did not require any additional active components to be plugged into the board. On the software side, we implemented the user feedback system on a regular PC and reused the libraries for the hardware interface and basic signal processing from the Hand-Held Doctor for Children project.

The extremity computing approach also defines the user interaction with the system. Instead of looking for a way to implement all user interaction on the bat or in a small proprietary computer, we used user interface capabilities, specifically sound and video output of a regular PC. Making the bat-to-PC connection wireless substantially improves usability of the system by eliminating wires that get in the way when the user moves around.

3.6 Summary

The *Hand-held Doctor for Children* project demonstrates both a change in user experience and a different approach to application design. Children interacted with regular computers or toys that "know" physiological parameters of the child through an extremity device. In the workshops, I observed that the wireless interface helps children to feel independent of the object that visualizes the signals. Yet these objects are perceived as an extension of the child's body. The small and robust sensor setup amplified the willingness of children to explore and learn how the sensors work. The basic architecture of the HHD board, which was the inspiration for *Extremity Computing*, makes it easy to connect wirelessly the biosensor extremity to a serial port of any computer. The sensor interface design of the HHD board also helps to prototype rapidly various body sensors.

Chapter 4
Extremity Computing

Extremity Computing is an approach to sensor/effector interface design that complies with the following principles:

(1) sensors and/or effectors are connected to a mobile extremity device that serves as an extension of a conventional host computer (desktop, laptop, wearable, PDA, etc);

(2) the extremity device digitizes signals from the sensors and/or activates the effectors;

(3) the extremity devices have one or more means of transferring data to or from the computer such as wired or wireless link or local storage component;

(4) the majority of user interface and information processing functions are implemented on the host computer;

(5) a desirable feature of the extremity device is an open and flexible design that allows users with different skill levels to modify and adopt the hardware and firmware for their tasks and scenarios;

(6) a desirable feature of the computer software to support *Extremity Computing* is an open and flexible design that allows users with different skill levels to modify and adopt the software for their tasks and scenarios.

The HHD device was my first attempt in creating a multipurpose sensor interface. It helped me to understand the goals and means of a new sensor design approach, but it had limitations. One of the problems of the HHD device is that data may be lost when the receiving computer is out of range or the wireless link fails to work because of interference. In applications that store information for further analysis this is unacceptable. A potential solution is to add a compact mass-storage device to the data-acquisition system.

Providing on-board storage was the motivation for my designing a new device called the Hoarder board. This device has a CompactFlash card interface and improved data-acquisition capabilities. The system is designed to fit in a belt buckle; it initially included amplifiers for EKG measurement, a one-gigabyte disk drive, and radio-frequency communication. Several versions were made.

After discussing the design issues with the Human Design group at the MIT Media Laboratory, I decided to add a daughter board and MIThril [94] interfaces to the Hoarder board. Daughter boards with different sets of data-gathering features can be independently designed and connected to the Hoarder board. A daughter board gets power and can provide conditioned analog signals to up to eight 10-bit A/D converter pins or use I^2C interface to transfer digital information. A customizable program on the Hoarder board can store the information on a CompactFlash card and/or transmit it to another system in real time using a two-way radio modem.

Since the Hoarder board can collect a large amount of information at various periods of time, it is important to time-stamp all the data. The Hoarder board uses a real-time clock chip to keep track of time and date. Compact size and low cost make the Hoarder board a good platform for various wearable applications (See Figure 10). One of the first activities for which it was used was Hackfest 2002 and 2003 [95], an IAP MIT workshop about wearable computers.

The Hoarder-board configuration can be assembled without all of the components. For example, the 2-way-radio modem can be left out if the application does not require it. The timer chip may not be necessary if the board is always connected to a computer. But the real advantage of Hoarder is in its facility in supporting user-experience experimentation.

4.1 Designing for *Every Sign of Life*

One of the challenges of *Every Sign of Life* is to design a personal health monitor that can both send vital signs in real time to a computer for immediate interaction and measure them over long periods of time away from a computer. I designed a health monitor consisting of the Hoarder board and a biometric board that amplifies EKG, temperature, and skin conductance.

Thus the first application of the Hoarder board was a personal health monitor. The project required a compact wearable device that could collect health information including EKG, temperature, skin conductance, and other parameters over a period of at least 24 hours. The device was also required to transfer the same information in real time to a computer for visualization. None of existing health-monitoring system fits these requirements. The Hoarder board, with a local storage device, becomes a computer extremity that reports what it senses to the computer either in real time or, if it gets too far away, with a delay.

Although the health monitor is similar in what and how it measures to a Holter or event monitor, the Hoarder-board-based device is customizable, can gather a broader range of information, and can be interfaced to a computer more readily. The health monitor in combination with the software is also designed as a prototype of a consumer device to provide information to the end user as opposed to a health-care specialist.

The software components include a stress monitor, a Bio-Analytical Game, and a biofeedback game, which are described in Chapter 6.

4.2 Technical overview

The health monitor consists of two components: the Hoarder board and the Biosensor board. These boards are detailed in the following sections.

4.2.1 Hoarder board

The Hoarder board (See Figure 12) is a component of the health monitor that carries a microcontroller, a battery pack, a compact flash card, and a radio modem. A general purpose of the board is to collect large amounts of sensor data. Besides the health monitor, the board can be configured and programmed for a wide range of data acquisition tasks. For example, it can record sound with a microphone add-on board, detect and measure motion with accelerometer or gyroscope sensor set, or detect nearby IR tags with an infrared sensor.

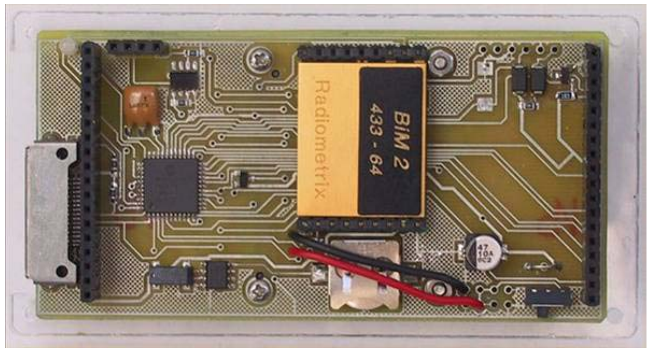

Figure 12   Back view of the Hoarder board

4.2.1.1 Features

- Board size 2" × 4"
- PIC16F877 20-MHz microcontroller
  - Controls: CF card, radio modem, serial port, I^2C port, real-time clock, LED, daughter-board components
  - Up to eight 10-bit A/D converter channels can be used to digitize analog signals
  - Reprogrammable on-board via serial port or using a programmer header
- CompactFlash connector
  - Type I or II CF memory cards including 1GB IBM Microdrive™
- Two-way half-duplex FM radio module
  - Allows the board to send and receive data wirelessly at 64 kbps
- Real-time clock
  - Keeps track of date and time
  - 12 mm backup battery good for over five years
- Serial port
  - PC-compatible (5 V inverted) serial port up to 115200 bps
- Programmer port
  - Initial microcontroller programming using standard programmer with passive adapter
  - Reprogramming when the serial programming function is not accessible
- Power supply
  - Four AAA rechargeable or alkaline batteries without power regulator
  - Optional 5 V power regulator for other battery or power adapter configurations
  - Sharing power on MIThril network
- MIThril port
  - I^2C and power sharing for MIThril wearable network
- Optional two-color LED
- Optional 2.5 V reference
- Daughter-board connector

4.2.1.2 Schematics

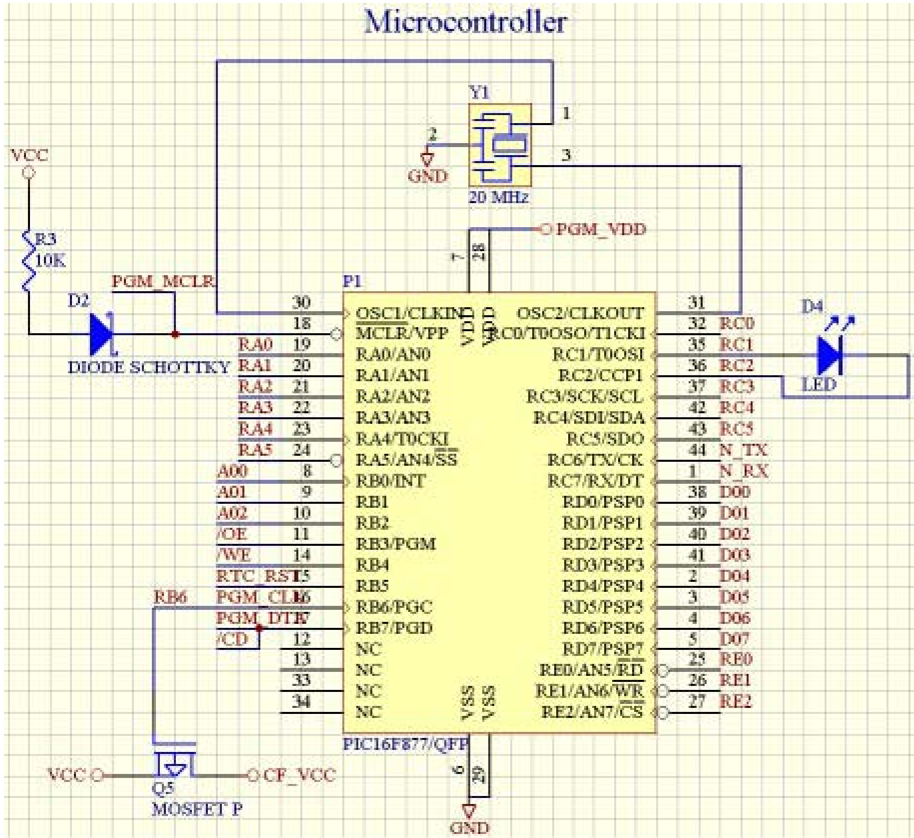

Figure 13 The Hoarder board microcontroller

At the heart of the Hoarder board is the PIC16F877 microcontroller (See Figure 13). At the time that the Hoarder board was designed, this microcontroller represented one of the best feature sets for the application. This microcontroller helped me achieve most of my design goals by exposing its features instead of adding new components. For example, the microcontroller has eight analog-to-digital converter inputs, hardware support for serial and I^2C ports, and enough I/O pins to control a CompactFlash interface and a real-time clock chip.

Besides the microcontroller, this schematic shows a protected programmer/power inputs, a 20 MHz ceramic oscillator, an indicator LED, and MOSFET-based power switch for the CompactFlash interface.

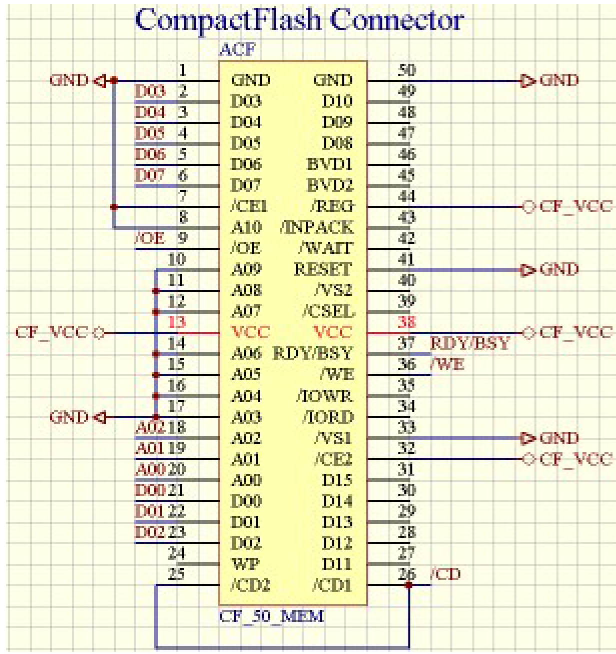

Figure 14 The Hoarder board CompactFlash connector

Shown in Figure 14 is the schematic of the CompactFlash interface connector. The design challenge here is to use a minimum of control pins of the microcontroller and additional components to access CompactFlash memory cards, without violating the CompactFlash specifications [27]. This is achieved by separating the connector pins into three categories:

(1) Pins of the CompactFlash interface that have specified acceptable internal connection to the ground or power (such as WP, D08–D15, BVD1, BVD2, /INPACK, /WAIT, /VS2, /CSEL, /IOWR, /IORD) stay disconnected.

(2) Pins that should be permanently tied up to the ground or power, but do not have a proper internal connection (such as /CE1, A03–A10, /REG, RESET, /VS1, /CE2) are connected directly to the ground or power.

(3) Pins that are actively used in the interface are connected directly to the microcontroller. The microcontroller I/O pin specs match or exceed the CompactFlash requirements. Such pins include A00–A02 for addressing the CompactFlash internal registers, D00–D07 comprise an eight-bit data bus, /OE and /WE for read/write data-flow strobes.

The CompactFlash device can be programmatically powered up or down by the microcontroller using the Q5 MOSFET that could switch the power to CF_VCC.

The presence of a CompactFlash device can be programmatically checked by the microcontroller by reading the B7 pin connected to /CD (card detect). B7 reads zero if a device is plugged into the CompactFlash interface and one otherwise. To work properly the weak pull-up feature of Port B of the microcontroller must be enabled. The power state of the CompactFlash device is not important for its detection.

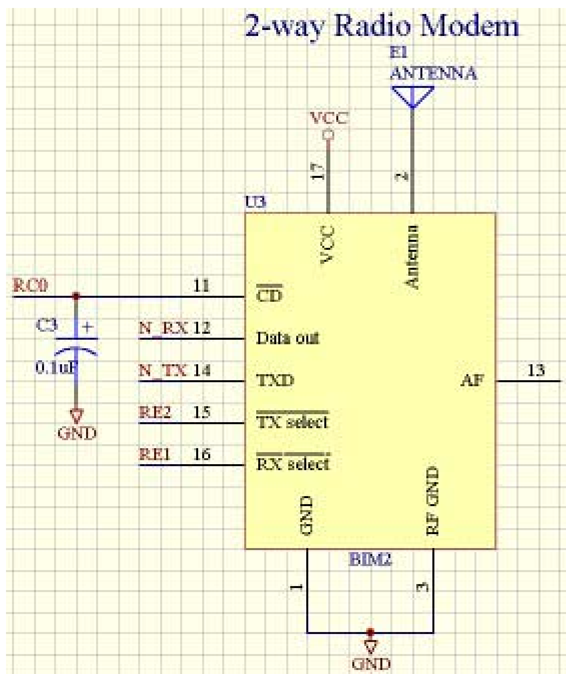

Figure 15 The Hoarder board radio modem

A 2-way-radio modem enables wireless data exchange between the Hoarder board and other devices that have standard serial interface. To expedite the design, a preassembled over-the-shelf radio module (BIM2 by Radiometrics) was used. These modules allow the system to send and receive data streams at speeds up to 64 kilobits/sec and operate as 433 MHz FM radio transmitters and receivers. A typical documented reception range is up to 100 meters of open space (limited by walls when used indoors). Although this component is optional, the health monitors assembled for *Every Sign of Life* had them to enable real-time monitoring.

The “Data-out” and TXD (transmit-data) pins of the modem are connected to receive and transmit pins of the hardware-supported serial interface of the microcontroller. To programmatically enable and disable the transmitter and receiver components of the modem “TX-select” and “RX-select” pins are connected to E0 and E1 pins of the microcontroller. The antenna is a quarter-wavelength trace on the printed circuit board.

The modem manufacturer recommends using Manchester-encoded data streams to ensure a perfectly balanced 0-to-1 ratio to avoid unstable receiver states. However, the modems are capable of practically errorless transfer of regular serial streams assuming long pauses in the data transmission are avoided and measures are taken to periodically balance a 0-to-1 ratio. I experimentally established that a continuous data transmission of 6- to 30-byte data packets with a CRC16 checksum works without errors within documented range at 38400 baud, even without ratio-balancing data. However, to ensure the best possible data communication in most applications I used balancing sequences between packets.

Since the modems can only use a single FM band they only support half duplex communication in the two-device case. In a multi-device situation the modems have to be either centrally coordinated to ensure single-transmitter multiple-receiver switching or engaged in a self-organizing viral network. In a brief study, I found that if several modems transmit simultaneously, a receiver often picks up a transmission from the closest modem as opposed to losing reception completely. The transmission power of the modem can be manipulated either by changing the antenna configuration or by changing the power voltage within a limited range.

In *Every Sign of Life* the health monitors worked in broadcast mode. When enabled, each monitor sent data disregarding possible collisions. Since only a few devices were used, this did not cause problems. In a more general case, with a large number of devices, measures have to be taken to ensure robust communication from the monitors to intended recipients.

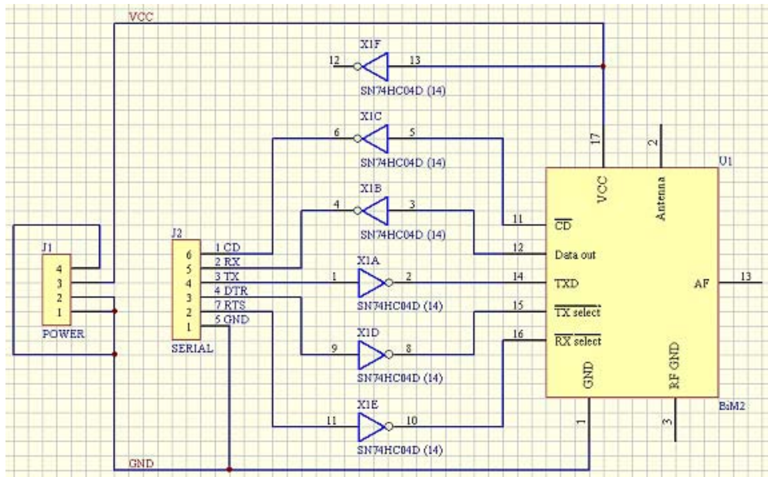

Figure 16 The serial adapter for the radio modem

A BIM2 modem can be directly interfaced to a serial port of a PC or PDA using an adapter that has a set of inverters and a 5V power connector that can be plugged either into keyboard, mouse, or USB socket. The adapter allows the PC to enable or disable receiver and transmitter of the modem using the standard serial interface signals RTS and DTR. The carrier detect (CD) signal of the modem is connected to the CD input of the serial port. Data can be received and transmitted using the standard serial interface routines.

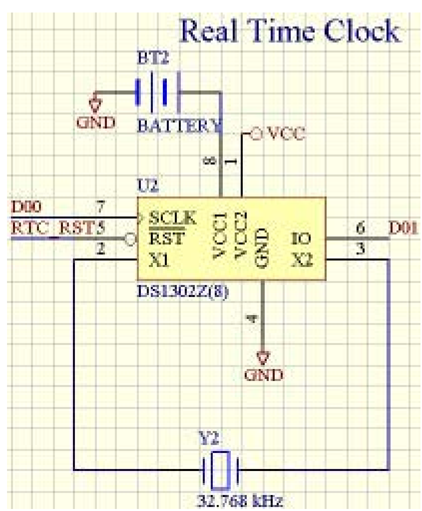

Figure 17 The Hoarder board real-time clock chip

One of the features necessary in many data-acquisition tasks is an ability to time-stamp the recorded data. The microcontroller, however, does not have real-time-clock circuitry.

Therefore a specialized real-time-clock chip (DS1302Z) is added to the Hoarder-board design to enable timekeeping independent of the microcontroller and main power supply states. The chip has secondary power supplied by a coin battery that does not require replacement for approximately ten years. The chip requires three pins for data exchange. To reduce the number of pins used on the microcontroller two of the real-time-clock pins are shared with the data bus of the CompactFlash interface. The third one is connected to a dedicated pin of the microcontroller. The three-pin data interface of this particular real-time clock chip allows for a rapid data exchange with a microcontroller.

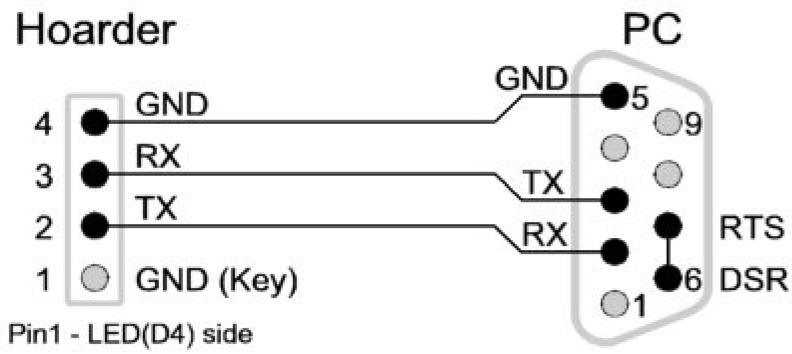

Figure 18 The Hoarder board serial-cable pinout

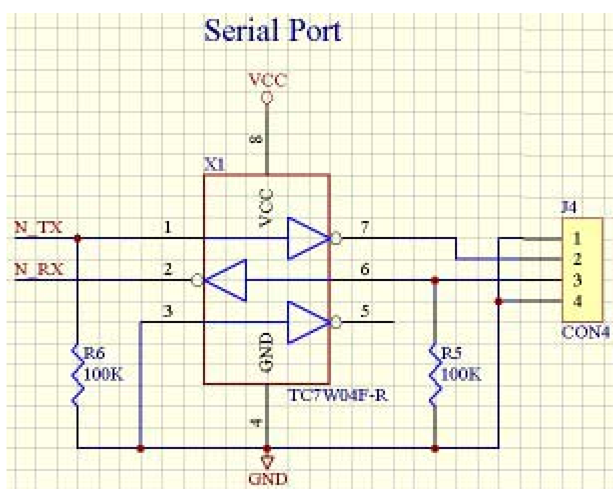

Figure 19 The Hoarder board serial port

The Hoarder board can be connected to a serial port of a personal computer or a PDA. According to the specifications a serial port of the PC can not only communicate with standard RS-232 devices at ±15V levels, but also can accept an inverted TTL level serial signal. Therefore, the Hoarder board has an inverter to allow buffered direct cable connection between the PC and the hardware-supported serial interface of the microcontroller (See Figure 18 and Figure 19).

One of the features of the microcontroller is an ability to change the code ROM in program. With a special program added to a predefined place in the memory of the microcontroller it is possible to reprogram the microcontroller using a serial connection. This makes programming and debugging the Hoarder board easier by eliminating the need for a programmer device.

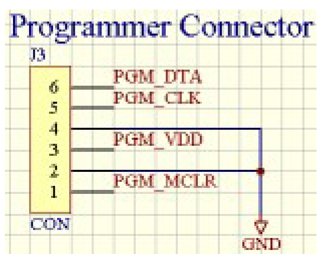

Figure 20 The Hoarder board programmer connector

The programmer connector is used to program the microcontroller using a programmer such as PICSTART® Plus (See Figure 17). A hardware programmer is necessary for initial programming as well as in cases when the serial programming feature is unavailable because of a bug in a microcontroller program.

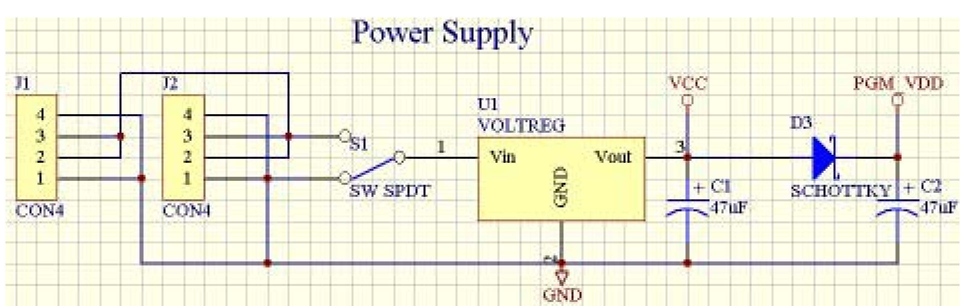

Figure 21 The Hoarder board power-supply circuit

The power supply has a dual battery or power supply connector, an optional voltage regulator, a power capacitor, and a protection diode (See Figure 21).

Even though the Hoarder board can use a variety power options, most of the boards are assembled with a four AAA battery pack and used with rechargeable AAA nickel metal-hydride batteries. Since the rechargeable batteries retain very stable voltage level over their discharge period and have very low internal resistance, the Hoarder boards can be used without the voltage regulator. The voltage level stays within specifications of the Hoarder board components. Alkaline AAA batteries do not exceed the voltage specification either and can also be used in configurations that do not require high-discharge rates.

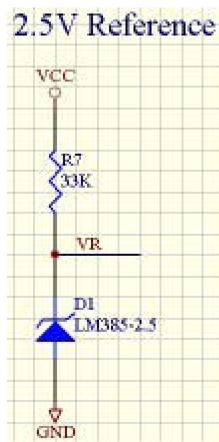

Figure 22 The Hoarder board voltage reference

In many data acquisition applications knowing an exact voltage value of some inputs is very important. But even with a voltage regulator, a constant power supply voltage cannot be guaranteed and used as a reliable voltage reference. To resolve this problem the Hoarder board has an optional Schottky diode circuitry to provide the microcontroller and other components with 2.5 V reference. In analog-to-digital conversion tasks the microcontroller can be programmed to use this as a reference level. Another technique used in some of the project applications to measure a precise voltage level is to measure both the signal of interest and the 2.5 V reference input against the power-supply voltage within a short time interval and calculate the signal-to-reference ratio.

