FAKULTÄT FÜR !NFORMATIK
Faculty of Informatics

Game-based Health Monitoring using Tangible User Interface Objects

DIPLOMARBEIT

zur Erlangung des akademischen Grades

Diplom-Ingenieurin

im Rahmen des Studiums

Medieninformatik

eingereicht von

Marianne Ternek
Matrikelnummer 0825379

an der
Fakultät für Informatik der Technischen Universität Wien

Betreuer: Priv. Doz. Mag. Dr. Hannes Kaufmann
Mitwirkung: Dipl.-Ing. Emanuel Vonach, Bakk.

Wien, 20.01.2015

(Unterschrift Verfasserin) (Unterschrift Betreuer)

Technische Universität Wien
A-1040 Wien ▪ Karlsplatz 13 ▪ Tel. +43-1-58801-0 ▪ www.tuwien.ac.at

FAKULTÄT FÜR !NFORMATIK
Faculty of Informatics

Game-based Health Monitoring using Tangible User Interface Objects

MASTER'S THESIS

submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Media Informatics

by

Marianne Ternek
Registration Number 0825379

to the Faculty of Informatics at the Vienna University of Technology

Advisor: Priv. Doz. Mag. Dr. Hannes Kaufmann
Assistance: Dipl.-Ing. Emanuel Vonach, Bakk.

Vienna, 20.01.2015

(Signature of Author) (Signature of Advisor)

Erklärung zur Verfassung der Arbeit

Marianne Ternek
Brückengasse 8a, 1060 Wien

Hiermit erkläre ich, dass ich diese Arbeit selbständig verfasst habe, dass ich die verwendeten Quellen und Hilfsmittel vollständig angegeben habe und dass ich die Stellen der Arbeit - einschließlich Tabellen, Karten und Abbildungen -, die anderen Werken oder dem Internet im Wortlaut oder dem Sinn nach entnommen sind, auf jeden Fall unter Angabe der Quelle als Entlehnung kenntlich gemacht habe.

(Ort, Datum) (Unterschrift Verfasserin)

Danksagung

Zu aller erst möchte ich mich bei meinen engsten Freunden aus Wien, Graz und Preding, allen voran natürlich bei Josef, bedanken, die im letzten Jahr immer ein offenes Ohr für mich hatten und mich durch technische Kompetenz, Hilfestellung bei sprachlichen Hürden, handwerkliches Geschick, ermutigende Worte oder auch nur durch ihre unendliche Geduld unterstützt haben.

Weiters möchte ich den Menschen danken, die mich fachlich in den letzten 15 Jahren voran getrieben und mir das Thema Informatik Stück für Stück näher gebracht haben: angefangen bei meinem HTL-Professor Dipl.-Ing. Dr. Heinz Schiffermüller, der den grundlegenden Baustein für meine weitere berufliche und schulische Laufbahn gelegt hat, erfahrenen Arbeitskollegen wie Andreas Hauk, die nicht müde wurden mir bestimmte Programmierkonzepte immer und immer wieder zu erklären, motivierten Professoren und Professorinnen der TU Wien, die mir während meines Studiums immer wieder neue Aspekte der Informatik zeigen konnten, bis hin zu Dipl.-Ing. Emanuel Vonach, der mir während der gesamten Zeit, in der ich diese Diplomarbeit verfasst habe, immer tatkräftig zur Seite stand.

Abstract

Patients being monitored in hospitals often do not behave as in their daily life. Especially for children such examinations can lead to stress associated with the clinical visit and the exposure to a different environment. These influencing parameters can result in false readings and furthermore in incorrect diagnosis.

This circumstance could be overcome with an interface that offers a stress-reducing distraction by recording medical data in an unperceived way. For that purpose we designed a tangible user interface which acquires health values during a game most suitable for children.

To determine the requirements for such a tangible user interface one of the first steps is to identify the possible medical sensors that could be used in a tabletop game and which of them are able to record representative and comparable medical values. Furthermore these sensors and the required equipment for their correct usage needs to be adapted to fit the physical objects used as input and output devices for the designed interface.

The combination of these developed tangibles in a game that also satisfies children brought us to our finally implemented interface called “StoryCubes”: The tangibles - realized as wooden cubes - tell a story when held in a proper way, at the right time and for a certain duration. These restrictions are needed to enable the sensors to perform accurately and therefore one challenge during this master thesis lies in providing enough information to let the users know how to use them correctly. This so-called affordance is realized through feedback, appropriate constraints and the cube design itself.

After completing the hardware and software, our game concept is evaluated with 20 participants. The participating children were asked about usability issues, for example if they are able to comprehend the game logic and if they enjoy playing. The test with a number of adults on the other hand was mainly used for representative medical measurements and proof of concept. The results of this study are promising and show a high acceptance for this kind of user interfaces, but also give us some improvement suggestions for the future.