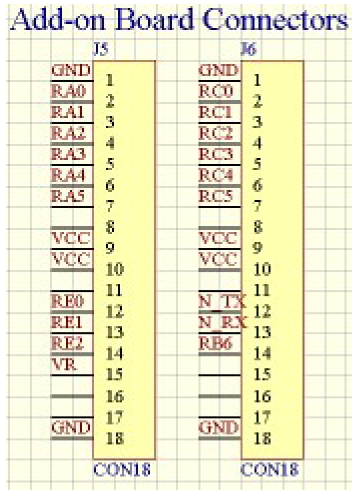

Figure 23 The Hoarder board add-on-board connectors

The Hoarder board is designed to be expandable and can be connected to different add-on boards. For example, in *Every Sign of Life* the Biosensor board connects to the Hoarder board to make a health monitor. The add-on board connectors transfer power and expose analog-to-digital inputs and other pins of the microcontroller (See Figure 23).

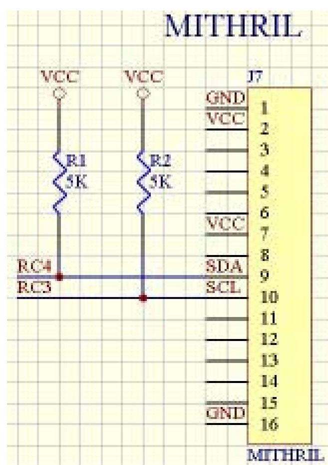

Figure 24 The Hoarder board MIThril connector

An optional MIThril connector is available to make the board compatible with some of the MIThril [94] hardware. In the current Hoarder-board implementation the connector only has an I^2C interface (See Figure 24).

4.2.2 Biosensor board

The daughter board allows the Hoarder board to collect EKG, EMG, EEG, skin conductance, and temperature signals.

4.2.2.1 Features

- Board size 2" × 4"
- No digital components
- One dual instrumentation op amp and two quad op amps
- Two channels to amplify weak electrical impulses (EKG, EEG, EMG)
- Two channels to measure electrical resistance (GSR or skin conductance)
- One precision amplifier to measure temperature

4.2.2.2 Schematics

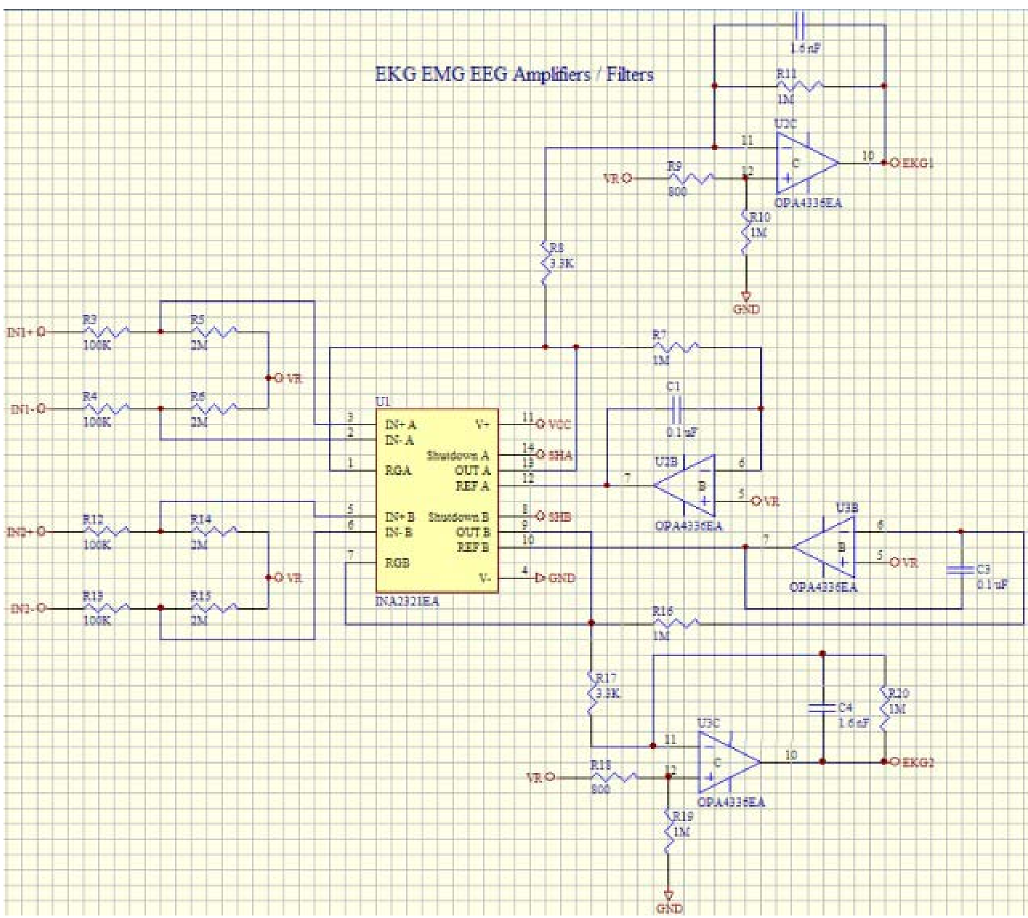

Figure 25 The Biosensor board EKG amplifiers

The board has a dual circuitry to amplify weak electrical potentials with a strong common-mode component. Those two circuits can be used to amplify EKG, EMG, or EEG signals (See Figure 25). Each circuit consists of an instrumentation amplifier and a set of operational amplifiers. Since both amplifier circuits are identical, only the one that goes from IN1+, IN1– to EKG1 will be described. The instrumentation amplifier increases the amplitude of the difference of electrical potential in two points (IN1+, IN1–) and eliminates the common mode. To make the instrumentation amplifier work with a single power supply, a 2.5 V bias voltage is added to the instrumentation amplifier inputs with a pair of resistors (R5, R6). A high-pass filter (U2B, C1, R7) dynamically corrects a DC shift. The operational amplifier U2C further amplifies the signal and (with C2) filters out high-frequency noise. The amplifier schematic is a modified example of an EKG amplifier from INA321 specifications.

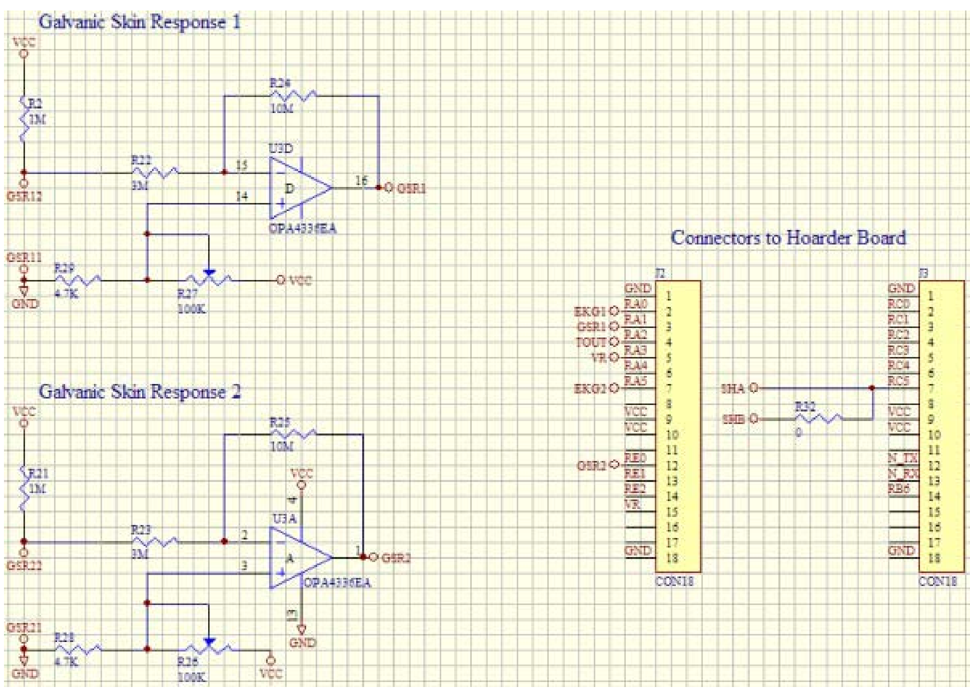

Figure 26 The Biosensor board GSR amplifiers and the Hoarder board connectors

The Biosensor board also has two amplifier circuits to measure skin conductance or galvanic skin response. The circuits have potentiometers to adjust the base line. The gain is set low to increase the range of measured resistance. A resistor of 1 MOhm or higher is desirable to make a current as low as possible throughout the skin.

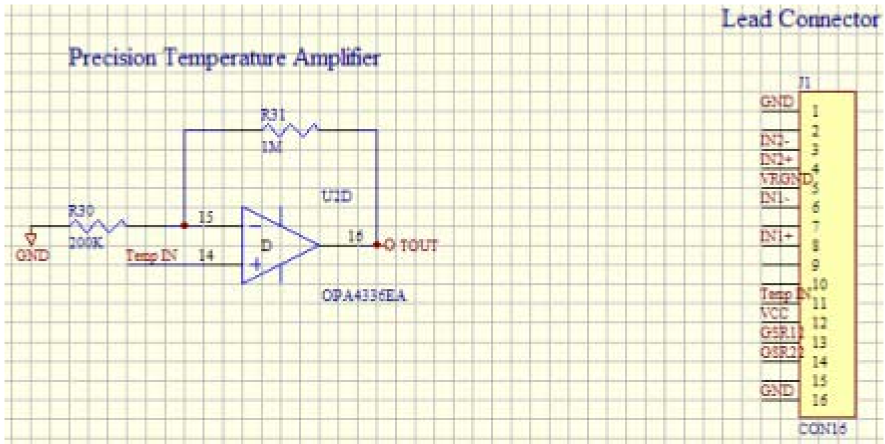

Figure 27 The Biosensor board temperature amplifier and lead connector

The temperature amplifier amplifies the voltage from a LM35CAZ temperature sensor. Precision resistors ±1% or better are needed to get acceptable temperature measurements. The EKG, GSR, and thermistor are connected throughout a set of flexible lead wires to the lead connector.

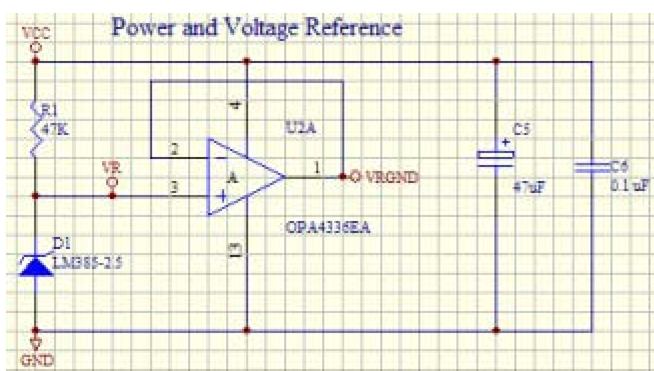

Figure 28 The Biosensor board power and voltage-reference circuits

The power circuit of the Biosensor board consists of optional power capacitors to eliminate power noise that may adversely affect the EKG signal. The Schottky diode voltage reference is not necessary if the Hoarder board has a voltage reference circuit the VRGND output from the U2A operational amplifier is used to provide a voltage bias to the third EKG, EEG, or EMG electrode that reduces noise.

4.3 Other applications of Extremity Computing

Both the Hoarder board and the Biosensor board were primarily designed for *Every Sign of Life*. However, both boards have demonstrated the value of the *Extremity Computing* idea throughout a variety of other projects (at MIT and elsewhere). In fact, the decision to separate the data gathering and signal conditioning parts of the health monitor stemmed from the high demand at the laboratory for a compact mobile device with a flexible architecture capable of collecting large amounts of information from a variety of sensors for a variety of research scenarios.

The health monitor can be used in other projects that analyze various physiological parameters. For example, the memory prosthesis designed in the *"What Was I Thinking?"* project [133] uses physiological parameters to expand or augment the memory cues.

The Extremity Computing approach developed as part of *Every Sign of Life* allows a new mode of user interaction with a health-monitoring device enabling both the wireless link for immediate interaction and continuous recording on a local storage device for long-term data collection. The two-way wireless link between the device and the PC allows the user to receive real-time health data, load stored information, or change device settings using a PC program. The user does not have to connect the device to the PC or put it into a cradle. The health monitor works as an immediate wireless extension of the PC. Although creating the Hoarder board took an extended period of time, implementing new scenarios with the board requires less effort than with a traditional approach because the board offers hardware and basic software frameworks to implement sensor interfaces, and allows the system creator to use well-developed programming environments and the rich user-interface capabilities of conventional computers.

4.3.1 Project at Rochester Center for Future Health

The Extremity Computing devices have been used to explore the behaviors of people in various environments. The Hoarder board, in combination with a daughter board designed by the Wearable Computing group at MIT, is also used in the Smart Home project at the Rochester Center for Future Health [94]. The daughter board has a microphone to keep track of sound, an accelerometer to detect and measure motion, and a tag reader to detect location or proximity to various objects. The system is used as a wearable device to record activities of inhabitants of the Smart Home.

The Hoarder board architecture allowed the Wearable Computing group to easily connect a set of sensors of their own and modify the Hoarder board software to serve their needs. The group successfully employed the extremity computing approach to implement their own user interaction scenario. Using a conventional computer for user interaction and a wearable component for data gathering allowed them to simplify the system design and made it possible to build and use a larger number of wearable components.

4.3.2 Shortcuts

Another similar example of experimental design with the Hoarder board that employs the extremity-computing approach is the project called Shortcuts by Tanzeem Choudhury [24], [25], [36]. The project explores social interaction among people at the Media Laboratory. A Hoarder board is used in combination with a daughter board and shoulder mount designed by the Human Design group. The system does analysis of motion, sound, and face-to-face encounters for each individual participant. The Hoarder board digitizes and stores all the data locally on a CompactFlash card. The researchers later analyzed the data to find the information-propagation patterns in a social group. The extremity-computing approach helped to produce data sets from wearable components for analysis on a PC.

4.3.3 Biometrics on cell phones

Even smaller computational devices can have data extremities. The Hoarder board can also be interfaced with other portable devices such as mobile phones. For example, the Hoarder board is used in an ongoing project that analyzes and displays on mobile phones stress information derived from the electrocardiogram inter-beat-intervals (IBI) [106]. The health monitor designed for *Every Sign of Life* uses a serial port to transfer an EKG signal to a Motorola phone in real time. The board simultaneously stores the signal on a

CompactFlash card for future analysis. The mobile phone provides computational power and a user interface to process and access the data.

In this application, the Hoarder board serves as a sensor extremity of a smaller computational device. As in other applications, the extremity computing approach helps to rapidly prototype both hardware and software for an experimental design.

The Hoarder board can be used not only in wearable computing applications, but also in other location-specific applications. For example, the system can be left in an attic or some hard-to-reach place to measure temperature and lighting changes over months or years. The board can stay in power-saving mode, waking up once every few minutes or hours to measure the parameters.

4.4 Extremity Computing and component programming

Components allow software engineers to develop applications faster with less coding and debugging overhead. In visual application-development environments such as Borland Delphi™ or Microsoft Visual Studio™ applications can be assembled from tested, precompiled components. Extremity Computing can provide software developers with easy-to-use components that encapsulate sensor interfaces and signal-processing algorithms exposing the most useful features and hiding the pre-tuned, extensive code supporting them.

As an example of Extremity Computing component I developed a HeartRate component for the Borland Delphi™ development environment. The component provides an application with a transparent interface to the heart-rate-detection algorithm that works with a wirelessly-connected personal health monitor developed for *Every Sign of Life*.

The HeartRate component has a SoundOn property that enables or disables a heartbeat sound, a HeartRate property that indicates the current detected heart rate, and an OnHeartbeat event that provides an application with a callback synchronized with detected heartbeats.

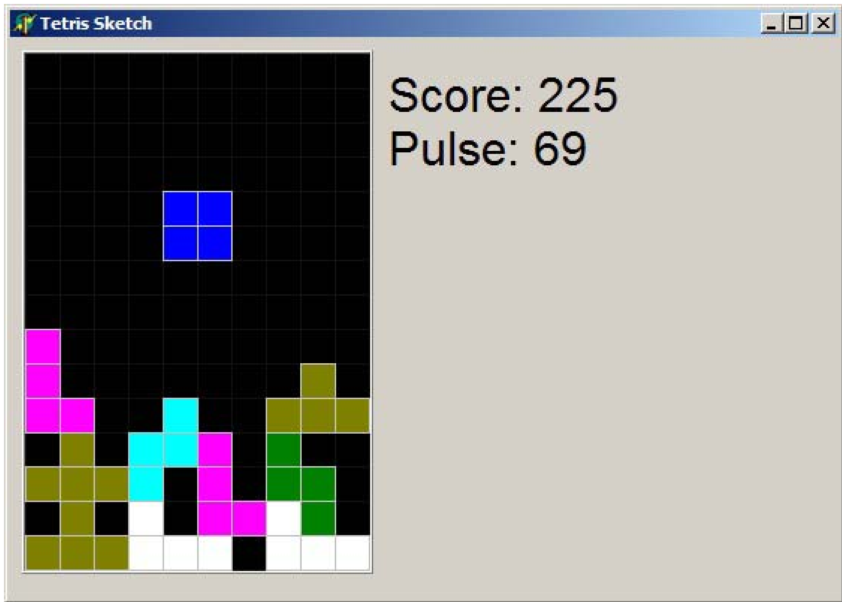

Figure 29 Tetris game with HeartRate component displaying player's pulse rate

The component can be used to quickly add biofeedback functionality to applications. For example, it was used in a demonstration of how to control a Tetris game by the heart rate of the player. In the version of Tetris application written for Microsoft Windows™, the game tempo is defined by a Timer component. Pieces fall one step with each timer event. I added the HeartRate component to the game. Instead of using a timer event, the modified application uses the OnHearbeat event to pace the movement of the pieces down the screen. Pieces move one step with each heartbeat. In addition, the application displays a label with the current pulse rate of the player [Figure 29].

Similar components can be developed to reflect other parameters and events detected by the sensor infrastructure of Extremity Computing. Using such components makes application development and debugging fast and easy.

4.5 Summary

The class of Extremity Computing devices proves to be valuable in rapid design and demonstration of robust scenarios: medical applications for a collaborative exercise game, stress monitoring and feedback, sports training, and many others. Such devices were successfully used in creating new wearable and embeddable systems as well as in augmenting existing computer systems with sensor interfaces.

The Extremity Computing devices provide a computer with practically unlimited sensory capabilities, and remove the range limitations of ordinary sensor interfaces. Computers can use data extremities to provide the user with necessary information from a multitude of sources around them.

The Extremity Computing approach expedites prototyping by allowing researchers to unify hardware design and to engage the rich user-interface capabilities of conventional computers. The approach makes it easy to include sensors into an experimental system. Devices such as HHD or the Hoarder board provide the system designer with a basic framework to connect sensors and implement wireless remote data transfer and gathering capabilities.

Extremity Computing also improves user experience by adding sensor capabilities to various objects—or to the body—and by substituting potentially poor proprietary user interfaces implemented on small devices with the well-evolved rich user interface of a conventional computer. The wireless data-transfer capabilities offered as a part of the extremity-computing concept are a must in many wearable and embeddable scenarios similar to ones discussed in this chapter.

In the next chapter, I discuss personal health monitoring as an application of Extremity Computing.

Chapter 5

Personal health monitoring

To investigate the possibility of making health information interesting, entertaining, and useful, I built a wearable health monitor that measures, stores, and transfers basic vital signs. To serve the needs of the project, the device had to be easy-to-modify and small, with sufficient storage capacity, and a flexible choice of sensors. There are no pre-existing health-monitoring devices that could provide me with all these options. The device I made for *Every Sign of Life* not only can measure and send information in real time, but also can collect data on a large local-storage device for future analysis.

Figure 30 A personal health monitor built from a Hoarder board and a Biosensor board

The basic concept is similar to that of the Holter [69],[63] or event monitor. The most important difference is that the information gathered by the device is intended to be presented to the person whose vital signs are measured, not just to the health-care professional [Figure 2]. This introduces the need for more on-board processing and off-board communication options than would be typical of an event monitor. The device is also more advanced than the classic Holter monitors in terms of sensor, data storage, and processing technology.

The basic parameters measured by the device include EKG, body temperature, respiration, and galvanic skin response. The EKG provides information about electrical activity of the heart. This parameter can be processed to obtain pulse rate, basic characteristics of the heartbeat, as well as respiration pattern. The body temperature can help to detect an onset and monitor progress of infectious diseases and keep track of metabolic activities. The GSR in combination with the other parameters helps to detect stress and possibly distinguish between some emotional states [108],[60].

The device has an on-board CompactFlash-based storage sufficient to save years of measured parameters at 250 samples per second. The CompactFlash card can be removed from the device and plugged into a personal computer for data analysis and visualization. A two-way RF modem is also included to support wireless control and data transfer to the PC or other devices. The use of CompactFlash cards provides the device with unlimited (for the application domain) storage and may also help to keep additional information such as individual medical records. The monitor can fit into a shirt-pocket, be put into a belt buckle, worn on the neck, or put in wearable holders designed for a specific application.

In case of an emergency the device may provide the doctor with medical records and a recent recording of the vital signs. Although the device has minimal processing capabilities, it is capable of detecting simple patterns in the data necessary to alert the user about potentially dangerous changes in vital signs. But in my research project I did not focus on these applications for the health monitor.

Health monitoring devices that were available before I began the *Every Sign of Life* investigation either kept track of a limited set of physiological parameters to assist in sports training [http://www0.mercurycenter.com/svtech/news/breaking/merc/docs/015908.htm] or collected extensive data about the patient for the doctor employing the traditional approach in health information flow [http://www.lifeshirt.com/index.html]. In neither case is the goal to make health information entertaining; rather they are tools for collecting and reporting health data to professionals. *Every Sign of Life* research also differs from these prior approaches because it neither focuses on a single human activity nor requires a doctor's interpretation of the data.

5.1 Biosensors

Unfortunately, most of the existing biosensor technology does not work without direct contact with the skin. For example, EKG requires electrodes that can either be adhered to the body or held in place by a tight elastic band or a piece of clothing. I chose to use adhesive electrodes that seemed less obtrusive and offered a better signal quality. A special piece of clothing would have to be rather tight, require individual fitting, and be harder to hide than a set of separate electrodes. A smart shirt [54] designed at Georgia Institute of Technology represents an alternative approach to health-monitor design.

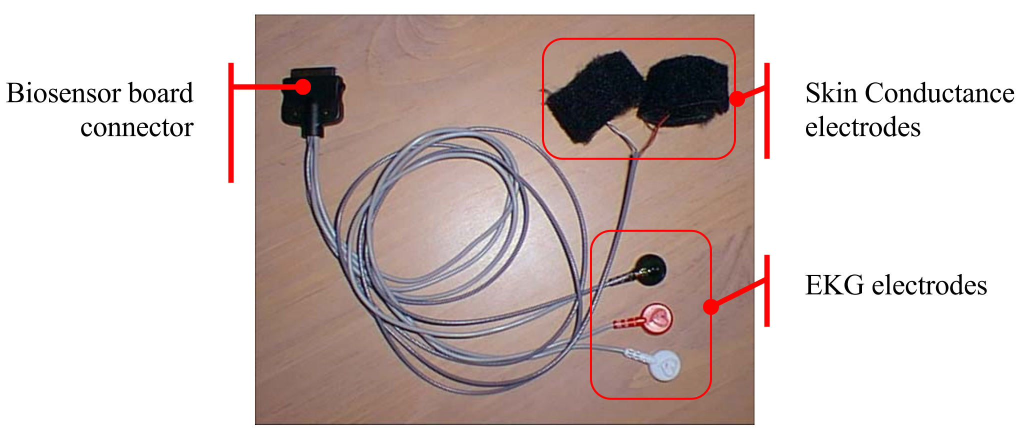

Figure 31 Biosensor wires

The health monitors used in the *Every Sign of Life* require a single EKG, single GSR, and temperature amplifiers. I use a standard Holter monitor set of snap-on wires with adhesive disposable EKG electrodes. The temperature sensor was attached to the reverse side of the ground EKG wire. To make the skin conductance electrodes, I soldered flexible wires to copper foil and used a sewing machine to attach the foil to pieces of Velcro. As a result the electrodes looked like small soft and flexible finger cuffs. The electrodes are more convenient to wear than the ones used in ProComp+ GSR sensor that had the same snap-on buttons as the EKG electrodes. Those buttons are too big to wear on fingers.

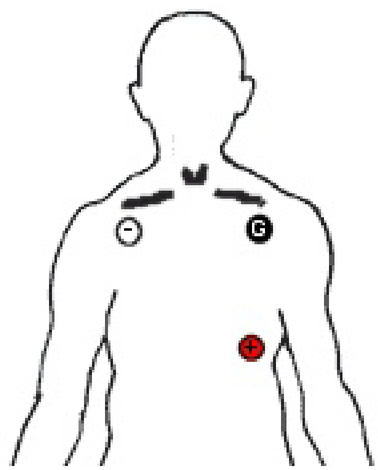

Figure 32 EKG electrode placement

All tests, studies, and experiments were conducted using the following EKG electrode placement: the ground (black) on the left shoulder, negative (white) on the right shoulder, positive (red) on the lower left part of the rib cage. This configuration measures Lead II: electrical depolarization and repolarization activity of the heart along the major electrical axis of the heart. This lead is most commonly used in patient monitoring. For a more comprehensive heart activity analysis more EKG leads have to be monitored simultaneously.

The EKG amplifiers were tested against an EKG sensor of ProComp+ monitoring device. When the ESL health monitor transferred data wirelessly, both devices provided matching waveforms with similar motion artifacts. When the ESL health monitor was connected to the computer with a serial cable, the output of the EKG amplifier had a strong 60-Hz noise added to the signal. This effect can be partially eliminated by a digital notch filter in the signal analysis software. However, the noise and filtering produces a slight distortion of the EKG signal. For the best results in measuring and recording the EKG signal, the health monitor should not be directly connected to any powered devices.

5.2 Data analysis and monitoring

Unprocessed data from the sensors is hardly interesting by itself. Data analysis is necessary to make the information easier for the layperson to understand. Stress, physical activity, and heart health are the characteristics that I hypothesize will interest people.

Research of the Affective Computing group at the Media Laboratory [108] indicates that signal analysis of a similar set of physiological parameters can distinguish states of physiological arousal that correspond to different emotional states. The researchers used a computer-learning model to detect an emotional state of a person deliberately expressing one of eight emotions achieving the success rate of over 80% for all the emotions. The group also developed a system for quantifying the physiological features of emotional stress of a car driver. The developed analysis techniques work especially well in detecting strong emotions and stress that cause a substantial change in signal patterns. Emotional variations are necessary for normal interaction of people with the outside world. A lack of emotional response impairs learning and social interaction. The personal health monitor may be helpful in keeping track of emotional dynamics.

Giardino et al. [51] speculate that periodic exposure to stress may be necessary to maintain self-regulation. Homeostatic reflexes may lose their function and efficiency if not engaged regularly. Periodic stress stimulates the reflexes providing sufficient exercise of them. Excessive chronic stress, on the other hand, is known to cause damage to self-regulatory mechanisms. The possibility of using the health monitor to objectively estimate changes in stress over various time periods can be used to verify this theory and to determine optimal work/play patterns for each individual.

Stress information can help people to choose a healthier lifestyle. For example, a person may pick a less stressful route from home to work. Stress may be as important as time or distance, if measured objectively. The stress information shared in a family may help to avoid unpleasant situations. People may also schedule their meetings to get better results if they can correlate stress with time of the day or certain events in their lives.

As Hirzel suggested, the system may also estimate the amount of physical activity during each day. A dedicated workout is not the only way to keep fit. Many people may get enough exercising in their daily life. For example, walking upstairs or moving heavy objects at work may contribute to the daily workout. However, this kind of physical activity may be hard to measure and evaluate without a health monitor.

Monitoring the heart activity is also important because various heart disorders are common and very dangerous. Monitoring heart continuously may help to predict and prevent life-threatening conditions such as a heart attack. According to U.S. statistics [4] coronary heart disease that causes heart attack and angina is the single leading cause of death in the United States responsible for nearly half a million deaths each year.

The area of EKG analysis is well developed. EKG can be used to identify acute cardiac diseases [123] and various chronic heart conditions [102]. Various function analysis techniques can be applied to identify different features of the EKG recording [5].

The health parameters may be presented in a variety of forms. In my research I shall explore what forms are appropriate and work best. For example, the health information may be shown as a health ticker or, as seen with *Hand-held Doctor for Children*, mapped onto animated cartoon or game controls. The health ticker can be a part of a news system. For example, a web page with local news, weather, and stock data may also have information about current health of the reader or people he/she cares about.

As is detailed in the next chapter, health parameters may also be mapped onto a computer game environment. Some parameters such as recorded or real-time heartbeat may be dynamically linked to the action in the game. Other parameters such as temperature may affect ambient features of the game. One of the challenges in my research is to design a game that meaningfully employs and makes interesting the health parameters.

5.3 R-wave-detection algorithm

One of the most important measures that can be derived from the EKG is the heart rate. A noise-free EKG signal clearly shows different phases of heart activity [Figure 1]. A heartbeat is the culmination of a contraction of the ventricles that coincides with the most prominent spike of the EKG signal the R-wave. The heart rate is usually measured in heartbeats per minute and updated after each heartbeat as a reciprocal of the time passed after the previous heartbeat. In heart rate variability research R-to-R time intervals are often used instead of the heart rate.

The top of the R-wave spike coincides with the maximum depolarization activity in the ventricles and is the most consistent timing feature of in the EKG. To convert an EKG signal to a heart-rate signal an algorithm has to be able to correctly recognize R-waves and determine the timing of the peak of the wave.

When a person whose EKG is being measured does not move, a simple threshold value can be used to reliably recognize R-waves. Since the R-wave is normally the tallest wave, when the EKG value moves above the threshold it is reasonable to assume that this is an R-wave. The top of the wave can be detected by simply looking for the sign change in the first derivative of the signal. Because the R-wave often corresponds to the steepest slope in the signal, an algorithm may alternatively threshold the first derivative; the top of the spike is detected by finding cross-over of the derivative from a positive to negative value. The challenge of these approaches is how to determine the threshold values. Under ideal, noise-free conditions the threshold value can be set between the average and maximum value of the EKG signal, but noise-free conditions are hardly the norm.

The simple threshold approaches do not work well with real EKG signals, especially when measured on moving people. The problems include: (1) motion artifacts from body muscle depolarization/repolarization and changes in contact features between the electrodes and the skin; (2) changes in overall amplitude and average level of the signal due to breathing or other phenomena that affect body conductance; and (3) external noise, e.g., 50 or 60 Hz noise from the power grid. Also the average level, height, and shape of the R-waves drift and differ from person to person.

Some of the noise in the EKG signal can be eliminated by adjusting the parameters of the filters in the EKG amplifier schematics or preprocessing data with digital filters. For example, the noise component that is present when the EKG amplifier is not galvanically decoupled from the power grid can be eliminated with a notch filter. The other problems, e.g., artifacts induced from muscle movement and overall changes in amplitude, are less readily addressed.

Since in the applications developed for *Every Sign of Life* people are expected to move, an R-wave detection algorithm has to be reliable in a presence of motion artifacts. In games such as Heartball described in Chapter 5, this is important to prevent “cheating” by introducing excessive motion noise to the signal. (An analogy could be made to tilting a pinball machine.) A second criterion that is driven by the application to games is low latency; detection of the R-wave peaks in real time, without noticeable delay, is important to create a sense of immediacy. An always desirable feature is low computational overhead, particularly when the detection is to be implemented on a microcontroller.

I developed a set of heuristics for R-wave detection in order to meet the demands of the *Every Sign of Life* applications. The heuristics are based upon a number of assumptions that I converged upon through a process of iteration. The basic set of assumptions, represented as constants in the algorithm describe below, include: (1) the maximum pulse rate is 200 beats per minute; (2) the minimum pulse rate is 30 beats per minute; (3) an R-wave peak must be at least 67 percent (two-thirds) of the previously detected peak; and (4) the maximum change in pulse rate between beats is 50 percent. It is the latter two constraints on the rate of change that allow the algorithm adapt to the relatively low-frequency variability of heart rate while filtering the relatively high-frequency artifacts due to noise.

In the real-time applications of *Every Sign of Life*, EKG samples are delivered asynchronously 250 times per second in separate data packets (256 in case of the ProComp+ hardware), using a message-dispatch mechanism. The R-wave-detection algorithm, **`DetectR`**, receives and processes samples one-by-one, utilizing just an eight-sample buffer (roughly 33 ms at 250 – 256 sampling rate) in order to calculate the instantaneous slope of the signal. If the first derivative of the signal stays positive for an entire buffer of data and then changes to negative for another sample, a peak is detected. If the peak is greater than the current threshold value, it is considered an R-wave. The requirement of positive derivative in consecutive sample periods effectively rejects sharp noise spikes caused by motion artifacts.

Every Sign of Life applications do not call the R-wave-detection method directly. There is a wrapper method, **`ProcessEKG`**, that calculates and maintains the adaptive threshold values. The variable **`LastRTime`** is used to store the timestamp of the most recent R-wave detected. **`LastR`** is the height of that wave. **`Pulse`** is the most recent pulse rate that has been calculated by the wrapper method.

Samples are fed to the **`ProcessEKG`** method of the **`TEKG`** class. This method calls the **`Update`** method of the **`DetectR`** class to place the new sample into the memory buffer of that class. If no spikes have been detected over the previous four seconds, i.e., if **`SampleTime`** minus **`LastRTime`** greater than 1000, **`LastR`** is set to zero. This is a mechanism for recalibration after a missing spike. The **`DetectR`** method is called with **`LastR`** times the scale factor **`PeakScale`**, the current threshold value for height. If a peak is detected and it passes the height threshold, then several time thresholds are invoked: **`SampleTime`** must be greater than **`LastRTime`** plus the buffer length, in which case **`LastR`**, **`LastRTime`**, and **`LastPulse`** are updated; **`Pulse`** is updated if **`SampleTime`** minus **`LastRTime`** is within the **`MinPulse`** to **`MaxPulse`** range and both greater than **`LastPulse`** times the **`DecreaseRatio`** and less than **`LastPulse`** times the **`IncreaseRatio`**, i.e., the change in pulse rate is not too abrupt. The **`SampleTime`** is always incremented in the end of the method. The output of the **`ProcessEKG`** method is the **`Pulse`** value of an instance of the **`TEKG`** class that represents the current detected heart rate and can be used in further processing.

```
(*
  TEKG fields:
  SampleTime - sample counter
  LastRTime - sample counter of the last detected R-wave
  LastR - height of the last R-wave spike
  Pulse - last detected pulse rate
  DetectR - instance of peak detector class
*)

const
  SamplingRate = 250; // or 256 for ProComp+
  PeakScale = 0.67; // at least 2/3 of the previous spike
  MaxPulse = 200; // maximum expected heart rate
  MinPulse = 30; // minimum expected heart rate
  DecreaseRatio = 1.5; // maximum expected beat-to-beat HR change
  IncreaseRatio = 1.5; // minimum expected beat-to-beat HR change

procedure TEKG.ProcessEKG (EKGSample: Integer);
var
  i: Integer;
  LastPulse: Real;
begin
  DetectR.Update(EKGSample);
  if (SampleTime-LastRTime>4*SamplingRate) then LastR:=0;
  if (SampleTime>LastRTime+NSpikeSamples) and
      DetectR.Spike(Round(LastR*PeakScale)) then
  begin
    LastPulse:=60/(SampleTime-LastRTime)*SamplingRate;
    LastRTime:=SampleTime;
    LastR:=DetectR.GetSpikeHeight;
    if (SampleTime>3*SamplingRate) and
       (LastPulse<MaxPulse) and (LastPulse>MinPulse) and
       ((LastPulse<Pulse) and (Pulse<DecreaseRatio*LastPulse)) or
       ((LastPulse>Pulse) and (LastPulse<IncreaseRatio*Pulse))
    then Pulse:=LastPulse;
  end;
  Inc(SampleTime);
end;
```

The **DetectR** class of type **TRWaveDetector** is used to recognize peaks of R-waves. The peak is detected when the first derivative of the EKG signal stays positive for **NSpikeSamples**-minus-two sample periods and changes to not positive in the following sample period. In addition, the total height of the spike has to be greater than or equal to the **Height** value passed as a parameter.

```
const
  NSpikeSamples = SamplingRate div 30; // ~33 ms slope

function TRWaveDetector.GetSpikeHeight: Integer;
begin
  Result:=Samples[NSpikeSamples-2]-Samples[0];
end;

function TRWaveDetector.Spike (Height: Integer): Boolean;
var
  i: Integer;
begin
  Result:=False;
  if Samples[NSpikeSamples-2]=Samples[0] then Exit;
  for i:=0 to NSpikeSamples-3 do
  if Samples[i]>Samples[NSpikeSamples-2] then Exit;
  if (Samples[NSpikeSamples-1]>=Samples[NSpikeSamples-2]) or
     (Samples[NSpikeSamples-2]-Samples[0]<Height) then Exit;
  Result:=True;
end;

procedure TRWaveDetector.Update(Sample: Integer);
var
  i: Integer;
begin
  for i:=0 to NSpikeSamples-2 do Samples[i]:=Samples[i+1];
  Samples[NSpikeSamples-1]:=Sample;
end;
```

The above algorithm was developed iteratively by testing various combinations of heuristics and internal parameters on datasets recorded during the development of the *Every Sign of Life* project. The resulting algorithm performed well in both real-time and post-processing applications, producing fewer visible motion artifacts in the heart-rate signal than algorithms used in other biofeedback systems such as BioGraph™ or CardioPro™. In a microcontroller implementation this algorithm requires less than 100,000 operations per second or 10% of processing power of a PIC™ microcontroller with 4MHz oscillator.

The current algorithm can probably be improved upon by adding a more sophisticated set of rules for the spike selection in the `ProcessEKG` method. The peak-detector algorithm can likely be improved by using autocorrelation methods to distinguish between the R-waves and the noise spikes.

5.4 Summary

In this chapter, I described the basic personal health-monitoring platform that I developed in support of *Every Sign of Life*. I presented a variety of scenarios where it has been deployed, both in my own studies and those of other researchers. In the next chapter, I discuss Bio-Analytical Games—games that incorporate biometrics into their play. I conducted user studies of these games that are also discussed.

Chapter 6

Bio-Analytical Games

A Bio-Analytical Game is a game that uses biosensor information to effect the game environment and complies with the following design principles: (1) physiological parameters control key elements of the game; (2) learning how to control physiological parameters is essential to win; (3) knowing how to control these parameters is not sufficient to win; (4) learning how to control the parameters is not trivial; and (5) playing the game is not dangerous to the health of the player.

Designing fun activities for adults is more challenging than for children. Adults are usually more focused on their daily routine, have more responsibilities, and more life experiences. They are often less willing to explore a new area of knowledge or play activities. Children readily discover new things and engage in exploration. Adults, on the other hand, know what they want and want what they know. The have stronger preferences for what they consider fun.

In *Every Sign of Life*, I tried three approaches to make health information fun for adults: (1) combination of sports, health-monitoring, and a computer game; (2) combination of biofeedback system and a video game; and (3) a combination of news, community participation, and scheduling as described in Chapter 2. The first two approaches I refer to as Bio-Analytical Games, because they combine analysis and reflection of biometrics in the midst of sports. The latter activities also bring in play reflection. It is an attempt to bring fun into areas not traditionally associated with play.

The first two approaches I refer to as Bio-Analytical Games, because they combine analysis and reflection of biometrics in the midst of sports. The latter activity also brings in play reflection. It is an attempt to bring fun into areas not traditionally associated with play.

6.1 Preparation for the studies

To test the accuracy of measured data the output of the developed device was compared to that of the certified medical device, ProComp+. I developed an application that received data directly from ProComp+ and could display and save data in a format of my choice. I then visually compared the shapes of the EKG signals and types of motion noise received with ProComp+ and the health monitor designed for *Every Sign of Life*.

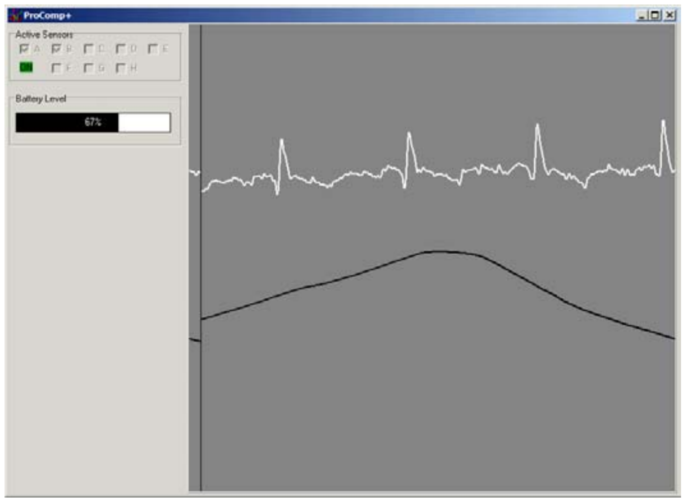

Figure 33 ProComp+ application displays EKG (white) and respiration (black) signals

The methods of calculating stress, physical activities, emotional states, and heart conditions are speculative and imprecise. I implement the best techniques described in literature. Examples of physiological signals of people with various diagnosed health conditions can be found in publicly available databases, such as PhysioNet [http://www.physionet.org], and used in diagnostic algorithm development.

I debugged the prototype monitor hardware and built several monitor units. The data processing and game algorithms were initially tested on myself. After establishing an example effect on me, colleagues were involved in debugging and testing of early versions of the applications to eliminate major problems and to verify the effects.

The protocols of all experiments involving human subjects were approved the MIT Committee on the Use of Humans as Experimental Subjects (COUHES) [http://web.mit.edu/committees/couhes] [92].

After the system was tested with a single person, a small group of volunteers from MIT community used it and participated in the scenarios and activities. To check the system usability and to investigate the user experience, I conducted several iterations of usability testing [32]. The objective of the tests was to iteratively improve the system and find scenarios, activities, and forms of health data presentation preferred by the group.

Every test subject answered a set of questions targeted at gathering background information to help interpret the data from the tests and at establishing an agreement regarding participation in the project. A set of questionnaires was used that consist of pre-test, post-task, and post-test parts. The pre-test questions check the participant's knowledge or view on health-related topics before the test. The post-task questions were asked during some of the games or other activities to obtain an immediate reaction to the participant's experience. The post-test questionnaires had the following goals: (1) to reveal problems with hardware, software, or user interface design; (2) to find out the participant's experience with the tested activities; and (3) to detect changes in the participant's knowledge or view on health-related topics.

The pre-test and post-test questionnaires included questions about the health and emotional state of the participants. One of the goals of the studies was to test the design principles for Bio-Analytical games.

6.2 Augmenting sports

Many adults enjoy not only watching sports, but also participating in sports. The challenge was to design a fun sports activity based on health monitoring. Since a computer system was necessary to visualize health parameters and keep track of the game progress, such an activity also had to be a form of a computer game.

6.2.1 Heartball

Heartball is a game designed specifically for *Every Sign of Life*. The game is designed to engage a group of people in a competitive activity that allows them to immerse into exploration of their heart-rate variability. The game can be classified as a combination of a video game and sports activity. The video-game element comes in a form of computer-assisted heart-rate monitoring system. The rules of interaction among players make the game a sports activity. The game interface can also be classified as an "exertion interface" as defined by Florian Mueller [99].

Heartball allowed me to achieve several of my goals. In a series of studies I establish that people evaluate Heartball as a fun, entertaining activity. Playing the game also changes players' knowledge about (and to some degree, control over) their heart-rate variability. The game also demonstrates that the Extremity Computing approach works in the design of rather sophisticated interactive-game scenarios.

A volleyball-size ball is used as the main game artifact. A player holding the ball is the center of attention of the computer-monitoring system, the other players, and spectators. In the Heartball study I conducted, the goal of the player holding the ball was to lower pulse as much as possible in a fixed time. A possible variant of the game would be for the player to increase pulse rate. This version would create a more sudden shift between periods of activity and relaxation.

It is usually hard to voluntarily lower heart rate below 50–60 beats per second, while a generally accepted estimate of the maximum heart rate is the formula 220–age. If the heart rate is not high when a player grabs the ball, it may be impossible to score many points. There is more room for pulse rate increase. By exercising intensively, a healthy person may raise their pulse rate as high as 200 beats per second from a resting pulse of 50–70. Therefore, Heartball is not just about lowering pulse rate, but also about how to effectively increase pulse rate before taking the ball. One of the goals of the study was to see how people approach this challenge.

I expected people to explore how their heart rate changes and establish some technique of altering their pulse. Three possible techniques I anticipated were exercising, breathing, and thinking about something stressful or relaxing.

The game was developed with the Bio-Analytical Game design principles in mind: (1) the heart rate of the players was the central focus of the game; (2) it was necessary to learn how to control the heart rate; (3) besides controlling the heart rate, players had to follow the game dynamics and interact with other players to win; (4) learning how to control the heart rate was not trivial; and (5) training to increase the heart-rate variability can potentially be beneficial for health.

6.2.2 Game rules

In the trials of Heartball, the game rules, as seen in Appendix A, were presented to the players.

The countdown interval mentioned in the rules was set to 15 seconds in the first two runs of the game, but was later increased to 20 seconds. The idea behind using a fixed interval is to find a balance between keeping the game more dynamic by not letting a player hold the ball for a long time (analogous to the 20-second rule in basketball) and giving players enough time to lower their pulse. The interval has to be neither too long nor too short. In the preliminary game runs, where I tested the game on myself and people who were familiar with the project, 15-second intervals seemed sufficient to get the lowest pulse. After discussion with the players, it became apparent that people new to the concept of lowering their pulse rate require longer intervals, in order to have sufficient time to explore strategies for altering pulse rate. The 20-second interval set in all following game studies made those games better balanced. One variant I didn’t try is to have the interval length decrease over the course of play.

Because of the scale of my investigation, only four players, two per team, participated in each study. The number of people was sufficient to demonstrate the general game concept. The studies were conducted indoors in an atrium and classrooms. Because of the specifics of the environment, a relatively low number of players, and a requirement to conduct studies with as diverse set of people as possible, the game was designed as a non-contact sport. In a more general case, the same game can be played as a contact sport. For example, the game rules may allow forcefully taking the ball from the player who holds it and protecting teammates from the other team.

6.2.3 Implementation

The implementation serves as an extended example of a scenario prototyping using the Extremity Computing approach. Hoarder board units are used to implement mobile components of the game, both the player units and the infrared tag device inside the ball. A laptop computer has a serial adapter for a radio modem to receive information from the player units and runs game monitoring software.

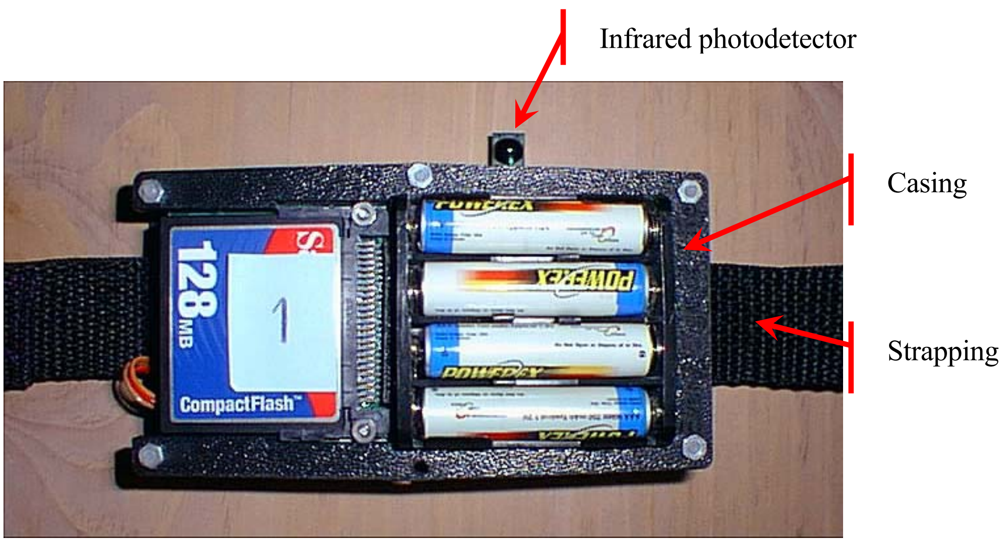

Figure 34 Player unit Number 1

The player units (See Figure 34) consisted of the Hoarder board, the biosensor board, a set of biosensor wires and plastic casing to protect the hardware and to attach strapping. I also added an infrared photodetector to the Hoarder board to detect the ball. The strapping, which consisted of one-inch nylon belt and buckles, was used to strap the system around the waist.

Since the game software had to monitor only one player at a time—the one that held the ball—it was possible to avoid implementing a sophisticated multinode network protocol for radio communication among player units and the computer. Instead I implemented dynamic activation/deactivation of transmitters on the player units based on an infrared proximity detector. Only the player unit of the player with the ball broadcasts EKG data.

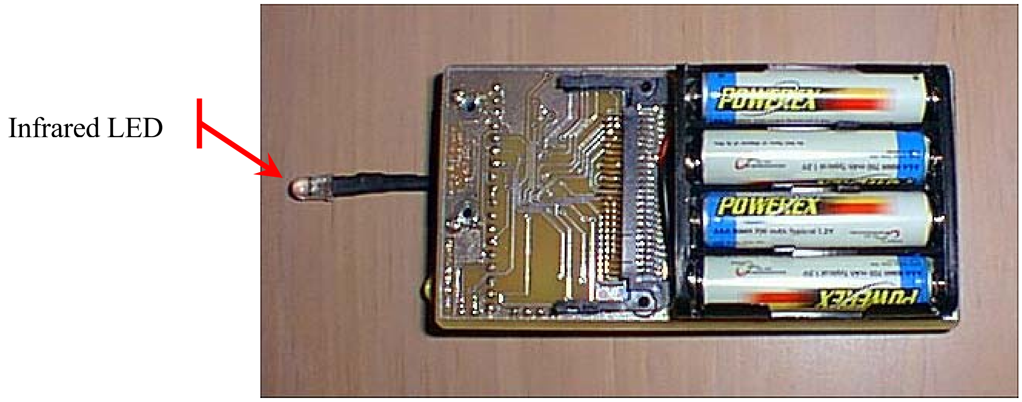

Figure 35 The Hoarder board in the Heartball

To implement the proximity detector, I placed the Hoarder board with an infrared LED (See Figure 35) inside the ball and attached the infrared photodetectors to the player units. The Hoarder board inside the ball was programmed to continuously send a blinking identification pattern using an infrared LED connected to port C0 of the PIC. This board is used as a passive device without a CompactFlash and radio modem.