Kurzfassung

Die Interaktion zwischen Menschen und medizinischen Diagnose- bzw. Aufzeichnungsgeräten läuft meist nach strikten Mustern ab. Das ärztliche Instrument wird geeignet platziert, der Patient wartet eine bestimmte Zeit, bis dann die abschließenden Ergebnisse vorliegen und präsentiert werden. Vor allem für Kinder bedeuten solche Untersuchungen einen zusätzlichen Stressfaktor, wodurch Werte verfälscht werden und somit zu inkorrekten Diagnosen führen können. Durch die Verwendung einer intuitiven und anfassbaren Benutzerschnittstelle könnte dieses als „Weißkittelhypertonie“ bekannte Problem umgangen werden.

Ziel dieser Diplomarbeit ist es, verschiedene medizinische Messgeräte in eigens dafür entworfene physische Objekte geeignet zu verpacken und in einem Spiel miteinander zu kombinieren, um die Interaktion mit solchen Systemen zu erleichtern. So eine neuartige Benutzeroberfläche könnte eine gute Ergänzung oder sogar Alternative für die bis dato gebräuchlichen Verfahren darstellen.

Diese Grundidee führte uns zu unserem implementierten Spiel namens „StoryCubes“, welches im Zuge eines Spieldurchgangs eine bestimmte vordefinierte Geschichte wiedergibt. Dabei werden bei korrekter Anwendung durch medizinische Sensoren vom Benutzer unbemerkt Daten wie Temperatur, Pulsfrequenz oder Atemvolumen aufgezeichnet. Durch die Spiellogik an sich, soll klar definiert sein, welcher Teil der Benutzeroberfläche, an welcher Stelle, für welchen Zeitraum berührt oder mit Atemluft versorgt werden soll. Dazu weist jedes Eingabegerät einen geeigneten Aufforderungscharakter auf, um ein intuitives Spiel, das die Sensoren passend kombiniert, zu ermöglichen.

Ein im Anschluss an die Design- und Implementierungsphase durchgeführter Testlauf macht ersichtlich, ob diese Art der greifbaren Interaktion vor allem für Kinder und Jugendliche ausreichend motivierend und unterhaltsam ist. Zusätzlich zu der Benutzerstudie mit Kindern, wurde ein weiterer Test mit Erwachsenen veranlasst, der die medizinischen Sensoren bzw. die Verarbeitung ihrer Werte auf ihre Richtigkeit bzw. Vergleichbarkeit überprüft. Die Ergebnisse dieser Evaluierung sind sehr vielversprechend und zeigen eine hohe Akzeptanz solcher Benutzerschnittstellen auf. Gleichzeitig liefern sie aber auch Erkenntnisse, welche Bereiche noch einer Verbesserung bedürfen und welchen für zukünftige Projekte eine erhöhte Aufmerksamkeit zuteil werden sollte.

Contents

CHAPTER 1

Introduction

New computer interface approaches, like tangible interfaces, promote the integration of computing entities into our environment. The goal of so-called "Tangible User Interfaces" (TUI) is to create an intuitive and touchable user interface that enables the user to easily interact with different systems. The interaction is usually based on direct manipulation of physical objects, like surfaces, volumes, toys or everyday objects. These tangibles often function as both input and output devices and provide users with a lot of potential benefits such as: natural interaction, good affordance, distributed interaction, multiple physical configurations, two-handed input and spatial and haptic immediate feedback [SV08]. These characteristics enable tangibles to be deployed in a wide variety of disparate areas, like music creation [Ser10], storytelling [TTA10], education [ZAR05] or urban planning [UI99]. Because TUIs are an emerging field of research, the design space of TUIs is constantly evolving [SH10] and enters completely new application areas.

In the field of health monitoring such interfaces could also be an extension or maybe even an alternative to common methods and could simplify the measuring procedures. Medical devices that monitor for instance heart beat, body temperature or lung volume wrapped in one TUI could combine the previous mentioned advantages of tangible interfaces and an unconscious recording of vital signs.

One opportunity to realize this unconscious recording is to design the tangibles in a way that intuitively implies its functionality and use. This so-called "affordance" can be communicated by the design (e.g. shape or color) of the physical objects itself. The design of interface objects should also cover an adequate feedback to ensure that users know what to do next in their tasks, constraints to the possible usages and a certain extent of consistency, to ensure that similar operations use similar elements to achieve similar tasks [RSP12].

By adding playful interaction to the appearance considerations users can be guided to touch each tangible for a specific time and to intuitively take the correct steps to measure their own vital signs. In several studies it has been shown that the usage of game elements in non-gaming systems improved user experience and user engagement [DSN$^+$11]. Thereby game aspects could act as potential means to shape user behavior in directions intended by the system designer.