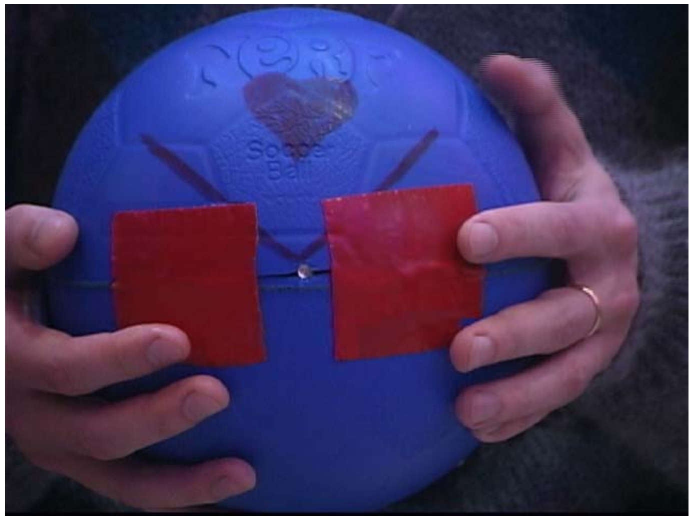

Figure 36 The Heartball

The Heartball was an eight-inch blue Nerf® soccer ball (See Figure 36) made of easy-to-cut rubber foam that fills the whole volume. I cut the external skin of the ball and removed some of the filling to make a compartment for the board. The LED, attached to the board with a flexible wire, extended about 2mm out from the surface of the ball. I painted several red arrows and put on two red duct tape patches to indicate the location of the LED, so that the player could easily see which side of the ball should be closest to their player unit.

Each player unit had an exposed infrared photodetector attached to power, ground, and C3 port of the PIC configured as input. The program on the player units included code to query the status of the photodetector inside the timer interrupt routine and to determine whether the detected pattern matches the blinking pattern of the ball device. The program enabled or disabled the transmitter of the radio modem depending on whether the patterns matched.

Figure 37 A player holds the Heartball.

In a sense, the ball worked as a remote control with a continuously held button to activate the transmitters on the player units. This design worked well in all studies. The only inconvenience of such an implementation is that the player has to make sure that the right side of the ball is facing his or her player unit (See Figure 37).

I designed two different plastic casings for the player units. One of them was made of transparent PET (polyethylene terephthalate) plastic using a vacuum-form machine. I made the cast for this casing out several layers of acrylic resin. The layers were cut with a laser cutter, drilled through, and connected with plastic bolts. The model for the casting was designed using CorelDRAW® graphics suite. This casing covered the player unit entirely potentially protecting it from adverse weather conditions. I cut the holes for the strapping and sensor wire connector.

Another casing was made of non-brittle black vinyl polymer. It consisted of two pieces: 1/4-inch-thick bracket that tightly fit around the battery holder and CompactFlash card on top of the Hoarder board and a 1/16-inch-think back plate that had holes to thread the strapping thru. Six plastic one-inch bolts with nuts held the two pieces together. This casing does not protect the board as well as the PET one, but is smaller and lighter.

The player units had CompactFlash cards to continuously record their vital signs and the ball proximity detection events. The recordings were later used to analyze the progress of the games.

The player units were programmed to sample, transmit, and store EKG and temperature signals from the biosensor board. The sampling rate was 250 times per second. (The sampling rate is excessive for temperature measurements, but it was convenient to utilize a unified data transfer and analysis libraries for all signals.) The skin conductance was not included in the set of measured signals for two reasons. First, this parameter is not essential for this game. Second, the skin conductance requires an additional set of electrodes on the fingers making the game setup more complicated.

The software on the monitoring computer was written in Borland Delphi™ 6. The program received the data packets from the player units through the serial port on the laptop computer. The packet processing thread verified a header and checksum of incoming packets, discarded packets with an incorrect check sum, and dispatched correct packets to the data processing part of the program.

Each data packet contained the header, packet number, player identifier, data samples from EKG and temperature sensors, and check sum. The header was a fixed (0xA5) byte. The packet number was one byte incremented with each consecutive packet. The player identifier was a one-byte number assigned to each player unit. The check sum was the standard CRC16. The packet number was necessary do calculate the number of packets lost between successfully received packets. Since the transmitting devices were very close to the receiver, the number of lost packets was very low—zero in most studies—and did not impact play.

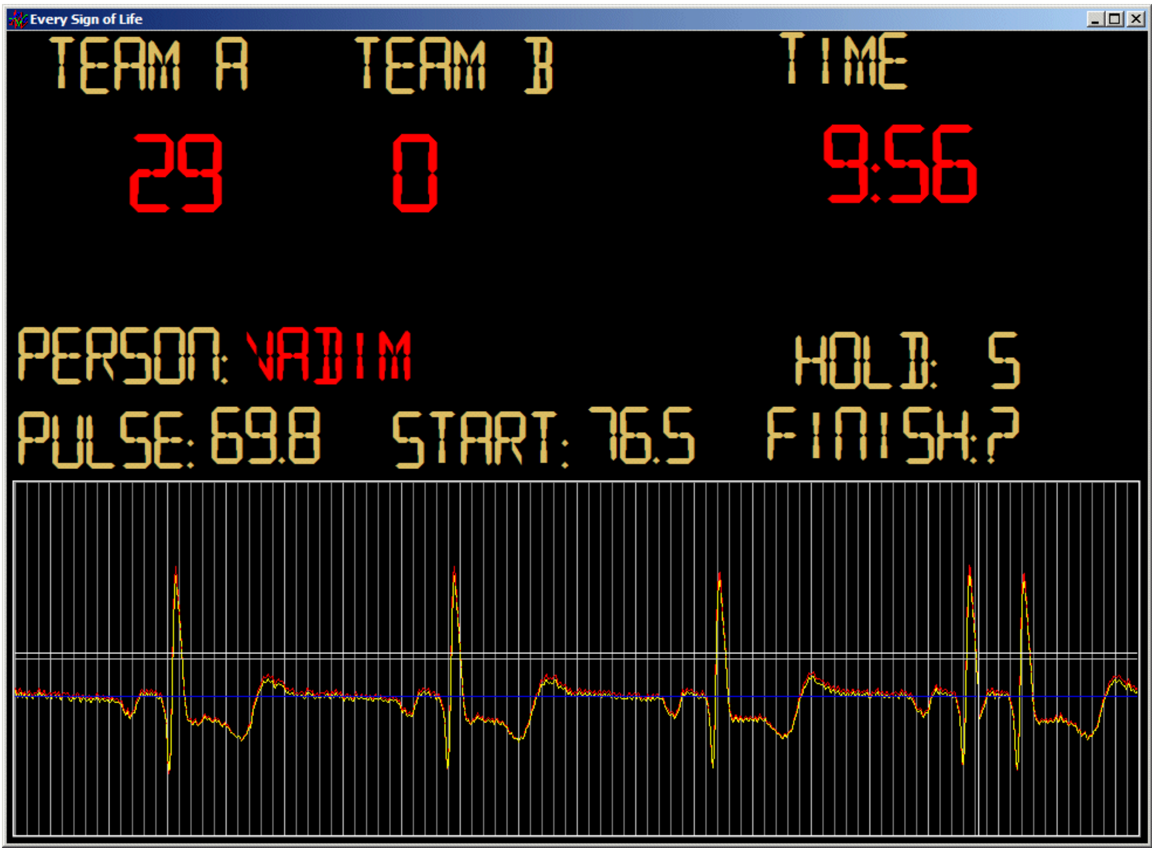

Figure 38 A screenshot from Heartball showing the team scores, the start and current pulse rates and the EKG signal of the current player

The program provided the players, investigators, and spectators with real-time game information using text, graphics (See Figure 38), and audio output. The text output included the score, game time countdown, name of the current player, ball-hold countdown, current pulse, start pulse, and finish pulse. The program also displayed the EKG of the player holding the ball in real time and made a heartbeat sound at the moments when the R-waves were detected.

The R-wave detection algorithm in this program is based on analysis of the first derivative of the EKG signal and the amplitude of detected spikes. A spike is detected by finding a sharp change in the first derivative of the signal from positive (rising) to negative (falling). Then the height of the spike is compared to a running average of previously detected R-waves. If the spike is high enough the algorithm assumes that the spike is an R-wave.

The parameters of the R-wave detection algorithm such as the slope detection thresholds, and the running average parameters were experimentally adjusted to make it robust in noisy situations and under changing conditions.

The heart rate (pulse) measured and displayed by the program is calculated as reciprocal of the current R-to-R-wave time interval.

The program used the Microsoft speech API to generate speech messages during play. The speech messages included an initial greeting, the name of the person who holds the ball, the start and finish pulse, the number of points given to each team, the ball-hold countdown, and final results.

This is an example of the speech message sequence:

> Welcome … Vadim holds the ball ... Start pulse 71 … Three, two, one, out of time … Finish pulse 69, team A gets no points … Walter holds the ball … Start pulse 80 … Three, two … Finish pulse 55, team B gets 25 points …

6.2.4 Experimental procedure

My study included five sessions and one informal full demonstration of Heartball. In the sessions, participants signed a consent agreement [Appendix B] and filled out questionnaires before [Appendix C] and after [Appendix D] the game. The questionnaires were used to survey the basic demographic information of the participants, ask them about their favorite fun activities, determine their knowledge of basic facts about heart-rate variability, and after the game, and ask their opinion about the experience.

Procedure:

(1) After signing the consent agreement and filling out the first questionnaire the participants read the game rules [Appendix A]. I then answered any questions regarding the rules.

(2) I gave every participant three disposable solid-gel EKG electrodes, which they adhered to their chests. The next step was to attach the wire leads to the electrodes and put on

the player units (See Figure 32). When all four players had donned the game equipment, I helped them to turn the units on.

(3) I started the game program on the laptop and began an equipment test. During the test, players held the ball one after another while I checked that the game system properly identified them and picked up clean EKG signals. At this stage, I corrected any problems. For example, on several occasions a player had to change the position of the electrodes to get a better EKG signal.

(4) The participants then played Heartball for 15 minutes.

(5) After the game the players removed the equipment and filled out the final questionnaire.

6.2.5 Experimental results

The five sessions were conducted at the MIT Media Laboratory. The requests for participation were posted on the bulletin boards at MIT campus and distributed via "msgs@media.mit.edu" mailing list. Each session required exactly four participants. Invitations to volunteers were managed individually to ensure the right number of players at each game.

The questionnaire results were tabulated and processed in Microsoft Excel® [Appendix E Table 6–Table 15]. I analyzed correlations between the answers to the questionnaires by looking at the correlation matrix and scatter plots. I had the total of 20 participants in the study. The minimum absolute values for statistically significant correlation coefficients in the case of 20 samples are 0.4438 for p=0.05, 0.5614 for p=0.01, and 0.6788 for p=0.001. In this analysis the corresponding correlation coefficients are shown in brackets.

Session Number	Date	Time	Final Score
1	11/07/2002	4:00pm	180:271
2	11/07/2002	7:00pm	317:267
3	11/21/2002	3:00pm	464:284
4	11/21/2002	4:00pm	254:377
5	12/05/2002	3:00pm	392:410

Table 2 Heartball game session scores

As I mentioned, one of the goals of the study was to observe how people approach the task of changing their heart rate. In all the sessions except for Session 2, after a two- to five-minute period of exploration, the players ended up increasing their pulse rate by exercising. The game in Session 2 progressed successfully, but all the players managed to find a way to change their heart rate without exercising. They used a combination of breathing and changing emotional stress. In Session 1, the players received a hint from spectator to try exercising and they immediately adopted this method of increasing their pulse rates.

In all the sessions the players attended to the game and gave predominantly positive feedback regarding the game. Sessions 1, 3, and 4 were conducted in an open, public area at the Media Lab MIT. The game attracted outside observers who found it interesting to watch as a form of sport.

The equipment worked without significant problems in the first four sessions. In the last session one of the player units stopped receiving the EKG signal about five minutes into the game because of a broken lead wire. The game continued with only one active player in team A and finished with a result close to a draw. The subjects in the first four sessions gave dissimilar answer to the question of whether the equipment worked well. One dominant problem of the system is unstable pulse rate detection when players were actively moving. This problem can be partially solved by further improving the R-wave-detection algorithm, but may not be resolved completely because of characteristic motion sensitivity of heart-monitoring sensors. The game program may also use various heuristics to detect and ignore the signal altered by motion artifacts.

Since I solicited volunteers at MIT, it is not surprising that most of my subjects (80%) were students. 75% of subjects considered themselves computer experts and the other 25% indicated that they had some knowledge of computers. Their ages ranged from 18 to 31. Since the group of subjects was small and relatively specific, I can only speculate on how the results may apply to the general population.

People who indicated preference for chess (0.53) and card games (0.47) were more likely to be the winners. Subjects who preferred dynamic puzzles (such as Tetris) (–0.37) were more likely to lose. This correlation is relatively high and interesting to note even though it is not statistically significant for the sample number. There was also a natural correlation between winning and indicating that one's team was stronger (0.48).

Older subjects in the study had a tendency to show less preference for Baseball/Softball (–0.51) and were less likely to indicate that the game may be dangerous for their health (–0.69).

The male-to-female ratio in the study was 3:1. Treating the gender information as a variable with 0 corresponding to male and 1 to female leads to the following correlations: The female subjects in the study were less likely to indicate that they like adventure (–0.45) or role-playing computer games (–0.52); and although nobody indicated that the game was boring, the male subject were more likely to rate the game higher on that scale (–0.47) as well as on "the game is dangerous for my health" (–0.56) and "I don't want to know my pulse rate" (–0.56).

In the case of age, gender, and winning the cause-effect relations are clear. For most of the other correlations the relation may not be as easy to determine.

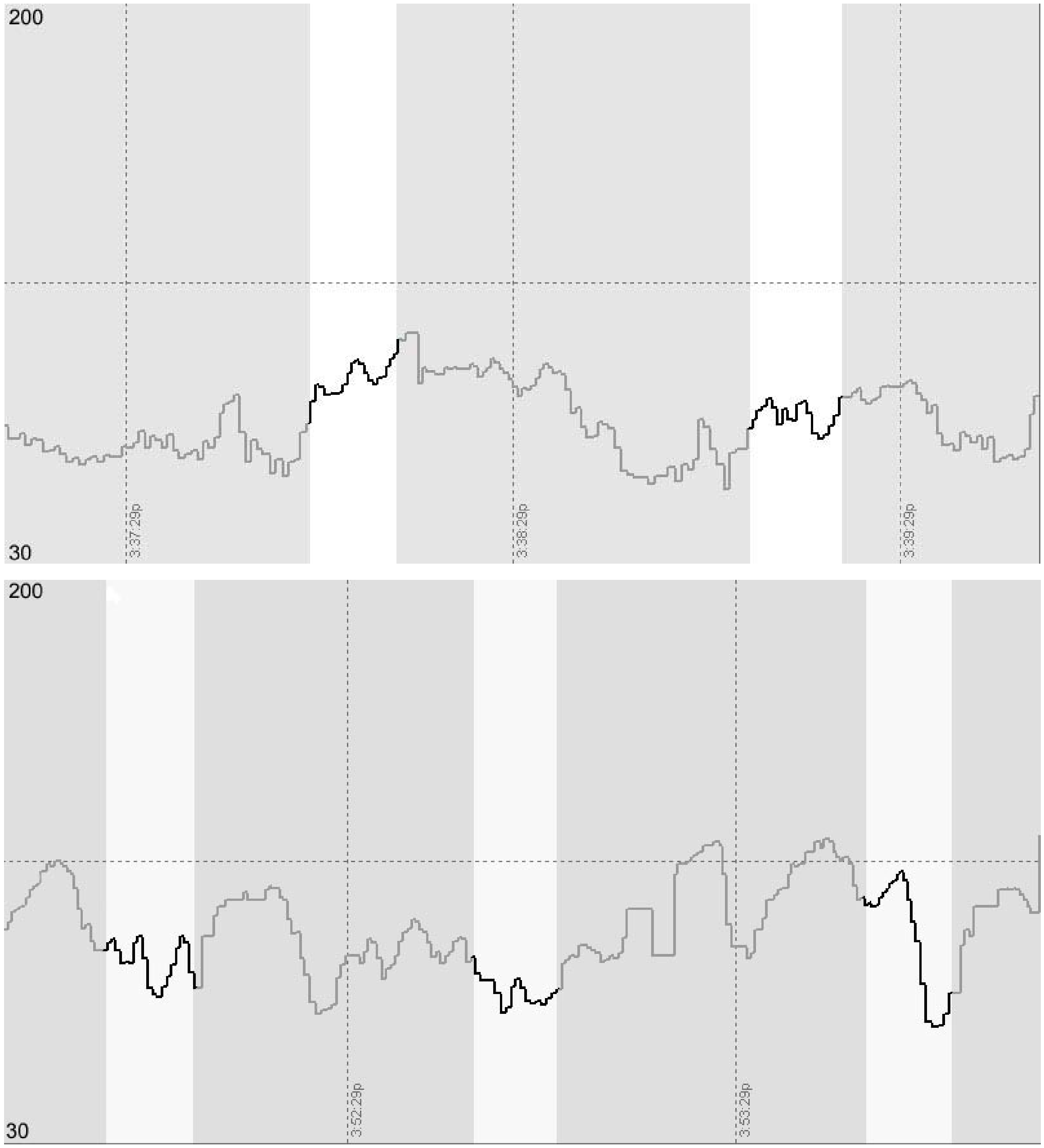

Figure 39 Heartball pulse-rate data over time. On the top, is shown the data from Subject 2 in the first quarter of play, when he scored no points. On the bottom, is shown the data from the same subject in the fourth quarter of play, when he consistently scored points by lowering his pulse while in possession of the ball. (The highlighted regions indicate times of possession of the ball.)

A jogging preference positively correlated (0.49) with the answer to the post-game statement "I can easily control my pulse rate", but negatively (–0.45) with the pre-game question "Do you know how to control your pulse rate?" There was also a positive correlation (0.54) between a jogging preference and finding the game relaxing. I would speculate that there might be some link between jogging and an ability to learn how to change heart rate with Heartball, since one of the ways to quickly increase the heart rate is to move quickly or jog, and people who like jogging may discover this more easily then the others. Contrary to my expectation there was no correlation between the answers to whether a person used heart-rate monitors and had a jogging preference. However, only three people indicated that they used heart-rate monitors.

There was a positive correlation between the preference for card games and frequency of playing computer games (0.45). The exercise frequency positively correlated with preference for Football/Soccer/Rugby (0.45), Baseball/Softball (0.54), and Jogging (0.46).

Every subject was asked to state his or her average heart rate both before and after the game. 25% of subjects indicated that they didn't know or were not sure about their average heart rate before the game. Usually pulse rate is measured at rest and the game involves some activity and, possibly, emotional stress. I thought that the subjects might see higher heart rate than they expected, so I had expected people to increase their estimations after the game. Apparently, this was true. Six subjects increased their average pulse rate estimate after the game, ten did not change their estimates, only one decreased it, and two subjects did not answer this question. Thus 45% of the subjects either learned or changed their opinion about their heart rate during the game.

Sessions 1 and 2 were videotaped and the video recording was used to review the games and tabulate the results (See Table 3). Some players improved their results during the game. However, no one could consistently get many points at each turn. Controlling heart rate in a competitive environment is difficult. Besides, the players also had to learn how to time their techniques to increase and decrease the heart rate in accordance to the play-sequence of the game.

	game1,player 1			game1,player 2			game1,player 3			game1,player 4		
	start	stop	score	start	stop	score	start	stop	score	start	stop	score
Q1	120	100	20	93	89	4	127	83	44	n/a	117	n/a
	122	117	5	75	71	4	115	114	1	138	110	28
	146	135	11	111	94	17	**144**	142	2	121	**78**	43
Q2	133	116	17	121	87	34	136	127	9	n/a	146	n/a
	139	134	5	**133**	115	18	82	144	0	77	89	0
	95	n/a	n/a	94	106	0	102	109	0	127	119	8
Q3	111	143	0	123	83	40	76	**77**	0	135	138	0
	82	115	0	105	90	15	143	149	0	**149**	109	40
	111	**58**	53	109	76	33	135	139	0	128	124	4
Q4	126	124	2	102	**61**	41	108	112	0	110	113	0
	120	120	0	112	113	0	101	116	0	n/a	107	n/a
	128	115	13	78	86	0	110	89	21	148	147	1
	n/a	134	n/a	102	n/a	n/a	94	115	0			
	average			**average**			**average**			**average**		
	start	**stop**	**score**	**start**	**stop**	**score**	**start**	**stop**	**score**	**start**	**stop**	**score**
Q1	129	117	12	93	85	8	129	113	16	130	102	36
Q2	122	125	11	116	103	17	107	127	3	102	118	4
Q3	101	105	27	112	83	29	118	122	0	137	124	15
Q4	125	123	5	99	87	14	103	108	5	129	122	1
T	119	118	13	104	**89**	**17**	113	117	6	**126**	116	14

Table 3 Heartball game analysis from video recording (data marked n/a were impossible to determine due to noise)

Although the equipment performed well in terms of the game logistics, heart-rate detection was far from perfect because of the noise added to the EKG signal when people moved. Several people were upset when the system miscalculated their pulse rate and a few people used the noise to their advantage to trick the system. However, most subjects followed the rules and tried to alter their heart rate and move less while holding the ball to make sure the pulse-rate detection works properly.

	game3,player 1			game3,player 2			game3,player 3			game3,player 4			game4,player 1		
	start	stop	score	start	stop	score	start	stop	score	start	stop	score	start	stop	score
Q1	78	**63**	15	74	101	0	90	**98**	0	94	**88**	6	86	94	0
	93	77	16	73	83	0	108	102	6	102	99	3	104	**66**	38
	77	72	5	68	76	0	120	126	0	112	114	0	126	128	0
	73	73	0				122	122	0	106	104	2			
	69	84	0							102	109	0			
Q2	85	89	0	60	**64**	0	128	142	0	120	111	9	104	107	0
	112	88	24	86	66	20	120	134	0	122	104	18	134	159	0
	111	93	18	110	100	10	125	122	3	119	110	9	126	118	8
	100	108	0				124	119	5	118	109	9			
										119	116	3			
Q3	88	78	10	94	86	8	132	128	4	106	104	2	160	160	0
	130	90	40	113	98	15	104	116	0	114	112	2	**184**	182	2
	120	108	12	92	78	14	128	131	0	106	102	4	143	150	0
	106	103	3	89	79	10	135	135	0	118	116	2			
	98	94	4							122	120	2			
Q4	95	88	7	107	78	29	124	132	0	**128**	124	4	174	172	2
	92	99	0	**117**	98	19	116	136	0	126	110	16	182	178	4
	110	106	4	109	89	20	**144**	132	12	108	98	10	115	142	0
	92	82	10				127	141	0	125	128	0			
										120	125	0			
	average			**average**			**average**			**average**			**average**		
	start	stop	score	start	stop	score	start	stop	score	start	stop	score	start	stop	score
Q1	78	74	7	72	87	0	110	112	2	103	103	2	105	96	13
Q2	102	95	11	85	77	10	124	129	2	120	110	10	121	128	3
Q3	108	95	14	97	85	12	125	128	1	113	111	2	162	164	1
Q4	97	94	5	111	88	23	128	135	3	121	117	6	157	164	2
T	96	89	9	92	**84**	**11**	122	126	2	114	110	5	**137**	138	5

Table 4 Heartball game analysis from the data recording

The EKG signals were recorded to the CompactFlash cards at every session for every individual. These recordings can be used in later game analysis (See Figure 39). For example, Table 4 shows analysis for four players from Session 3 and one player from Session 4. The total score is different from the actual game score because this analysis does not take into account the wireless-interface switching delays, which sometimes caused disparity between the memory card records and what was displayed on the laptop to the subjects. The progress of Player 1 in Session 4 is interesting because this player got the highest pulse rate observed in the games. Unfortunately, this high heart rate was a result of an equipment problem. The ball failed to engage this player’s unit because clothing covered the IR sensor. After the game the player wrote a comment that the game needed “a better working IR interface.” Some more general observations can be made. Players consistently had their lowest pulse rate towards the beginning of the game, usually in the first quarter of play. The highest pulse rates were consistently in the latter half of play. This would suggest that the excitement of play and the physical activity they engaged in to increase their heart rate might have caused their pulse rate to climb. Most of the scoring occurred in the second through fourth quarters of play, suggesting that players learned to control their pulse rate during the course of play. The players who managed to achieve the lowest average pulse rate consistently scored the most points. The contrast between pulse rate toward the beginning of play and the end of play is shown in Figure 39.

Perhaps the most important statistic is that everyone reported that they had fun.

6.3 Respiratory sinus arrhythmia training

At a very young age I discovered that I could stop my heart for a couple of seconds by taking a deep breath and holding it. I found this amusing and sometimes did this exercise just for fun. I rediscovered this phenomenon several years ago and found out that researchers explore the dependence of heart rate on breathing, a phenomenon called Respiratory Sinus Arrhythmia or RSA.

Most biofeedback systems can be fun for the first few minutes. But after an initial exploration, they become rather boring because biofeedback is often a monotonous activity that lacks game elements. I designed a computer game, Breathing Pac-Man, based on respiratory sinus arrhythmia to explore how to add more fun to biofeedback and conducted a short study to explore whether the game adds more fun to biofeedback, and whether the game works as a biofeedback exercise.

6.3.1 Breathing Pac-Man

I tested my system with a biofeedback exercise designed to achieve a physiologically desirable increase in the respiratory sinus arrhythmia (RSA) [76],[57]. Many biomonitors including ProComp+ have software to perform RSA training. The difference in my project is a computer-game approach to the design of the application. Ideally, experiment participants would use the application twice a day and the tests would be performed on four different days within a month. I was only able to conduct some preliminary studies of this game: thirteen subjects participating in one session each.

The RSA training consists of two phases: measuring the baseline of the parameters and breathing-training exercise. During the exercise the participants are provided with a breath-pacer indicator and information about changes in their bio-parameters. The breath pacer helps the user to maintain slow, even, and deep breathing pattern.

My study of the RSA training application was used to answer the following questions:

(1) Can the participants operate the monitor and software correctly?

(2) Does the hardware and software accurately acquire heartbeat and breathing information? A proper detection of R-spikes (the highest spikes in EKG corresponding to systoles) is the most important factor in the heart-rate monitoring.

(3) Does the breathing exercise increase RSA as expected? Theoretically the increase should be at least 25% comparing to the baseline for every person. The most substantial change should be observed in the 0.05–0.15 Hz range of the power spectrum of the heart beat signal.

(4) Is the application capable of holding the user's attention for at least 12 minutes to complete the exercise?

(5) Is there an indication that the participants learn from their experience with the application? To answer this, the users are asked similar questions about their heart rate before and after the test to find out what they know or think about relevant physiological facts. The difference in answers indicates a change in the participant's opinion or knowledge during the tests. The subjects are also asked a direct question about whether they think they learned from the experience.

I developed and tested a set of two biofeedback exercise games. The objective of the first one (See Figure 40) was to help people learn how to increase their respiratory sinus arrhythmia or dependence of their heart-rate variability on breathing. Instead of offering an explicit breathing pacer in this exercise I only provided the subjects with a measure of heart-rate variability and instructed them to try different variations of breathing rhythm and depth to maximize the parameters they could see: breathing depth and rate. I expected that the ability to move the Pac-Man from the top to the bottom row of pills would coax the subjects to breath deeply. The second one (See Figure 41) made subjects breathe in a deep and even pattern of varying frequency. The research objectives of the second exercise was to determine at what breathing frequency people achieve the maximum variation in heart rate and to develop a fun way of making people follow a certain breathing pattern.

In both games, the subjects wore ProComp+ EKG and respiration sensors. I decided to use the ProComp+ device instead of the *Every Sign of Life* health monitor because the quality of the respiration sensors I developed myself were not of sufficiently high fidelity to measure RSA.

In both games, a “Pac-Man” eats spherical pills attached to a rotating cylinder. The pills are placed at different height. The player can move the Pac-Man up and down to get close to the pills by inhaling and exhaling.

In the heart-rate variability training game, the pills change their size depending on the amplitude of the recent change in the heart rate—the program keeps track of the absolute difference between the maximum and minimum heart rate over a moving 10-second window and translates this measurement to the size of the pills. Each pill eaten by the Pac-Man gives a player a number of points proportional to its size. To maximize the score, a player has to develop a strategy to maximize the change in heart rate. The pills are located on lines perpendicular to the motion, at the top, bottom, and in the middle of the cylinder, so that the Pac-Man can eat only one of three (top, bottom, middle) pills at a time. This positioning of the pills ensured that players do not attempt to sharply inhale or exhale to capture a greater number of pills. The players can also see a numeric value representing the heart-rate change, calculated at each heartbeat (R-wave) in beats per minute.

The first game was developed based on the Bio-Analytical game design principles: (1) changes in heart rate controlled the size of the pills; (2) the pill size had a direct effect on the score; (3) besides controlling the size of the pills the player had to capture them with the Pac-Man; (4) learning how to increase the pill size was not trivial; and (5) training to increase the respiratory sinus arrhythmia can potentially be beneficial for health.

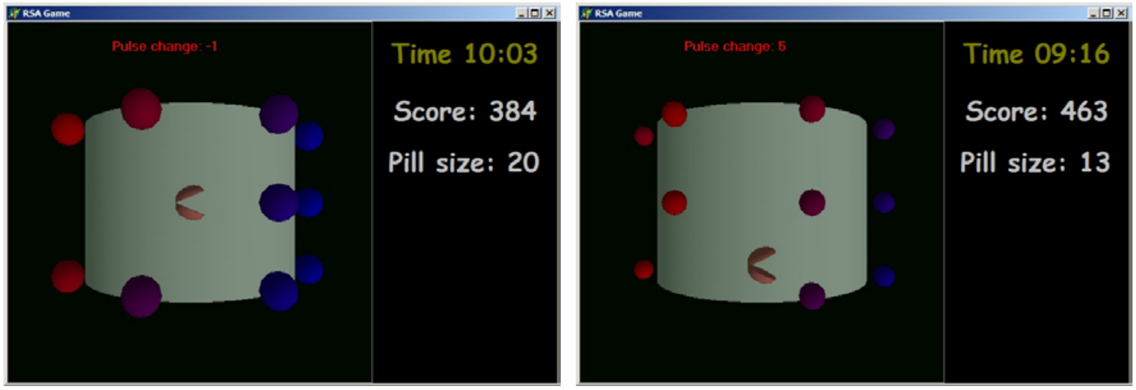

Figure 40 The Breathing Pac-Man heart-rate biofeedback exercise

In the second game the pills are placed consecutively in a sinusoidal pattern, so that to follow the pill trail the player has to breathe evenly at frequency dictated by the cylinder rotation speed.

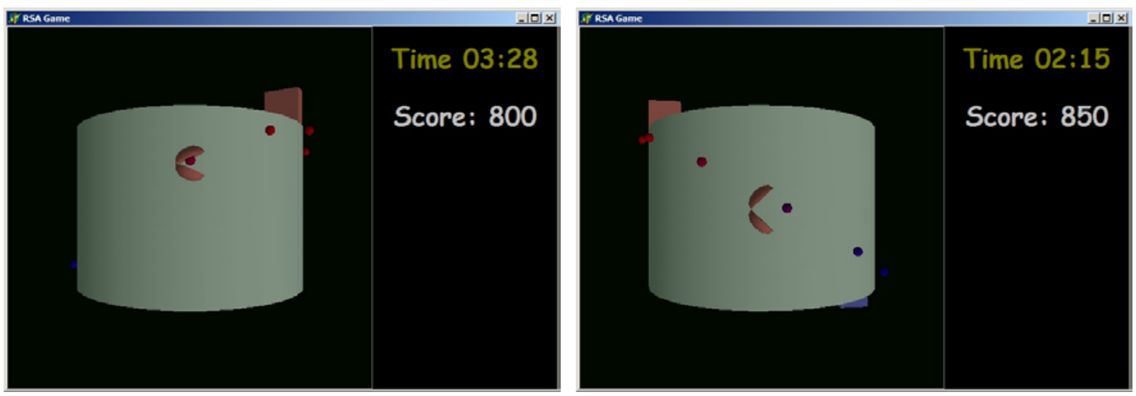

Figure 41 The Breathing Pac-Man breathing-frequency exercise

6.3.2 Experimental procedure

I conducted case studies with 13 subjects. In the case studies, participants signed a consent agreement [Appendix G] and filled out questionnaires before [Appendix H] and after [Appendix I] the game. The questionnaires were used to survey the basic demographic information of the participants, ask them about their favorite fun activities, determine their knowledge of basic facts about heart-rate variability, and after the game, to ask their opinion about their experience.

Procedure:

(1) After signing the consent agreement and filling out the first questionnaire the participants read the game rules [Appendix F]. I then answered any questions regarding the rules.

(2) I gave every participant three disposable solid-gel EKG electrodes, which they adhered to their chests. Then they attached the wire leads to the electrodes and put on the breathing sensor.

(3) I turned on the ProComp+ and tested the sensor functionality by running the test application and examining the signal plots (See Figure 33).

(4) I started the game program on the laptop. The program said, "Please relax and wait for further instructions in one and a half minutes." The subjects waited for 90 seconds, looking at the countdown timer while the program recorded their signal in order to analyze their heart-rate variability.

(5) Five seconds before the game started the program said, "Get ready. The game starts soon."

(6) The participants then played the heart-rate biofeedback exercise game (See Figure 40) for 12 minutes.

(7) After the game, the program said, "Game over. The final score is [the score]" and "Thank you for playing. Please wait for one and half minutes."

(8) The subjects waited for 90 seconds while the program kept recording the signals after the game and displayed the countdown timer.

(9) After that the players filled out the after-game questionnaire.

(10) Then the subjects were offered to play the breathing frequency exercise game (See Figure 41). Within a 20-second period the program said, "Please relax and wait for further instructions. Please take a deep breath. As deep as possible. Please exhale completely. The game starts soon."

(11) Then the game started and the subjects played it for five minutes as the cylinder rotation gradually slowed down from one rotation in five seconds (0.2 Hz) to one rotation in 20 seconds (0.05 Hz).

(12) At the end of the game the program announced the final score, thanked the subjects for playing, and wished them a nice day.

(13) After that the subjects took off the sensors.

Three of the 13 subjects were asked to do a biofeedback exercise. Instead of playing the heart-rate biofeedback game, they could only see the numeric values of their heart rate, inter-beat heart-rate change, and amplitude value that was the same as the pills size in the game version. There was no Pac-Man. These subjects served as a control group to test whether this exercise is more or less fun than the game.

6.3.3 Experimental results

The EKG recordings were visually tested with the R-spike detection algorithm used for further analysis to make sure that the derived heart rate signal has no substantial noise artifacts. EKG recording quality was acceptable for all subjects except for subject 6. One of the snap-on EKG electrodes was not properly attached to the electrode on the body and fell off in the second half of the heart-rate biofeedback game. As a result the EKG channel recorded only noise for a substantial period of the first game and the full length of the second game. The respiration signal recordings were free of visible noise in all sessions. The data from the heart-rate biofeedback game for Subject 11 was not recorded because of my mistake. Subject 7 played only the second game and did not participate in the heart-rate biofeedback game.

In the signal analysis of the heart-rate biofeedback game I was interested in quantitative comparison of the heart-rate variability during the game and the periods before and after the game. To accomplish that I used autoregressive modeling methods for power spectrum estimation. Software developed for the *Every Sign of Life* project detected R-spikes and produced R-to-R interval data re-sampled at two Hz. The data was split into segments that corresponded to the 95-second period before the game, six-minute first half of the game, six-minute second half of the game, and 90-second period after the game. The linear component calculated by the least-square method for each segment was then subtracted from the data. The power spectrum density of every segment was estimated using the Burg method. This particular method works well with short data records and always produces a stable model. The power-spectrum estimate was split into three frequency bands: (1) high frequency (HF) 0.15–0.5 Hz; (2) low frequency (LF) 0.05–0.15 Hz; and (3) very low frequency (VLF) <0.05 Hz.

The power density was summed up for each frequency band and displayed on a bar graph. The total height of a bar on the bar graph corresponds to the total power in all three frequency bands. Each bar is colored to visualize the contribution of each frequency band to the total power.

Three out of the four subjects who had the best score in the game had a substantial increase in heart-rate variability during the game (See Figure 43 and Figure 44). Subject 6 had a loose EKG wire connection and probably achieved a higher score (third place) as a side effect of wrong heart-rate detection on the noisy data. The data recording from Subject 6 was too noisy for the analysis.

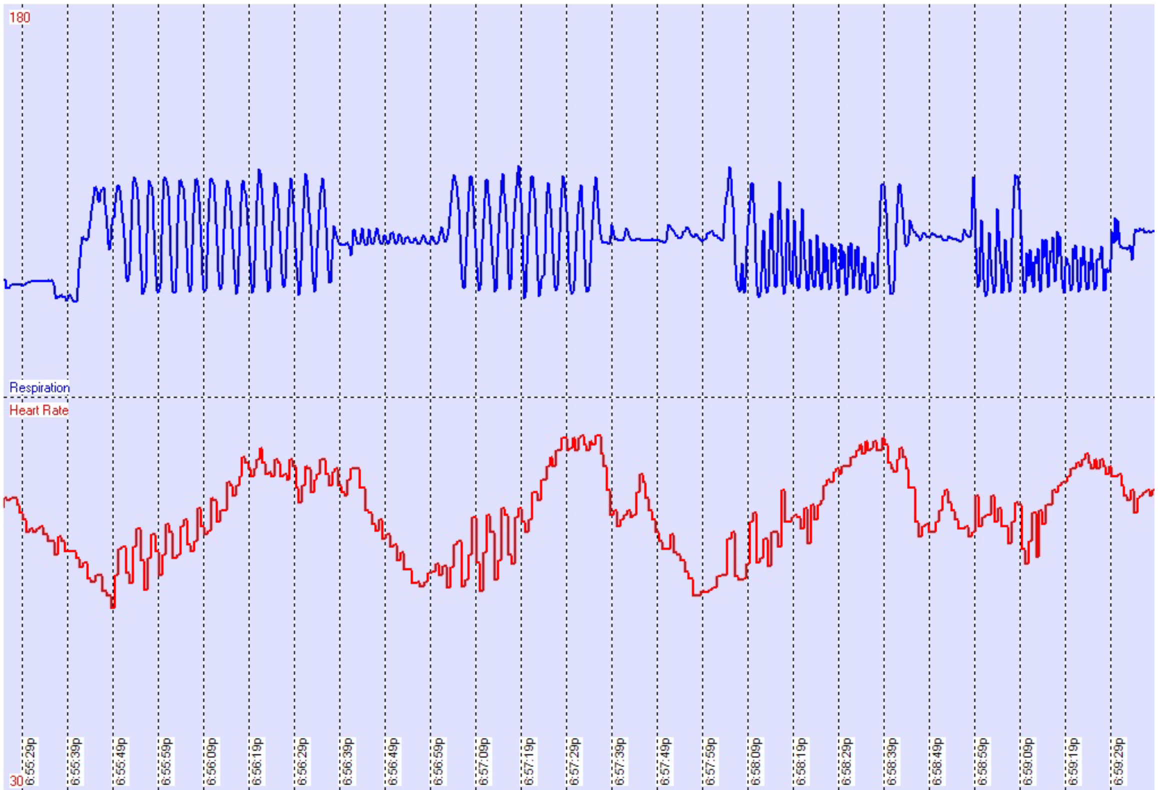

Figure 42 Subject 2 breathing pattern vs. heart rate change

Subject 2 had a substantial increase of the heart rate variability in the VLF range. Even though such an increase is usually attributed to stress [89], in this case it is induced by an unusual breathing pattern [Figure 42]. The pattern consisted of periods of rapid breathing (17.5 or 35 times per minute) interleaved with periods of holding breath or shallow breathing. The subject was also very successful in capturing pills, which partially helped him to get a higher score than the other players. The pills moved by the Pac-Man exactly 35 times per minute. This explains the precise breathing frequency of the subject. The fact that some players may have a tendency to breathe at the exact frequency of pill appearances can be used in future game designs to dictate the resonant frequencies necessary to achieve desired physiological effects.

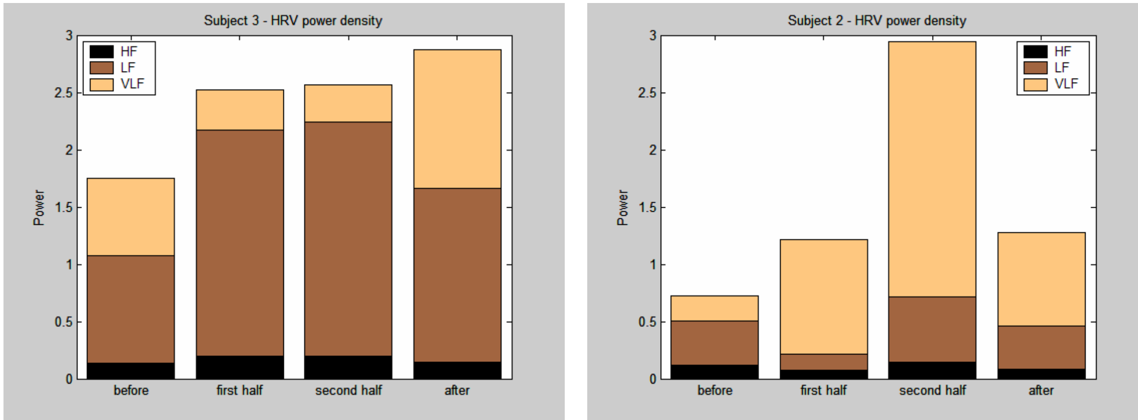

Figure 43 Subjects 3 and 2 (first and second place)

Subject 4 had a substantial increase in the heart-rate variability throughout the game and in the period after the game. The power level, however, is noticeably lower than for other individuals. This subject reported that he didn't like the game and was sleep deprived. The subject also had the lowest score of all the participants in the game.

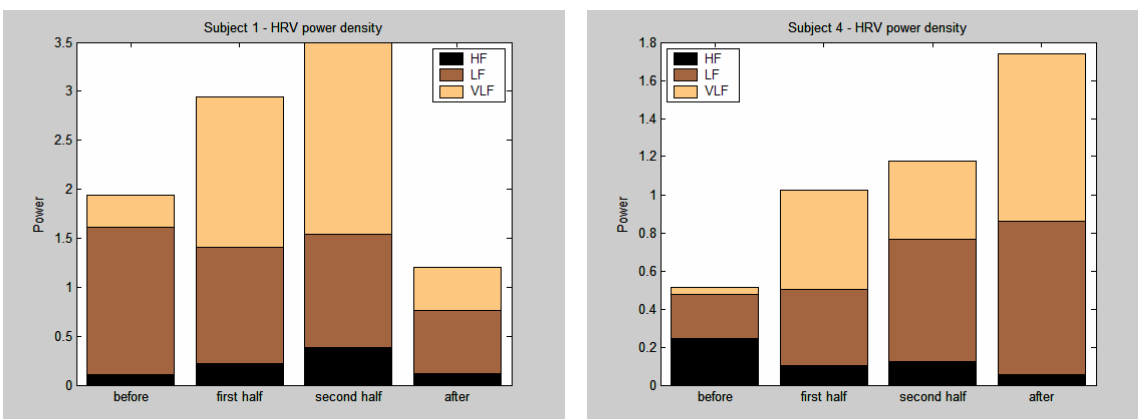

Figure 44 Subjects 1 and 4

Subject 8 had a high overall heart-rate variability level before the game (See Figure 45) that decreased when the game started. However, in the second half of the game the subject increased the heart rate variability in the low frequency range.

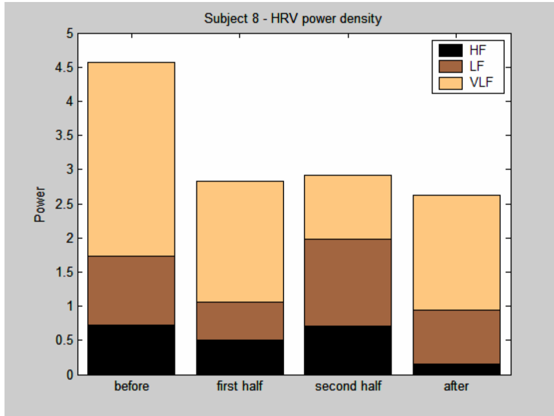

Figure 45 Subject 8

Subjects 5 and 9 reduced their heart-rate variability to a very low level during the game (See Figure 46) and got the score substantially lower than all of the other subjects except for Subject 4 (See Figure 44). Both subjects kept breathing rapidly throughout the whole game (See Figure 47) and did not try other breathing techniques. Subject 5 was the only one who answered "no" to the question whether he/she knows how to control his/her pulse rate after the game. Subject 9 wrote a comment, "I thought I knew how to control my pulse rate but sometimes I could not make the pills grow."

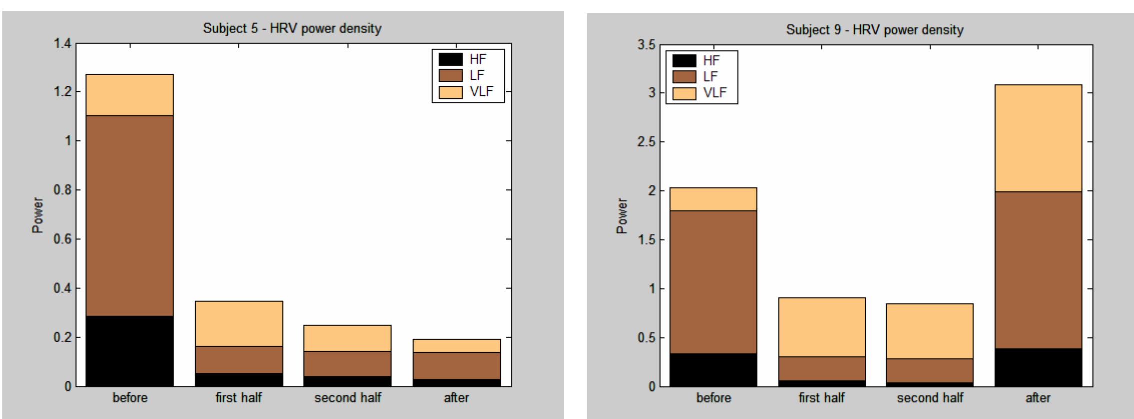

Figure 46 Subjects 5 and 9

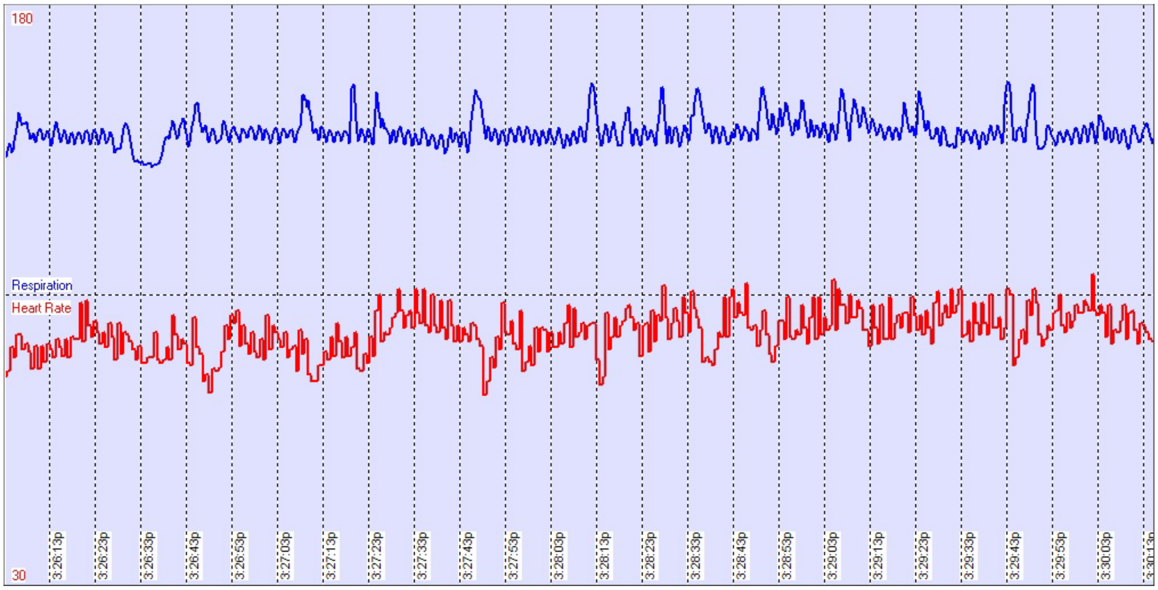

Figure 47 Subject 5 had rapid breathing throughout the game.

The control group (Subjects 10–12) who participated in the non-game version of the exercise reported that the biofeedback activity was boring. However, the heart-rate variability during the game for Subjects 10 and 12 (See Figure 48) was substantially higher than in the periods before and after the game. This indicates that the lack of fun did not prevent them from successfully following the biofeedback and learning how to achieve a higher variation in their heart rate. In fact, they did relatively better than the test group. The fun activity may add a distraction to the biofeedback exercise and increase sympathetic arousal. For example, moving the Pac-Man up and down to capture the pills may reduce the concentration of the subject on the biofeedback task.

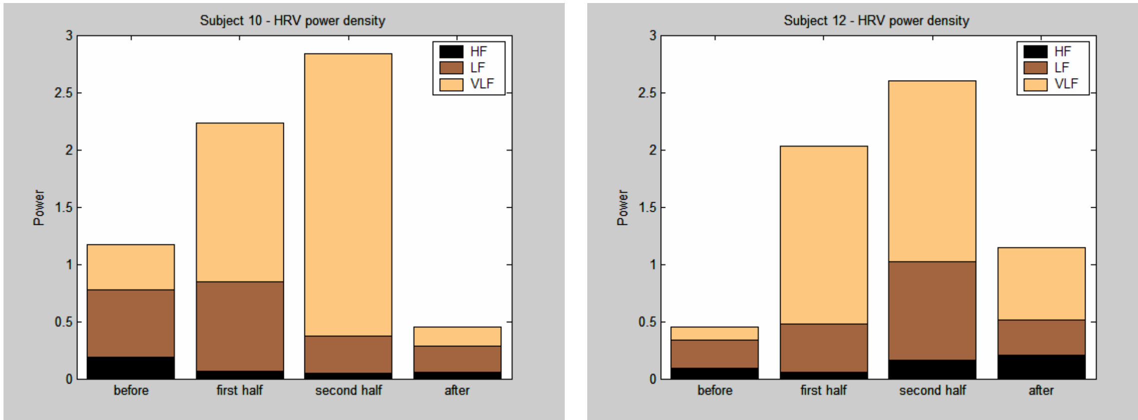

Figure 48 Subjects 10 and 12

The equipment and R-wave-detection algorithms worked well during the game for most subjects. The exceptions were subject 6 (loose EKG wire) and subject 12 (failure of R-wave detection algorithm at the end of the game as a result of reversed + and – electrodes). All subjects in the test group reported that they strongly agree that the game equipment worked well. Although I did not make any changes to the equipment setup and R-wave detection algorithm for the control group, all three subjects in that group reported lower marks on the same question. A few incorrectly detected R-waves were manually fixed for the spectral analysis.

According to my observations the breathing sensor worked well, allowing the subjects to move the Pac-Man up and down easily. The question about whether Pac-Man is easily moved scored an average of 4.5 out of 5.

The power-spectrum analysis of the game data also revealed several problems. One of the problems was the use of too short period before and after the game to acquire a robust baseline of the heart-rate variability parameter. Since the study was about fun, the reason to choose shorter periods was to reduce the time during which the subjects may get bored. The subjects did not have enough time to relax. As a result, the heart-rate variability might be higher than average for these people. This might have substantially raised the "before" bar on the charts. Also, the number of data points is too close to a practical minimum for the spectral analysis. Too avoid this problem in the future it is necessary to have at least a 3–5 minute period to acquire these data.

Another problem was that Subjects 1, 2, 10, and 12 noticeably increased the heart-rate variability in the VLF band instead of LF band. This may indicate that they either changed their heart rate by means other than breathing or they used breathing intermittently to get a variation in the heart rate and then waited until the heart-rate variation indicator (pill size or number) got smaller. The intermittent breathing pattern may produce a shift towards VLF band in the power spectrum. The increase in the VLF range can also be attributed to sympathetic arousal. Computer games may cause relaxation for some, but stress for others. To fix this problem it may be necessary to replace the amplitude indicator with another measurement of the heart-rate variability based on the spectral analysis of the heart-rate signal or covariance of the heart rate and breathing. For example, a real time power spectrum-density measure for the LF range may produce better RSA training results.

Table 5 lists the mean questionnaire answers [Appendix J] for each group. The numbers range from 1, strongly disagree, to 5, strongly agree. Although the groups are too small for statistically sound analysis, the data gives an indication of how people tend to rate these activities. Subject 4, who was sleep deprived, strongly agreed that the game was boring and disagreed that the game was fun. Out of three people in the control group one agreed and one strongly agreed that the activity was boring. In general, the subjects indicated that the game activity is less boring, more fun, more engaging, had better defined rules than the biofeedback without the game elements.

	Test	Control
I enjoyed the game	4.0	3.7
The gameis relaxing	2.8	2.3
The game is boring	2.3	4.0
The game is easy to play	3.8	3.0
The rules are poorly defined	2.0	3.7
The game equipment works well	5.0	3.0
I would play this game again	3.9	2.3
The game is engaging	4.0	2.3
Multi-player game would be better	3.8	3.3
The game is fun	4.1	3.3
I learned how to change size of pills (HR)	4.4	3.3
The game rules are good	3.9	n/a
I could easily move pacman up and down	4.5	n/a
I learned more about my breathing	4.1	3.0
The game is dangerous for my health	1.8	1.0
I felt dizzy during game	3.5	1.3
Pill size (HR) changed unpredictably	2.5	2.3
The game is stressful	2.5	2.3
I felt frustrated during game	2.4	3.3

Table 5 Average questionnaire answers in test vs. control group

An important result is that when asked whether they would play the game again, the subjects from the test group gave more positive replies than the subjects from the control group. Of course, not all people enjoy playing computer games and not everyone would be interested in a biofeedback/game exercise, but adding more fun to biofeedback may attract more people and make people do such exercises more often.

The game can be improved and made more sophisticated and engaging by enhancing the game scenario: adding additional obstacles or challenges, improving graphics, and adding a table of results.

The objectives of the breathing-frequency exercise was to establish whether a game activity can make people breathe in a predetermined way and also to see how the amplitude of variation in the heart rate depends on the breathing frequency.

Based on visual analysis of the breathing pattern, only three (Subjects 1, 3, and 11) out of 13 subjects who participated in the activity lost the pill trail in the middle of the exercise.

All subjects required about 3–10 seconds to start following the trail. A typical recording of a successful exercise is shown for Subject 2 (See Figure 49).

Because of the specifics of the game (the requirement to catch the pills) several subjects readjusted the position of the Pac-Man in front of the pills with slight inhaling/exhaling (See Figure 50). This effect was especially noticeable towards the end of the game when breathing had to be slow, but the pills were moving much slower and arrived with much higher time intervals than in the beginning of the game. The game could be changed to eliminate this effect and to obtain the intended breathing pattern by increasing the number of pills and/or making it easier for the Pac-Man to capture the pills.

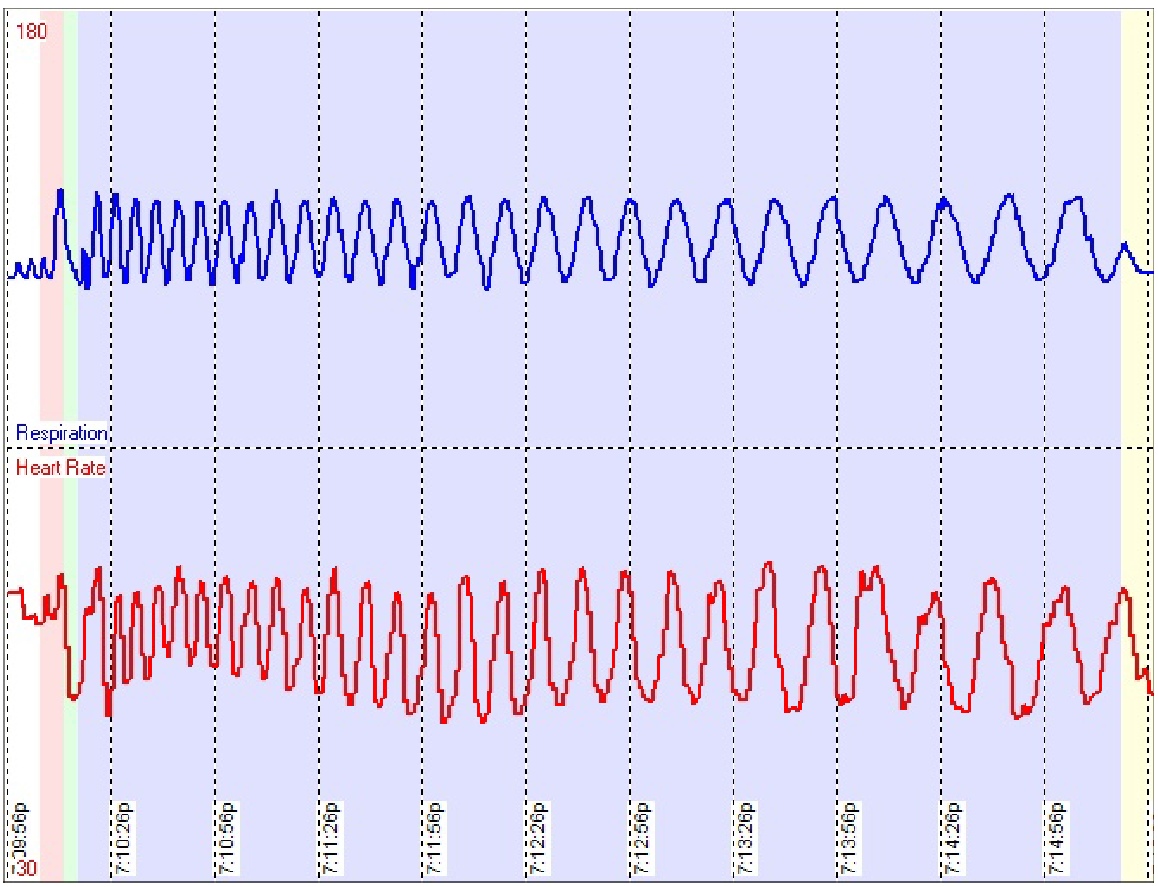

Figure 49 Subject 2 breathing-frequency exercise data

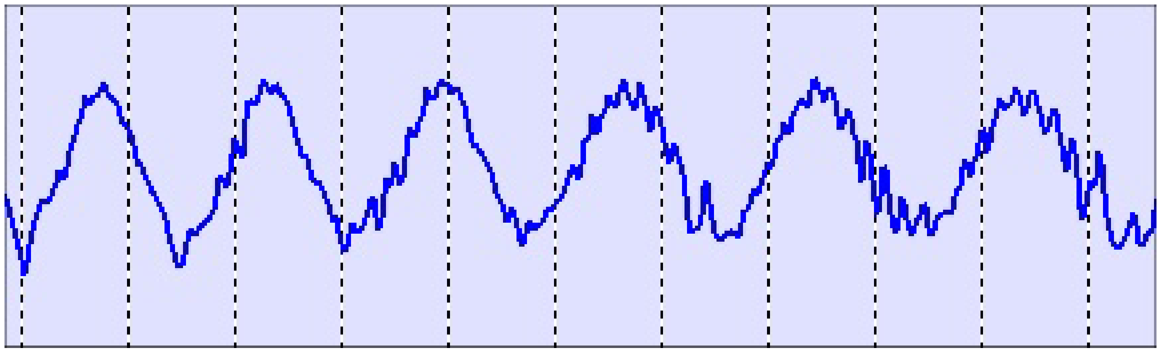

Figure 50 Subject 6 breathing at the end of the exercise (vertical lines show 10-second intervals)

To quantify the effect of breathing frequency on the heart-rate variability for this particular activity I calculated the absolute values between the maximum and minimum heart rate within one breathing period over the course of the game for all eight subjects who followed the breathing pattern. Then I calculated the average of these data for the eight subjects. The result is shown as the function of respiration frequency (See Figure 51).

The logistics of this activity do not allow me to make definite conclusions about how amplitude of heart-rate change depends on the respiration frequency. For example, the rapid frequency change may have a different effect than the constant breathing at a particular frequency. Since breathing has a delayed effect on the heart rate, it is not possible to precisely match the values on the graph to the effective breathing frequency. However, the graph shows over 30% variation in amplitude at different stages of this activity. There are peaks that correspond to 0.06, 0.1, 0.12, and 0.14 Hz current breathing rate and troughs at 0.07, 0.09, 0.11, and 0.13 Hz. The peaks and troughs may be a result of an inter-beat effect between the changing respiration frequency and the resonant frequency of respiratory-induced heart-rate oscillations [79]. An extended study may establish whether this pattern is coincidental or corresponds to a physiological phenomenon.

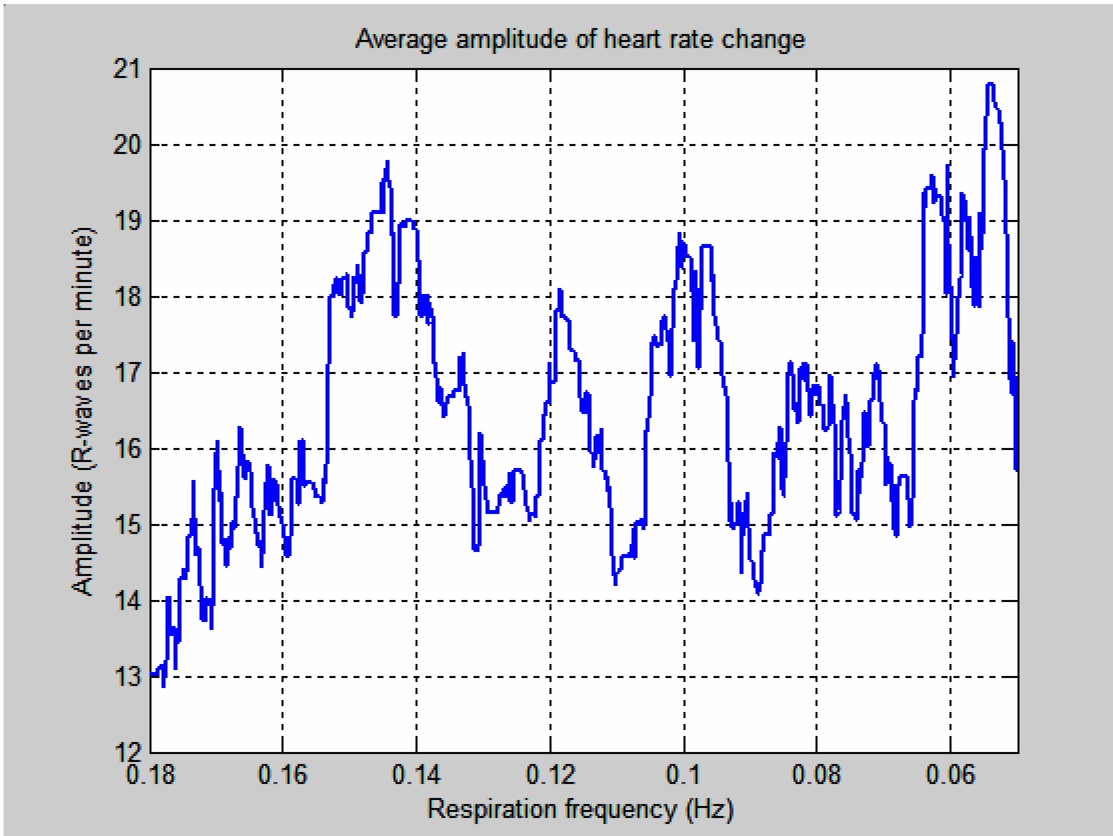

Figure 51 Dependence of heart-rate changes on breathing frequency

6.4 Summary

In this chapter I described two examples of activities that combine biofeedback and computer games. Those two examples define a new genre of Bio-Analytical Games.

I explored the robustness the scenarios and the Extremity Computing hardware and software, which worked well in most circumstances. However, analysis of data recorded during Heartball games suggests that it is necessary to improve techniques to eliminate or filter out the noise added to the EKG signal by players' motion.

In this chapter I also discussed the results of analysis of the experience of participants and changes in their knowledge about physiology based on both answers to the questionnaires and physiological signals recorded during the studies. The analysis of the data from biofeedback games indicated that the games produce physiological effects similar to those of a regular biofeedback exercises. However, the subjects considered the games more fun than the non-game exercise.

Chapter 7

Conclusion

Every Sign of Life developes a new approach to design of sensor peripherals and wearable computer components called Extremity Computing. This approach provides a computer with an extended sensor capability and removes the range limitations of ordinary sensor interfaces. Computers can use data extremity devices to sense and affect a multitude of people or objects around them. The Extremity Computing approach allowed me to rapidly prototype and implement robust hardware and software to support the scenarios described in this thesis.

I developed scenarios that show how to use the Extremity Computing approach to improve user experience by adding sensors to various objects or to the body and using rich user interface capabilities of a conventional computer. The approach also led me to redefine biosensor monitoring from periodic to continuous (ultimately saving all the data over a lifetime). A compact health monitor with a large local-storage device may continuously store biosensor information and transfer the data to a conventional computer on demand. The studies conducted as a part of *Every Sign of Life* suggest that *continuous* health monitoring can be practical and beneficial. Ultimately both patients and doctors may be interested in collecting and analyzing biosensor data over the whole lifetime period.

I have described how to design robust hardware and software to support Bio-Analytical Games. I found that in creating a combination of sports and biofeedback it is necessary to develop a way of eliminating or filtering out the noise added to the signals by the players' motion.

In *Every Sign of Life* I have also developed a new approach to adding implicit biofeedback to computer games. For example, an extremity system can change the behavior of a character on the screen in first-person action games to reflect the emotional or physiological state of the player. The rest of the game environment may also change according to parameters measured by a health monitor. The technique of growing and shrinking pills in the Breathing Pac-Man game can be extended to change the size, shape, motion, or internal characteristics of objects in other games.

I have developed a new genre of games that straddles the boundary between sports and computer games. Sports and computer games are very common forms of entertainment. Most computer games are creatively designed, but solitary activities that do not involve any physical exercise. Sports, on the other hand, are often group activities that lack the imaginative elements and diversity of scenarios of the computer games. I have developed a set of five design principles for Bio-Analytical Games and applied them to create two different games, Heartball and Breathing Pac-Man, which bring these two worlds together. According to the study most people who played the games indicated that the games were fun.

One of the conclusions is that Bio-Analytical Games can produce physiological effects similar to those of regular biofeedback exercises and affect a player's knowledge of physiology. The most important conclusion is that people can have more fun with biofeedback when it is combined with computer games. Bio-Analytical Games can be more engaging, attract more people, and make people spend more time exploring their health parameters than regular biofeedback exercises.

I have also developed a new approach to bio-informatics, geared towards the consumer. Instead of treating biosensor devices as medical equipment I have demonstrated how such devices could be used to provide consumers with fun and engaging information about their health. I have also conducted a series of experiments that suggest the efficacy of this approach and the need for longitudinal studies.

Finding new techniques of visual and auditory presentation for the physiological signals is one of the open-ended goals of this research. These techniques will be useful not only in self-monitoring, but also in professional healthcare, e.g., self-monitoring in hospitals. They may also be beneficial in educational settings.

Every Sign of Life project has demonstrated that health information can be fun. And fun can be the key element in helping people to learn more about their health and to lead healthier lifestyles.

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APPENDIX A – HEARTBALL GAME RULES

Heartball is a two-team competitive ball game. The objective of each team is to get more points than the other team within 15 minutes of play. Each player can get points for his/her team by grabbing the ball, lowering his/her pulse rate and releasing the ball. The game computer automatically adds points based on the difference between the “grab” and “release” pulse.

- If the “release” pulse is greater or equal to the “grab” pulse the team does not get any points.
- If a player holds the ball for more than *the countdown interval* the player’s team does not get any points no matter what the pulse difference is. The game computer counts down *the countdown interval* for each player and tells the player “three, two, one, out of time” unless the player passes the ball.
- If a player hold the ball less than *the countdown interval* and the “release” pulse is lower than the “grab” pulse the team gets the number of points equal to the difference between the pulses in beats per minute.

The rules regarding passing the ball and taking the ball from other players can be arbitrary. However, since the game is under development and every player is a beginner at this point please follow the following recommendations for passing the ball.

- Each player holds the ball no longer than about 20 seconds. A player has to pass the ball before or right after the game computer says “out of time”.
- Each player passes the ball to a player from the opposite team.
- The ball goes around in an established pattern, i.e., player 1 team A → player 1 team B → player 2 team A → player 2 team B.
- Do not touch the player who holds the ball and do not engage in any physical struggle during the game. You may however talk to other players or try to distract the player who holds the ball from lowering his/her pulse rate.

The game ends in 15 minutes. The team that has more points wins. The game computer announces the winner.

Please remember that this game is under development. This is one of the first test runs of the game. Please excuse possible glitches in the game system. Your comments are very important for the future development of games of this kind.

APPENDIX B – HEARTBALL INFORMED CONSET AGREEMENT

Informed Consent Agreement

Title of Study: Every Sign of Life

Principal Investigators: Vadim Gerasimov, Walter Bender

Participation in this research is voluntary. I understand that I am free to withdraw my participation at any time without prejudice.

This research explores the role of fun in improving health-awareness of people. The purpose of the experiments is to investigate how generally healthy people can benefit from collecting their own physiological parameters in real time and over long periods of time and exploring these data with software designed for their entertainment.

Procedure

In this study we evaluate an interactive game based on real-time health information of the players. You will be asked to participate in the game and fill out questionnaires before and after the game. If you have any questions, at any point during the experiment, the experimenter will answer them.

Commitment

I understand that by agreeing to participate in this experiment, I will be asked to wear a health monitor during the experiment.

I understand that the health monitor will measure and store my electrocardiogram and skin temperature.

I understand that the information given to the investigators will be kept private and my identity will not be disclosed in the published results of the research.

I understand that my participation in this experiment includes taking part in a game and filling out questionnaires.

I understand that I may decline a request to participate in an individual activity, yet continue to participate in the experiment.

I understand that the game will be videotaped for research purposes.

Medical Issues

I understand that the data collected by the device as well as any information derived from these data by any means are intended for my entertainment and education only and should not be interpreted as medical advice or used for self-diagnostics without consulting with a medical doctor.

I certify that to the best of my knowledge I do not have any pre-existing health problems or medical conditions that could make my participation in the experiments harmful for me or anybody else.

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the M.I.T. Medical Department, including first aid emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available; or providing it, does not imply that such injury is the Investigator's fault. I also understand that by my participation in this study I am not waiving any of my legal rights.

Questions

I understand that I may address any concerns or questions to either Vadim Gerasimov (vadim@media.mit.edu, 617-253-5127) or Walter Bender (walter@media.mit.edu, 617-253-7331).

I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T. 617-253-6787, if I feel I have been treated unfairly as a subject.

Limitations

I understand participation in this research project is voluntary and I am free to withdraw my consent at any time without prejudice. I further understand that, either before or after my withdrawal, I may request the deletion of any portion of any data I contribute.

Signatures

By signing two copies of this document I agree to participate in the described experiment. The first copy will be given to me; the second copy will be kept by the principal investigators.

I have read this document and agree to participate in the described experiment.

--	-----------------------------------	----------------------
Print Name	Signature	Date

Subject's participation in the experiment confirmed and approved.

--	-----------------------------------	----------------------
Principal Investigator's Name	Signature	Date

APPENDIX C – HEARTBALL QUESTIONNAIRE BEFORE THE GAME

Age: ___________________

Gender: F __   M __

What is your education level?

(a) __ Up to high school
(b) __ Some college
(c) __ College
(d) __ Graduate degree

What is your employment status?

(a) __ Part-time
(b) __ Full-time
(c) __ Unemployed
(d) __ Retired
(e) __ Student
(f) __ Homemaker

How acquainted are you with the use of computers:

(a) __ None at all
(b) __ Some knowledge
(c) __ Expert

How often do you play computer or video games:

(a) __ Never
(b) __ Rarely
(c) __ Once a week
(d) __ Two or three time per week
(e) __ Every day

Exercise practices:

How often do you exercise?

(f) __ Never
(g) __ Rarely
(h) __ Once a week
(i) __ Two or three time per week
(j) __ Every day

Where do you usually exercise? ____

Have you ever used a pulse monitoring device during exercise?

__ Yes   __ No

What type of exercise?

(a) __ Low intensive level exercise (e.g. walking)
(b) __ Follow a supervised exercise program
(c) __ Aerobic exercise
(d) __ High-intensity exercises
(e) __ Weight-bearing exercises
(f) __ High-resistance exercise
(g) __ Others (explain):____

Please rate how much you enjoy engaging in these activities (not including watching or attending games):

	Never Tried	Dislike Strongly		Neutral		Enjoy Strongly
Football/Soccer/Rugby	0	1	2	3	4	5
Baseball/Softball	0	1	2	3	4	5
Tennis/Squash/Racquetball	0	1	2	3	4	5
Walking	0	1	2	3	4	5
Jogging	0	1	2	3	4	5
Chess	0	1	2	3	4	5
Reading	0	1	2	3	4	5
Card Games	0	1	2	3	4	5
Solving Puzzles	0	1	2	3	4	5
Computer or video games:						
Shoot-em-up Games	0	1	2	3	4	5
Adventure Games	0	1	2	3	4	5
Role-playing Games	0	1	2	3	4	5
Dynamic Puzzle Games	0	1	2	3	4	5
Simulation Games	0	1	2	3	4	5
Other games or activities you like/dislike:						
________________________		1	2	3	4	5
________________________		1	2	3	4	5
________________________		1	2	3	4	5
________________________		1	2	3	4	5
________________________		1	2	3	4	5

What is your average pulse rate (if not sure try to guess)?

___ 40 or less

___ 40-60

___ 60-80

___ 80-100

___ 100-120

___ 120 or more

Do you know how to voluntarily affect your pulse rate?

___ Yes ____

___ Maybe

___ No

Please write any comments regarding this questionnaire:

____

____

____

____

APPENDIX D – HEARTBALL QUESTIONNAIRE AFTER THE GAME

Please rate your team experience with the game:

	Strongly Disagree		Neutral		Strongly Agree
Our team was stronger	1	2	3	4	5
Our team knew how to control pulse	1	2	3	4	5
Our team learned how to change pulse	1	2	3	4	5
The other team knew how to control pulse	1	2	3	4	5
The other team learned how to change pulse	1	2	3	4	5
Our team was more organized	1	2	3	4	5
Our team was more cooperative	1	2	3	4	5
Our team was more competitive	1	2	3	4	5

Please rate your experience with the game:

	Strongly Disagree		Neutral		Strongly Agree
I enjoyed the game	1	2	3	4	5
The game is relaxing	1	2	3	4	5
The game is boring	1	2	3	4	5
The game is easy to play	1	2	3	4	5
The rules are poorly defined	1	2	3	4	5
The game equipment works well	1	2	3	4	5
I would play this game again	1	2	3	4	5
The game is engaging	1	2	3	4	5
Single-player game would be better	1	2	3	4	5
The game is fun	1	2	3	4	5
I liked competing with the other team	1	2	3	4	5
The game rules are good	1	2	3	4	5
I would play this game with my friends	1	2	3	4	5
I learned more about my heart	1	2	3	4	5
The game is dangerous for my health	1	2	3	4	5
This is a physically active game	1	2	3	4	5
I can easily control my pulse rate	1	2	3	4	5
The game is stressful	1	2	3	4	5
I don’t want to know my pulse rate	1	2	3	4	5
I liked collaborating with my teammate	1	2	3	4	5
I liked to see heartbeat of other players	1	2	3	4	5

How would you change the rules or setup to make the game more interesting?

____

____

What is your average pulse rate (if not sure try to guess)?

___ 40 or less

___ 40-60

___ 60-80

___ 80-100

___ 100-120

___ 120 or more

Do you know how to voluntarily affect your pulse rate?

___ Yes ___ Maybe ___ No

Did you learn how to change you heart rate during the game?

___ Yes ___ Maybe ___ No

Please write any other comments or recommendation regarding the game:

____

____

____

____

APPENDIX E – HEARTBALL QUESTIONNAIRE ANSWERS

Table 6 Heartball Session 1: The pre-game questionnaire

Session		11/07/2002 4PM Score 180:271			
Player		1	2	3	4
Age		24	31	25	31
Gender		f	m	m	m
Education		Grad	Grad	Grad	Grad
Employment		Student	Student	Student	Student
Computer use		Some knowledge	Expert	Expert	Some knowledge
Computer games		Rarely	Rarely	Rarely	Rarely
Exercise	how often	1/week	1/week	Rarely	2-3/week
	where	indoors	home		along the river
	ever used pulse monitor	no	yes	no	no
	type	Pilates	Aerobic		
Fun	Football/Soccer/Rugby	5	5	4	5
	Baseball/Softball	3	2	0	3
	Tennis/Sqash/Racquetball	3	4	4	4
	Walking	5	2	5	2
	Jogging	4	2	3	5
	Chess	3	4	5	3
	Reading	4	3	5	4
	Card games	3	2	4	3
	Solving Puzzles	3	4	4	3
Computer or video games	Shoot-em-up	3	2	3	2
	Adventure	4	4	3	2
	Role-playing	4	4	3	3
	Dynamic puzzle	4	4	3	2
	Simulation	3	4	3	3
Other		Dancing 5	Eating 4 Sleeping 4 Swimming 5		Field hockey 4
What is your average pulse rate?		no idea	60-80		40-60
Do you know how to control your pulse rate?		yes Through breathing and relaxation	yes relax/ get stressed/ active		no
Comments regarding questionnaire					very consise

Table 7 Heartball Session 1: The post-game questionnaire

Session		11/07/2002 4PM Score 180:271			
Player		1	2	3	4
Team Experience	Our team was stronger	3	4	4	4
	Our team knew how to control pulse	2	4	3	4
	Our team learned how to change pulse	4	1	3	3
	Other team knew how to control pulse	4	3	3	3
	Other team learned how to change pu	4	3	3	3
	Our team was more organized	2	4	4	4
	Our team was more cooperative	3	5	4	3
	Our team was more competitive	3	4	3	3
Your experience	I enjoyed the game	4	5	4	4
	The game is relaxing	2	2	2	4
	The game is boring	2	2	2	1
	The game is easy to play	3	2	2	1
	The rules are poorly defined	3	3	1	4
	The game equipment works well	4	1	5	3
	I would play this game again	4	5	3	5
	The game is engaging	3	4	4	4
	Single-player game would be better	4	2	2	1
	The game is fun	4	4	4	5
	I liked competing with the other team	3	4	4	5
	The game rules are good	4	3	3	3
	I would play this game with my friends	2	4	2	4
	I learned more about my heart	3	2	2	2
	The game is dangerous for my health	1	2	3	1
	This is a physically active game	3	4	4	3
	I can easily control my pulse rate	3	3	3	3
	The game is stressful	2	4	4	1
	I don't want to know my pulse rate	1	2	3	1
	I liked collaborating with my teammate	3	4	3	5
	I liked to see heartbeat of other players	4	2	3	3
How to change rules or setup to make game more interesting?		I would make people change places & positions in space	Make HR more accurate		Ensure there is a requrement to attempt to distract the other players
What is your average pulse rate?		80-100	60-80	80-100	100-120
Do you know how to voluntarily affect your pulse rate?		yes	yes	maybe	yes
Did you learn how to change your heart rate during tha game?		yes	no	no	maybe
Comments					

Table 8 Heartball Session 2: The pre-game questionnaire

Session		11/07/2002 7PM Score 317:267			
Player		1	2	3	4
Age		18	18	18	18
Gender		m	m	m	m
Education		Some college	Some college	Some college	Some college
Employment		Student	Student	Student	Student
Computer use		Some knowledge	Expert	Expert	Some knowledge
Computer games		1/week	every day	rarely	rarely
Exercise	how often	1/week	Rarely	1/week	2-3/week
	where	weight room	running outside	rockwell cage	Z-center
	ever used pulse monitor	no	no	no	yes
	type	Weight-bearing	Aerobic	badminton	low/high intensity
Fun	Football/Soccer/Rugby	2	5	2	3
	Baseball/Softball	4	3	2	5
	Tennis/Sqash/Racquetball	2	3	3	5
	Walking	3	1	4	5
	Jogging	2	4	4	4
	Chess	3	5	5	4
	Reading	4	5	5	4
	Card games	5	5	4	2
	Solving Puzzles	5	5	5	4
Computer or video games	Shoot-em-up	5	2	1	3
	Adventure	3	5	3	5
	Role-playing	4	5	4	2
	Dynamic puzzle	4	3	5	4
	Simulation	4	2	3	4
Other					
What is your average pulse rate?		60-80	60-80	80-100	80-100
Do you know how to control your pulse rate?		yes breathing	maybe	maybe	maybe
Comments regarding questionnaire					

Table 9 Heartball Session 2: The post-game questionnaire

Session		11/07/2002 7PM Score 317:267			
Player		1	2	3	4
Team Experience	Our team was stronger	3	3	3	4
	Our team knew how to control pulse	4	2	4	5
	Our team learned how to change pulse	4	4	3	5
	Other team knew how to control pulse	4	2	5	5
	Other team learned how to change pu	4	2	4	4
	Our team was more organized	3	3	2	1
	Our team was more cooperative	3	3	2	4
	Our team was more competitive	4	4	2	3
Your experience	I enjoyed the game	4	5	4	5
	The game is relaxing	1	2	1	4
	The game is boring	2	2	1	2
	The game is easy to play	4	4	3	5
	The rules are poorly defined	3	1	1	1
	The game equipment works well	2	2	3	4
	I would play this game again	3	4	3	3
	The game is engaging	4	5	4	4
	Single-player game would be better	2	2	1	1
	The game is fun	4	5	3	4
	I liked competing with the other team	3	5	3	4
	The game rules are good	3	3	4	3
	I would play this game with my friends	2	4	3	3
	I learned more about my heart	3	2	4	3
	The game is dangerous for my health	4	3	4	3
	This is a physically active game	3	4	4	2
	I can easily control my pulse rate	4	3	4	2
	The game is stressful	4	2	4	3
	I don't want to know my pulse rate	2	1	2	2
	I liked collaborating with my teammate	3	1	3	3
	I liked to see heartbeat of other player	3	5	4	3
How to change rules or setup to make game more interesting?		Have it take pulse averages over a slightly bigger interval (~2s)	Take away points if your pulse rises; also make the sensors work slightly better		
What is your average pulse rate?		60-80	60-80	80-100	80-100
Do you know how to voluntarily affect your pulse rate?		yes	maybe	yes	maybe
Did you learn how to change your heart rate during tha game?		yes	maybe	no	no
Comments		Good idea	WOULD BUY FROM AGAIN A+++++++++++++ </Ebay reference> I liked the game. With more players it would have been even better.		The 15 second time limit makes the pace of the game more engaging, but I don't know if it's enough time for someone to effectively change their heart rate. Though, upon playing the game I would still prefer a faster pace over slower pace.

Table 10 Heartball Session 3: The pre-game questionnaire

Session		11/21/2002 3PM Score 464:284			
Player		1	2	3	4
Age		30	25	27	27
Gender		m	f	f	f
Education		Grad	Grad	Grad	Grad
Employment		Student	Student	Full-time	Student
Computer use		Expert	Expert	Expert	Expert
Computer games		1/week	Rarely	Every day	Rarely
Exercise	how often	Rarely	2-3/week	Rarely	1/week
	where	Dance studio	outside and/or gym	swimming pool	dance class
	ever used pulse monitor	no	no	no	no
	type	dance	Aerobic	swimming	Aerobic
Fun	Football/Soccer/Rugby	3	5	3	0
	Baseball/Softball	0	3	3	0
	Tennis/Sqash/Racquetball	3	5	5	0
	Walking	5	5	4	4
	Jogging	1	5	2	3
	Chess	4	5	3	3
	Reading	2	5	4	5
	Card games	4	3	4	4
	Solving Puzzles	3	4	4	4
Computer or video games	Shoot-em-up	4	0	3	1
	Adventure	4	0	4	2
	Role-playing	3	0	3	1
	Dynamic puzzle	2	4	5	3
	Simulation	4	4	3	3
Other		Dance 5 Badmin 5 RTS games 5	Dance 5 Write 5 Camping 5 Rock climbing 5 Mountain biking 5		
What is your average pulse rate?		80-100	80-100	40-60 not sure	60-80
Do you know how to control your pulse rate?		maybe	maybe	yes change in breathing pattern (again not sure)	no
Comments regarding questionnaire		not sure what constitutes "exercise". I walk a lot for example, but I don't think of it as exercise.			

Table 11 Heartball Session 3: The post-game questionnaire

Session		11/21/2002 3PM Score 464:284			
Player		1	2	3	4
					not submitted
Team Experience	Our team was stronger	4	5	3	
	Our team knew how to control pulse	4	5	5	
	Our team learned how to change pulse	3	5	5	
	Other team knew how to control pulse	3	5	5	
	Other team learned how to change pu	4	5	5	
	Our team was more organized	1	4	3	
	Our team was more cooperative	1	5	3	
	Our team was more competitive	1	3	3	
Your experience	I enjoyed the game	4	5	5	
	The game is relaxing	1	3	2	
	The game is boring	2	1	1	
	The game is easy to play	4	5	4	
	The rules are poorly defined	1	5	1	
	The game equipment works well	4	4	2	
	I would play this game again	4	5	5	
	The game is engaging	4	5	5	
	Single-player game would be better	1	3	2	
	The game is fun	4	5	5	
	I liked competing with the other team	5	5	4	
	The game rules are good	4	5	4	
	I would play this game with my friends	4	5	5	
	I learned more about my heart	4	5	5	
	The game is dangerous for my health	1	1	1	
	This is a physically active game	3	5	5	
	I can easily control my pulse rate	1	5	3	
	The game is stressful	4	4	2	
	I don't want to know my pulse rate	1	1	1	
	I liked collaborating with my teammate	4	5	5	
	I liked to see heartbeat of other player	3	5	5	
How to change rules or setup to make game more interesting?		-have loger time to lower pulse - get rid of wrong pulse estimates (i.e. debug) - couple with music|dance		I think it was very well done.	
What is your average pulse rate?		80-100	80-100	100-120	
Do you know how to voluntarily affect your pulse rate?		maybe	yes	maybe	
Did you learn how to change your heart rate during tha game?		maybe	yes	maybe	
Comments		- it affected the game that beginning pulse would sometimes be incorrect, making it futile to actually try to lower it - or giving a team lots of points for doing nothing -- would be great if fixed	I think that the system has a delay at detecting who has the ball and when they give it to others. It's really fun.	Sometimes, worrying about whether or not the equipment is working raised my heart rate I think.	

Table 12 Heartball Session 4: The pre-game questionnaire

Session		11/21/2002 4PM Score 254:377			
Player		1	2	3	4
Age		20	28	22	26
Gender		m	m	f	m
Education		Grad	Up to high school	College	Grad
Employment		Part-time	Unemployed	Part-time	Student
Computer use		Expert	Expert	Expert	Expert
Computer games		Rarely	Rarely	1/week	Rarely
Exercise	how often	2-3/week	Never	1/week	1/week
	where	rehearsal rooms		outside	gym, basketball court
	ever used pulse monitor	no	no	no	no
	type	Aerobic, Theater performance warmups		Low-intensity (walking)	Aerobic, Weight-bearing
Fun	Football/Soccer/Rugby	5	1	2	4
	Baseball/Softball	4	1	3	4
	Tennis/Sqash/Racquetball	5	1	5	5
	Walking	4	3	4	3
	Jogging	2	1	4	2
	Chess	1	1	5	5
	Reading	4	5	5	5
	Card games	3	3	4	5
	Solving Puzzles	2	5	5	5
Computer or video games	Shoot-em-up	5	5	5	5
	Adventure	3	5	3	5
	Role-playing	5	3	3	4
	Dynamic puzzle	3	3	4	5
	Simulation	3	3	4	3
Other			web surfing 5 programming 5		
What is your average pulse rate?		60-80	60-80 no idea	60-80	40-60 around 60?
Do you know how to control your pulse rate?		yes	yes activity	yes take a deep breath	yes
Comments regarding questionnaire					

Table 13 Heartball Session 4: The post-game questionnaire

Session		11/21/2002 4PM Score 254:377			
Player		1	2	3	4
Team Experience	Our team was stronger	3	3	5	2
	Our team knew how to control pulse	3	4	5	5
	Our team learned how to change pulse	3	5	5	5
	Other team knew how to control pulse	3	3	4	4
	Other team learned how to change pu	3	5	4	4
	Our team was more organized	3	3	5	5
	Our team was more cooperative	3	3	5	5
	Our team was more competitive	3	4	5	5
Your experience	I enjoyed the game	4	5	5	4
	The game is relaxing	1	1	1	3
	The game is boring	2	1	1	3
	The game is easy to play	3	5	5	4
	The rules are poorly defined	3	2	1	2
	The game equipment works well	1	5	3	2
	I would play this game again	3	5	5	4
	The game is engaging	4	5	5	5
	Single-player game would be better	1	1	2	2
	The game is fun	4	5	5	4
	I liked competing with the other team	4	5	5	4
	The game rules are good	4	4	5	3
	I would play this game with my friends	3	5	5	4
	I learned more about my heart	1	5	4	2
	The game is dangerous for my health	3	1	1	1
	This is a physically active game	4	5	4	4
	I can easily control my pulse rate	1	2	3	2
	The game is stressful	5	1	1	2
	I don't want to know my pulse rate	2	1	1	2
	I liked collaborating with my teammate	4	5	5	5
	I liked to see heartbeat of other player	4	5	4	4
How to change rules or setup to make game more interesting?		a better working infrared interface	Additional rules w/ more action.	Not allow the system to let one team go again (so it knows it must go A-B-A-B)	pulse readings a bit flakey -> results in gaming the system to get points
What is your average pulse rate?		80-100	60-80	80-100	60-80 70
Do you know how to voluntarily affect your pulse rate?		maybe	yes	yes	yes
Did you learn how to change your heart rate during tha game?		maybe	yes	yes	yes
Comments		Thanx! That was fun!	very interesting!		

Table 14 Heartball Session 5: The pre-game questionnaire

Session		12/05/2002 3PM Score 392:410			
Player		1	2	3	4
Age			21	21	22
Gender		m	m	m	m
Education		College	Some College	College	College
Employment		Student	Student	Student	Student
Computer use		Expert	Expert	Some knowledge	Expert
Computer games		Every day	1/week	2-3/week	Every day
Exercise	how often	Rarely	Rarely	2-3/week	1/week
	where	Home	In various locations on campus	DuPont Weight room/ wrestling room	Weight room
	ever used pulse monitor	no	no	no	yes
	type	Dance games	Low-intensity (walking); climbing/urban exploration	Aerobic, High-intensity, Weight-bearing	Weight-bearing
Fun	Football/Soccer/Rugby	3	1	5	5
	Baseball/Softball	3	2	3	4
	Tennis/Sqash/Racquetball	2	1	3	0
	Walking	4	4	3	3
	Jogging	4	4	4	3
	Chess	2	4	4	4
	Reading	2	5	5	4
	Card games	4	4	4	4
	Solving Puzzles	3	5	5	4
Computer or video games	Shoot-em-up	4	3	5	4
	Adventure	5	4	5	3
	Role-playing	3	5	5	3
	Dynamic puzzle	5	5	4	3
	Simulation	3	4	4	4
Other		Rhythm Games 5		Martial Arts 5	
		Platformer 4		Dancing 5	
		Survival Horror 4			
What is your average pulse rate?		100-120	60-80	60-80	60-80
Do you know how to control your pulse rate?		maybe	no	maybe	no
Comments regarding questionnaire					

Table 15 Heartball Session 5: The post-game questionnaire

Session		12/05/2002 3PM Score 392:410			
Player		1	2	3	4
Team Experience	Our team was stronger	2	3	4	5
	Our team knew how to control pulse	2	3	3	4
	Our team learned how to change pulse	4	4	4	3
	Other team knew how to control pulse	4	3	3	4
	Other team learned how to change pu	3	4	4	4
	Our team was more organized	4	3	4	2
	Our team was more cooperative	4	3	4	3
	Our team was more competitive	3	3	4	4
Your experience	I enjoyed the game	5	4	5	4
	The game is relaxing	3	3	4	1
	The game is boring	2	2	1	1
	The game is easy to play	2	4	4	3
	The rules are poorly defined	2	4	1	2
	The game equipment works well	2	2	3	2
	I would play this game again	4	4	4	4
	The game is engaging	4	3	4	4
	Single-player game would be better	2	1	1	2
	The game is fun	4	4	4	4
	I liked competing with the other team	4	4	4	4
	The game rules are good	4	3	4	4
	I would play this game with my friends	3	4	4	4
	I learned more about my heart	4	4	3	4
	The game is dangerous for my health	1	3	2	2
	This is a physically active game	2	3	2	4
	I can easily control my pulse rate	4	2	4	2
	The game is stressful	2	3	3	4
	I don't want to know my pulse rate	2	2	1	1
	I liked collaborating with my teammate	2	4	4	5
	I liked to see heartbeat of other player	4	4	4	4
How to change rules or setup to make game more interesting?		Have the heart rate after 20 second count to the score.		define a little better the option of distraction	Adding other physical activities simultaneously
What is your average pulse rate?		80-100	60-80	60-80	100-120
Do you know how to voluntarily affect your pulse rate?		yes	maybe	yes	maybe
Did you learn how to change your heart rate during tha game?		yes	maybe	yes	yes
Comments				Fun game. It was engaging since it motivated players to see how high they can get their heart rate and how low they can drop it to get maximum points	

Table 16 Correlation of HeartBall questionnaire answers

	win	age	gender	computer games	how often	ever used pulse monitor	Football/Soccer/Rugby	Baseball/Softball	Tennis/Sqash/Racquetball	Walking	Jogging	Chess	Reading	Card games	Solving Puzzles	Shoot-em-up	Adventure	Role-playing	Dynamic puzzle	Simulation	know how to change pulse	Our team was stronger	Our team knew how to control pulse	Our team learned how to change pulse	Other team knew how to control pulse	Other team learned how to change pulse	Our team was more organized	Our team was more cooperative	Our team was more competitive	I enjoyed the game	The game is relaxing	The game is boring	The game is easy to play	The rules are poorly defined	The game equipment works well	I would play this game again	The game is engaging	Single-player game would be better	The game is fun	I liked competing with the other team	The game rules are good	I would play this game with my friends	I learned more about my heart	The game is dangerous for my health	This is a physically active game	I can easily control my pulse rate	The game is stressful	I don't want to know my pulse rate	I liked collaborating with my teammate	I liked to see heartbeat of other players	know how to change pulse
win																																																			
age	0.04																																																		
gender	-0.12	0.18																																																	
computer games	0.21	-0.25	-0.02																																																
how often	0.18	-0.17	0.10	-0.27																																															
ever used pulse monitor	-0.14	0.00	-0.24	0.05	0.24																																														
Football/Soccer/Rugby	0.38	0.06	-0.14	0.19	0.45	0.25																																													
Baseball/Softball	0.07	-0.51	-0.08	0.23	0.54	0.32	0.41																																												
Tennis/Sqash/Racquetball	0.15	0.06	0.16	-0.19	0.41	-0.04	0.45	0.35																																											
Walking	-0.23	-0.06	0.39	-0.30	0.05	-0.12	-0.23	-0.19	0.17																																										
Jogging	0.13	-0.33	0.22	0.02	0.46	-0.05	0.23	0.28	0.12	0.04																																									
Chess	0.53	-0.13	0.07	0.00	0.14	0.12	0.17	-0.02	0.27	0.02	0.37																																								
Reading	0.16	-0.25	0.21	-0.28	0.11	-0.26	-0.17	0.00	0.01	-0.11	0.28	0.33																																							
Card games	0.47	-0.31	-0.07	0.45	-0.34	-0.52	-0.21	-0.06	-0.26	-0.22	-0.10	0.28	0.22																																						
Solving Puzzles	0.23	-0.28	-0.06	0.06	-0.24	-0.05	-0.38	-0.01	-0.18	-0.32	0.03	0.49	0.63	0.44																																					
Shoot-em-up	0.17	-0.16	-0.32	0.21	-0.16	-0.07	-0.04	0.26	-0.02	-0.07	-0.49	-0.35	-0.15	0.26	0.06																																				
Adventure	-0.23	-0.18	-0.45	0.32	-0.42	0.13	-0.04	0.13	-0.07	-0.24	-0.32	-0.15	-0.21	0.12	0.21	0.54																																			
Role-playing	-0.04	-0.33	-0.52	0.17	-0.14	-0.12	0.20	0.19	-0.02	-0.44	-0.17	-0.08	0.01	0.28	0.15	0.47	0.58																																		
Dynamic puzzle	-0.37	-0.38	0.15	0.10	-0.05	-0.04	-0.20	0.34	0.15	0.16	0.17	0.18	0.13	0.16	0.39	0.01	0.25	0.16																																	
Simulation	0.17	0.02	0.00	-0.13	0.32	0.43	-0.06	0.14	-0.01	0.29	-0.01	0.19	-0.18	-0.26	0.12	0.17	-0.19	-0.19	0.09																																
know how to change pulse	-0.19	-0.01	0.18	-0.03	-0.04	-0.08	0.07	0.33	0.44	-0.05	-0.45	-0.25	-0.12	-0.08	0.05	0.43	0.31	0.24	0.32	-0.02																															
Our team was stronger	0.48	0.00	-0.08	0.07	0.26	0.36	0.50	0.24	0.37	0.06	0.22	0.37	-0.03	-0.30	0.01	0.06	-0.21	-0.05	-0.20	0.54	0.00																														
Our team knew how to control pulse	0.27	0.09	-0.07	-0.08	0.17	0.26	0.16	0.40	0.57	0.07	-0.12	0.28	0.01	-0.17	0.21	0.19	-0.05	-0.12	0.20	0.44	0.36	0.65																													
Our team learned how to change pu	0.19	-0.32	0.07	0.19	-0.09	-0.21	0.07	0.50	0.39	0.16	0.13	0.08	0.19	0.13	0.29	0.37	0.27	0.04	0.37	0.05	0.39	0.35	0.59																												
Other team knew how to control pul	0.00	-0.27	0.05	0.09	0.18	0.18	0.22	0.56	0.48	0.33	0.16	0.19	-0.11	-0.15	0.05	0.07	0.00	-0.08	0.53	0.30	0.35	0.50	0.75	0.67																											
Other team learned how to change	0.09	-0.03	0.00	0.03	-0.06	0.03	0.12	0.32	0.30	0.25	-0.11	0.04	0.00	-0.13	0.19	0.30	0.10	0.03	0.33	0.40	0.41	0.58	0.78	0.76	0.81																										
Our team was more organized	0.38	0.08	-0.09	0.06	0.04	-0.21	0.36	0.25	0.46	-0.31	0.16	0.19	0.16	0.14	0.22	0.28	0.03	0.24	0.28	0.00	0.29	0.33	0.39	0.41	0.26	0.31																									
Our team was more cooperative	0.24	-0.07	-0.05	0.00	0.23	0.23	0.46	0.49	0.58	-0.10	0.23	0.29	0.10	-0.20	0.20	0.20	0.10	0.06	0.40	0.24	0.35	0.51	0.54	0.51	0.51	0.44	0.82																								
Our team was more competitive	0.34	-0.20	-0.20	0.20	0.03	0.17	0.36	0.57	0.30	-0.45	0.01	0.15	0.23	0.11	0.41	0.51	0.32	0.39	0.27	0.10	0.45	0.43	0.49	0.57	0.37	0.45	0.76	0.80																							
I enjoyed the game	0.14	-0.16	-0.24	0.30	-0.07	0.16	0.43	0.43	0.48	-0.13	0.09	0.10	-0.16	-0.19	0.13	0.27	0.36	0.26	0.26	0.16	0.42	0.65	0.62	0.69	0.65	0.70	0.56	0.71	0.67																						
The game is relaxing	0.13	-0.03	-0.22	0.01	0.36	0.10	0.42	0.41	0.39	-0.06	0.54	0.19	-0.01	-0.24	0.00	-0.06	0.22	0.06	0.24	0.12	-0.17	0.25	0.25	0.40	0.32	0.25	0.40	0.53	0.29	0.46																					
The game is boring	0.07	-0.16	-0.47	-0.08	-0.12	0.07	0.31	0.29	0.33	-0.01	-0.23	0.11	-0.30	0.12	-0.09	0.36	0.49	0.48	0.22	-0.05	0.32	0.01	0.17	0.28	0.23	0.16	0.29	0.39	0.37	0.36	0.29																				
The game is easy to play	0.18	-0.33	0.02	0.09	-0.08	-0.01	-0.02	0.37	0.31	0.15	-0.09	0.19	0.21	0.05	0.43	0.35	0.25	0.07	0.27	0.33	0.46	0.47	0.64	0.83	0.56	0.76	0.20	0.41	0.49	0.65	0.15	0.23																			
The rules are poorly defined	0.04	0.14	-0.02	-0.32	0.28	-0.02	0.33	0.29	0.11	-0.06	0.26	-0.15	-0.05	-0.31	-0.22	-0.16	-0.41	-0.01	0.05	0.24	0.04	0.29	0.23	0.16	0.25	0.33	0.36	0.36	0.23	0.24	0.33	0.20	0.08																		
The game equipment works well	0.23	0.08	-0.04	-0.22	-0.17	-0.12	0.08	-0.18	0.21	0.41	0.09	0.15	0.10	-0.22	0.07	0.06	0.05	-0.21	-0.18	0.09	0.00	0.50	0.37	0.52	0.39	0.57	0.09	0.20	0.10	0.44	0.24	0.07	0.46	0.04																	
I would play this game again	0.22	0.28	-0.03	0.20	-0.12	0.05	0.41	0.24	0.38	-0.24	0.05	0.07	-0.15	-0.20	0.06	0.16	0.13	0.14	0.10	0.16	0.35	0.64	0.63	0.56	0.50	0.69	0.63	0.61	0.62	0.83	0.38	0.17	0.48	0.44	0.37																
The game is engaging	0.37	-0.07	-0.21	0.27	-0.11	0.00	0.40	0.39	0.55	-0.21	-0.08	0.18	0.00	0.05	0.21	0.30	0.21	0.18	0.15	0.00	0.46	0.59	0.75	0.73	0.63	0.70	0.63	0.65	0.70	0.88	0.28	0.34	0.68	0.18	0.42	0.79															
Single-player game would be better	0.18	-0.03	0.37	0.14	0.00	0.01	0.51	0.30	0.29	0.13	0.20	0.22	-0.08	-0.01	-0.09	-0.05	-0.08	-0.03	0.26	-0.02	0.37	0.33	0.18	0.38	0.48	0.38	0.36	0.51	0.42	0.42	0.12	0.34	0.24	0.38	0.26	0.46	0.37														
The game is fun	0.33	0.01	-0.13	0.24	-0.10	-0.02	0.46	0.38	0.48	-0.20	0.07	0.05	-0.06	-0.09	0.05	0.27	0.16	0.21	0.01	0.05	0.34	0.67	0.63	0.72	0.54	0.69	0.61	0.61	0.67	0.89	0.40	0.31	0.61	0.40	0.47	0.90	0.89	0.46													
I liked competing with the other tea	0.40	0.10	-0.28	0.18	-0.11	0.02	0.43	0.21	0.44	-0.18	0.04	0.13	-0.13	-0.12	0.01	0.24	0.16	0.15	-0.15	0.11	0.18	0.71	0.61	0.60	0.40	0.59	0.55	0.54	0.55	0.83	0.39	0.30	0.57	0.32	0.50	0.85	0.86	0.24	0.92												
The game rules are good	0.20	-0.14	0.06	0.22	0.03	-0.07	0.37	0.32	0.40	0.20	0.10	0.06	-0.13	-0.12	-0.05	0.27	0.00	0.10	0.18	0.25	0.40	0.70	0.59	0.65	0.71	0.79	0.45	0.50	0.46	0.78	0.15	0.11	0.63	0.29	0.49	0.74	0.76	0.49	0.75	0.72											
I would play this game with my frien	0.24	0.18	-0.05	0.25	-0.12	0.06	0.25	0.23	0.35	-0.24	-0.02	0.15	0.02	-0.10	0.23	0.17	0.13	0.08	0.11	0.21	0.28	0.61	0.70	0.60	0.45	0.69	0.52	0.51	0.55	0.76	0.29	0.03	0.64	0.27	0.28	0.89	0.81	0.16	0.81	0.84	0.71										
I learned more about my heart	0.00	-0.05	0.13	0.29	-0.34	-0.03	-0.14	0.08	-0.01	0.26	0.02	0.05	-0.10	-0.02	0.24	0.09	0.05	-0.17	0.34	0.33	0.17	0.46	0.55	0.65	0.68	0.83	0.14	0.22	0.21	0.60	0.09	-0.12	0.64	0.17	0.50	0.63	0.55	0.29	0.55	0.51	0.73	0.66									
The game is dangerous for my hea	0.00	-0.69	-0.56	-0.05	0.09	0.16	0.05	0.26	0.03	-0.11	0.05	0.19	0.16	0.13	0.26	0.04	0.11	0.51	0.16	0.06	-0.04	0.18	0.11	0.04	0.23	0.09	-0.03	0.06	0.17	0.22	0.00	0.34	0.19	0.04	0.01	-0.16	0.16	-0.09	0.09	0.04	0.04	-0.14	-0.06								
This is a physically active game	0.17	0.11	0.00	0.04	-0.23	-0.02	0.31	0.13	0.40	-0.12	-0.22	0.13	0.18	-0.03	0.15	0.06	-0.09	0.10	0.09	-0.09	0.41	0.51	0.64	0.47	0.50	0.64	0.48	0.45	0.51	0.61	-0.09	0.16	0.50	0.31	0.33	0.69	0.80	0.43	0.72	0.65	0.65	0.70	0.50	0.14							
I can easily control my pulse rate	0.25	-0.26	0.05	0.21	0.15	-0.13	0.33	0.29	0.28	-0.08	0.49	0.30	0.07	0.06	0.27	-0.18	-0.14	0.00	0.42	0.10	0.15	0.41	0.31	0.41	0.58	0.44	0.55	0.56	0.40	0.60	0.41	0.02	0.25	0.34	0.30	0.48	0.50	0.54	0.48	0.33	0.53	0.30	0.46	0.24	0.33						
The game is stressful	0.11	-0.28	-0.41	-0.05	0.23	0.29	0.40	0.16	0.20	0.21	-0.16	0.16	-0.23	-0.11	-0.19	0.03	-0.15	0.23	0.03	0.38	0.04	0.45	0.28	-0.05	0.37	0.30	0.00	0.16	0.03	0.28	-0.02	0.38	0.19	0.27	0.07	0.04	0.24	0.14	0.15	0.19	0.35	0.05	0.10	0.64	0.31	0.20					
I don't want to know my pulse rate	-0.07	-0.29	-0.56	-0.23	-0.06	0.14	0.11	0.14	0.30	0.15	-0.08	0.13	-0.10	-0.03	0.01	0.19	0.21	0.34	0.34	0.05	0.06	0.12	0.24	0.12	0.35	0.17	0.34	0.43	0.27	0.33	0.23	0.68	0.05	0.15	0.15	0.02	0.27	0.10	0.18	0.16	0.11	-0.09	-0.05	0.65	0.21	0.23	0.57				
I liked collaborating with my teamm	0.25	0.33	-0.02	-0.09	0.12	0.11	0.27	0.26	0.37	0.02	-0.15	0.02	0.03	-0.22	0.03	0.33	-0.11	0.01	0.05	0.42	0.28	0.64	0.81	0.48	0.54	0.78	0.50	0.49	0.51	0.52	0.23	0.05	0.46	0.43	0.33	0.75	0.62	0.19	0.65	0.63	0.65	0.77	0.53	-0.15	0.65	0.18	0.20	0.06			
I liked to see heartbeat of other play	0.13	-0.29	-0.03	0.36	-0.21	-0.24	0.29	0.38	0.26	-0.06	0.11	0.02	0.17	0.15	0.18	0.22	0.21	0.25	0.29	-0.16	0.33	0.39	0.43	0.81	0.58	0.71	0.43	0.41	0.54	0.75	0.24	0.18	0.69	0.25	0.39	0.68	0.79	0.44	0.78	0.69	0.78	0.71	0.67	0.13	0.72	0.47	0.14	0.07	0.49		
know how to change pulse	0.17	0.03	-0.10	-0.11	0.15	-0.12	0.27	0.30	0.28	-0.19	0.18	0.03	-0.04	-0.10	0.19	0.20	0.07	0.17	0.31	0.14	0.48	0.33	0.43	0.42	0.51	0.53	0.65	0.60	0.58	0.58	0.33	0.19	0.28	0.43	0.32	0.62	0.54	0.45	0.51	0.42	0.58	0.41	0.38	0.00	0.35	0.71	0.03	0.19	0.46	0.40	
learned how to control pulse	0.37	-0.09	0.14	0.34	-0.03	-0.28	0.17	0.38	-0.10	-0.09	0.02	-0.18	0.00	0.31	0.11	0.53	0.08	0.08	0.13	0.15	0.34	0.19	0.18	0.58	0.26	0.48	0.42	0.33	0.54	0.34	0.10	0.07	0.44	0.33	0.15	0.46	0.39	0.46	0.45	0.34	0.54	0.40	0.44	-0.30	0.23	0.32	-0.14	-0.26	0.42	0.56	0.52
MAX	0.53	0.33	0.39	0.45	0.54	0.43	0.51	0.57	0.58	0.41	0.54	0.49	0.63	0.44	0.43	0.54	0.58	0.51	0.53	0.54	0.48	0.71	0.81	0.83	0.81	0.83	0.82	0.80	0.70	0.89	0.41	0.68	0.69	0.44	0.50	0.90	0.89	0.54	0.92	0.84	0.78	0.77	0.67	0.65	0.72	0.71	0.57	0.19	0.49	0.56	0.52
MIN	-0.37	-0.69	-0.56	-0.32	-0.42	-0.52	-0.38	-0.19	-0.26	-0.45	-0.49	-0.35	-0.30	-0.31	-0.22	-0.18	-0.41	-0.21	-0.20	-0.16	-0.17	0.01	0.11	-0.05	0.23	0.09	-0.03	0.06	0.03	0.22	-0.09	-0.12	0.05	0.04	0.01	-0.16	0.16	-0.09	0.09	0.04	0.04	-0.14	-0.06	-0.30	0.21	0.18	-0.14	-0.26	0.42	0.40	0.52

Shades of red (from dark to light) correspond to statistical significance p=0.001, p=0.01, p=0.05.

APPENDIX F – BREATHING PAC-MAN GAME RULES

Breathing Pac-Man is a one-player computer game. The objective is to get as many points as possible in a 12-minute period. To get points the Pac-Man controlled by your breathing has to eat pills. The pills grow or shrink depending on the amplitude of change of your heart rate. To be successful in the game you have to make the pills as big as possible. Each pill gives you the number of points equal to its size. Color or position of the pill does not matter.

To achieve a good result you have to learn how to breathe to change your heart rate. For example, you can try to change the rhythm or depth of your breathing to see what works best. The red label on top of the game window helps you to see your heart rate change from heartbeat to heartbeat. For example, if it says "Pulse change: -9" your heart rate has just slowed down by 9 beats per minute. When you successfully increase the amplitude of heart rate changes the pills will grow.

The Pac-Man moves up or down depending on your breathing. When you inhale it moves up; when you exhale it moves down.

Please remember that this game is under development. This is one of the first test runs of the game. Please excuse possible glitches in the game system. Your comments are very important for the future development of games of this kind.

APPENDIX G – BREATHING PAC-MAN INFORMED CONSENT AGREEMENT

Title of Study: Every Sign of Life

Principal Investigators: Vadim Gerasimov, Walter Bender

Participation in this research is voluntary. I understand that I am free to withdraw my participation at any time without prejudice.

This research explores the role of fun in improving health-awareness of people. The purpose of the experiments is to investigate how generally healthy people can benefit from collecting their own physiological parameters in real time and over long periods of time and exploring these data with software designed for their entertainment.

Procedure

In this study we evaluate a computer game based on real-time health information of the player. You will be asked to participate in the game and fill out questionnaires before and after the game. If you have any questions, at any point during the experiment, the experimenter will answer them.

Commitment

I understand that by agreeing to participate in this experiment, I will be asked to wear a health monitor during the experiment.

I understand that the health monitor will measure and store my electrocardiogram and respiration.

I understand that the information given to the investigators will be kept private and my identity will not be disclosed in the published results of the research.

I understand that my participation in this experiment includes taking part in a game and filling out questionnaires.

I understand that I may decline a request to participate in an individual activity, yet continue to participate in the experiment.

Medical Issues

I understand that the data collected by the device as well as any information derived from these data by any means are intended for my entertainment and education only and should not be interpreted as medical advice or used for self-diagnostics without consulting with a medical doctor.

I certify that to the best of my knowledge I do not have any pre-existing health problems or medical conditions that could make my participation in the experiments harmful for me or anybody else.

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the M.I.T. Medical Department, including first aid emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available; or providing it, does not imply that such injury is the Investigator's fault. I also understand that by my participation in this study I am not waiving any of my legal rights.

Questions

I understand that I may address any concerns or questions to either Vadim Gerasimov (vadim@media.mit.edu, 617-253-5127) or Walter Bender (walter@media.mit.edu, 617-253-7331).

I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T. 617-253-6787, if I feel I have been treated unfairly as a subject.

Limitations

I understand participation in this research project is voluntary and I am free to withdraw my consent at any time without prejudice. I further understand that, either before or after my withdrawal, I may request the deletion of any portion of any data I contribute.

Signatures

By signing two copies of this document I agree to participate in the described experiment. The first copy will be given to me; the second copy will be kept by the principal investigators.

I have read this document and agree to participate in the described experiment.

---	----------------------------------	----------------------
Print Name	Signature	Date

Subject's participation in the experiment confirmed and approved.

---	----------------------------------	----------------------
Principal Investigator's Name	Signature	Date

APPENDIX H – BREATHING PAC-MAN QUESTIONNAIRE BEFORE THE GAME

Age: __________________

Gender: F __ M __

What is your education level?

(a) __ Up to high school (c) __ College
(b) __ Some college (d) __ Graduate degree

What is your employment status?

(a) __ Part-time (c) __ Unemployed (e) __ Student
(b) __ Full-time (d) __ Retired (f) __ Homemaker

How acquainted are you with the use of computers:

(a) __ None at all (b) __ Some knowledge (c) __ Expert

How often do you play computer or video games:

(a) __ Never
(b) __ Rarely
(c) __ Once a week
(d) __ Two or three time per week
(e) __ Every day

Exercise practices:

How often do you exercise?

(f) __ Never
(g) __ Rarely
(h) __ Once a week
(i) __ Two or three time per week
(j) __ Every day

Where do you usually exercise? ____

Have you ever used a pulse monitoring device during exercise?

__ Yes __ No

What type of exercise?

(a) __ Low intensive level exercise (e.g. walking)
(b) __ Follow a supervised exercise program
(c) __ Aerobic exercise
(d) __ High-intensity exercises
(e) __ Weight-bearing exercises
(f) __ High-resistance exercise
(g) __ Others (explain):____

Please rate how much you enjoy engaging in these activities (not including watching or attending games):

	Never Tried	Dislike Strongly		Neutral		Enjoy Strongly
Football/Soccer/Rugby	0	1	2	3	4	5
Baseball/Softball	0	1	2	3	4	5
Tennis/Squash/Racquetball	0	1	2	3	4	5
Walking	0	1	2	3	4	5
Jogging	0	1	2	3	4	5
Chess	0	1	2	3	4	5
Reading	0	1	2	3	4	5
Card Games	0	1	2	3	4	5
Solving Puzzles	0	1	2	3	4	5
Computer or video games:						
Shoot-em-up Games	0	1	2	3	4	5
Adventure Games	0	1	2	3	4	5
Role-playing Games	0	1	2	3	4	5
Dynamic Puzzle Games	0	1	2	3	4	5
Simulation Games	0	1	2	3	4	5
Other games or activities you like/dislike:						
________________________		1	2	3	4	5
________________________		1	2	3	4	5
________________________		1	2	3	4	5
________________________		1	2	3	4	5
________________________		1	2	3	4	5

What is your average pulse rate (if not sure try to guess)?

___ 40 or less

___ 40-60

___ 60-80

___ 80-100

___ 100-120

___ 120 or more

Do you know how to voluntarily affect your pulse rate?

___ Yes ____

___ Maybe

___ No

Please write any comments regarding this questionnaire:

____

____

____

____

APPENDIX I – BREATHING PAC-MAN QUESTIONNAIRE AFTER THE GAME

Please rate your experience with the game:

	Strongly Disagree		Neutral		Strongly Agree
I enjoyed the game	1	2	3	4	5
The game is relaxing	1	2	3	4	5
The game is boring	1	2	3	4	5
The game is easy to play	1	2	3	4	5
The rules are poorly defined	1	2	3	4	5
The game equipment works well	1	2	3	4	5
I would play this game again	1	2	3	4	5
The game is engaging	1	2	3	4	5
Multi-player game would be better	1	2	3	4	5
The game is fun	1	2	3	4	5
I learned how to change size of pills	1	2	3	4	5
The game rules are good	1	2	3	4	5
I could easily move pacman up and down	1	2	3	4	5
I learned more about my breathing	1	2	3	4	5
The game is dangerous for my health	1	2	3	4	5
I felt dizzy during game	1	2	3	4	5
Pill size changed unpredictably	1	2	3	4	5
The game is stressful	1	2	3	4	5
I felt frustrated during game	1	2	3	4	5

How would you change the rules or setup to make the game more interesting?

____

____

Do you know how to voluntarily affect your pulse rate?

___ Yes ___ Maybe ___ No

Did you learn how to change you heart rate during the game?

___ Yes ___ Maybe ___ No

Please write any other comments or recommendation regarding the game:

____

____

____

____

APPENDIX J – BREATHING PAC-MAN QUESTIONNAIRE ANSWERS

Table 17 Breathing Pac-Man questionnaire answers

		1	2	3	4	5	6	7	8	9	10	11	12
Player		1	2	3	4	5	6	7	8	9	10	11	12
Score		2637	2736	2791	1445	1995	2686		2562	1834			
Place		4	2	1	8	6	3		5	7	Control	Control	Control
Age		25	26	36	33	31	24	47	28	25	21	29	37.5
Gender		m	m	f	m	m	f	m	m	f	m	f	m
Education		Grad	Grad	Grad	Grad	Grad	Grad	Grad	Grad	Grad	College	Grad	Grad
Employment		Student	Student	Homemaker	Full-time	Part-time	Student	Unemployed	Student	Student	Student/Part-time	Student	Student
Computer use		Expert	Some knowledge	Some knowledge	Expert	Expert	Some knowledge	Expert	Expert	Expert	Expert	Expert	Some knowledge
Computer games		Rarely	Rarely	Rarely	Rarely	Never	Rarely	Rarely	1/week	Never	Rarely	1/week	Never
Exercise	how often	Rarely	1/week	2-3/week	1/week	1/week	2-3/week	2-3/week	2-3/week	Every day	Every day	2-3/week	2-3/week
	where	where appropriate	outside	outdoors	MIT Gym	apartment gym	indoors	indoors-basement	gym	Gym, Park	MIT Boat house	MIT gym outside if warm	gym
	ever used pulse monitor	no	no	no	yes	no	no	yes	yes	no	yes	yes	no
	type	Low intensive, Aerobic, Bicycling	Aerobic	Low intensive, Swimming	Aerobic, Weight-bearing, Sports		Low intensive, Yoga	Aerobic, Weight-bearing, Tae-bo	Aerobic, Weight-bearing	Aerobic	Supervised exercise program, Aerobic, high-intensity	low intensive, Aerobic, high-intensity, yoga	Weight-bearing
Fun	Football/Soccer/Rugby	4	4	3	4	5	5	4	4	5	5	2	3
	Baseball/Softball	0	4	3	5	0	3	5	2	3	4	2	3
	Tennis/Sqash/Racquetball	4	4	4	5	3	3	5	2	5	5	0	4
	Walking	5	4	5	3	3	5	5	4	5	3	5	4
	Jogging	0	4	3	2	3	4	4	4	5	2	5	3
	Chess	5	4	3	4	0	2	3	3	4	3	4	2
	Reading	5	4	5	3	4	4	5	5	5	4	5	4
	Card games	4	4	4	4	3	2	5	3	2	3	4	3
	Solving Puzzles	3	3	5	3	3	3	5	3	4	5	5	2
Computer or video games	Shoot-em-up	4	4	1	3	3	4	3	2	0	4	3	2
	Adventure	4	4	5	3	4	3	3	5	0	4	5	2
	Role-playing	4	4	3	3	3	5	2	5	0	2	4	3
	Dynamic puzzle	4	2	4	3	3	4	5	3	0	3	5	3
	Simulation	4	3	4	3	3	3	2	3	0	1	2	4
Other						Field hockey 4 Dancing 4 Watching sports 5	Dancing 5	Bicycle riding 5 Hiking 5 Birding 5		Rock climbing 5 Martial arts 5 Dancing 5	Rowing 5 Backpacking 5 Rock Climbing 5	yoga 5 writing 5 cooking 5	Bicycle 4 Skiing 4 Sailing 4
What is your average pulse rate?		80-100	60-80	60-80	40-60	60-80	100-120	60-80	100-120	80-100	60-80	60-80	guess 40-60
Do you know how to control your pulse rate?		maybe	yes do something aerobic	yes	yes Relaxation combined with slow regular breathing	no	yes Breathing	yes Breathing/ relaxation	maybe	yes	maybe	yes e.g. jump up and down. Get very upset or excited.	no
Comments regarding questionnaire		it's a bit long!							Hello.				
								not submitted					
Your experience	I enjoyed the game	2	4	5	2	5	5		4	5	4	4	3
	The gameis relaxing	1	4	4	3	2	3		4	1	3	1	3
	The game is boring	3	3	2	5	1	1		2	1	4	5	3
	The game is easy to play	4	5	5	4	1	4		2	5	5	2	2
	The rules are poorly defined	2	3	1	3	1	1		4	1	2	5	4
	The game equipment works well	5	5	5	5	5	5		5	5	4	3	2
	I would play this game again	3	5	5	1	4	5		3	5	4	1	2
	The game is engaging	2	5	5	2	5	5		3	5	3	1	3
	Multi-player game would be better	4	5	1	4	5	5		3	3	3	3	4
	The game is fun	3	5	5	2	5	5		3	5	4	3	3
	I learned how to change size of pills (HR	5	5	4	5	4	5		4	3	3	3	4
	The game rules are good	4	3	5	3	4	5		2	5			2
	I could easily move pacman up and dow	4	5	5	4	5	3		5	5			
	I learned more about my breathing	4	5	5	3	4	4		4	4	4	1	4
	The game is dangerous for my health	3	1	1	3	3	1		1	1	1	1	1
	I felt dizzy during game	4	2	1	5	4	4		4	4	1	1	2
	Pill size (HR) changed unpredictably	2	2	4	2	1	4		4	1	2	2	3
	The game is stressful	2	1	1	2	4	3		3	4	1	4	2
	I felt frustrated during game	4	2	2	2	4	1		3	1	2	5	3
How to change rules or setup to make game more interesting?		make the game shorter; make results clearer - is this or that score/behavior good	less time (5:00 min) more information about heart rate		12 minutes is too long to do the same thing. Having levels/stages or other challenges would be nice. "super pill" -one worth more obstacles - ways of loosing points	I would make it easier to see the pulse variation and pill sizes all together. They should be next to each other.	I would not change the rules, but sometimes it was difficult to eat the pills, I guess I was not well positioned, but it seemed to me that I was.		better visual relationship between heart+breathing				
Do you know how to voluntarily affect your pulse rate?		maybe	yes	yes	yes	yes	yes		maybe	maybe	maybe	yes	maybe
Did you learn how to change your heart rate during tha game?		maybe	yes	yes	no	yes	yes		maybe	maybe	maybe	yes	yes
Comments					In the final 2 minutes I dozed of momentarily. Partially due to sleep deprivation.		Music might engage you more like a tiny little sound when the pills are small & a drum sound when the pills are huge			I thought I knew how to control my pulse rate but sometimes I could not make the pills grow	Some kind of feedback that would give me knowledge to answer the two questions above.		