As a first step to implement a game-based tangible interface that monitors vital signs we are going to gather background information to get an overview of the state of the art in this field of work and use this information as theoretical foundation for the subsequent practical part. This part starts with analysing, realizing and implementing some selected medical sensors as tangible prototypes. Some possible sensors for this stage are: temperature, skin conductance, lung volume and heart rate. With these medical sensors a game is developed and therefore the tangibles have to be adapted to comply with the game play. The main focus in this stage is to design the tangibles with an appropriate affordance character to ensure an intuitive and correct handling. In the final step the developed prototype is tested during a user study. The results are analysed and further research topics are pointed out.

CHAPTER 2

Motivation

Usually the interaction between humans and medical devices adhere strictly to predefined patterns. After placing the medical equipment in a proper way at a specific part of the body and waiting a certain time period, the results are computed and finally presented to the patient. A well-known issue with this procedure is a possible bias in the resulting values, also known as "White Coat Syndrome" [BLRL11]. Patients being monitored in hospitals often do not behave as in their daily life, due to the stress associated with the clinical visit and the exposure to a different environment. Especially for children such examinations can also lead to a certain anxiety caused by the unknown medical staff. These influencing parameters can result in false readings and furthermore in incorrect diagnosis.

One possible way to reduce this stress is to relocate the examination to a known familiar environment. Since the usage of medical sensors, like infrared thermometers, pulse or blood pressure measuring devices, is getting more and more common, they also can be found in a large number of households, but none of the existing approaches offer any stress-reducing distraction. Consequently the user is fully aware of the measurement during the entire acquisition of data and with those measuring procedures a certain influence factor on the recorded values remains.

To deal with this problem the basic idea of this master thesis is to use tangibles for the measurements. Tangible user interfaces are used in different fields of application to benefit from natural interaction, but so far there is no interface that is designed to monitor vital signs. In most of the existing interfaces the position and orientation of the tangibles are tracked and used as input to trigger different events, but currently no further user data is measured by these tangible objects.

Within this master thesis different medical devices are placed inside tangible objects and are combined in a game play to unconsciously measure vital signs. The intuitive and easily understandable game mechanics should motivate the user to interact with them to facilitate health monitoring by providing a certain joyful distraction during the measurements. Where to hold a tangible and for how long, should be communicated in an unambiguous way through the game design. This requires that each tangible is designed in a way that users intuitively take the correct steps in the right order to accomplish their goals. Providing a proper affordance of the input devices is a major focus during the design phase.

In previous works the topic of game-based measurements of vital signs is not widespread. All approaches in this area do not analyse the recorded vital signs during the game, they just use them to control specific parts of the game. Therefore the proposed way of acquiring data can open a fully new view on health monitoring.

Thus, the envisioned goal of this thesis is to design a tangible user interface that monitors vital signs in a game-based way. Although this prototype is not intended to fulfil the standards or accuracy of common medical devices used in hospitals, it should open new perspectives in health monitoring.

CHAPTER 3

State of the art

To cover the topic of game-based health monitoring using tangible user interface objects, an extensive literature research was conducted, including different subareas. Each of these areas has innovative research results.

An early example of a tangible user interface, which helps to simplify the interaction with common problems, is the Urban Planning Workbench (Urp) [UI99] shown in Figure 3.1. Urp uses scaled physical models of architectural buildings to configure and control an underlying simulation of shadow, light reflection, wind flow and traffic congestion. Also included are a clock tool to change the position of the sun, a wind tool to change wind direction, and an anemometer to measure wind speed.

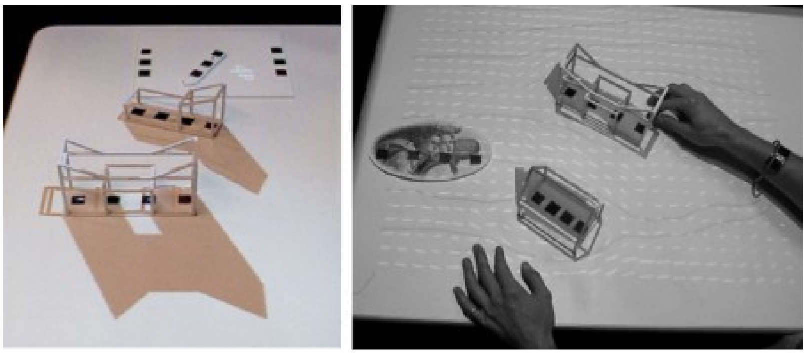


Figure 3.1: **Urp: an urban planning workbench.** [UI99]

But not only scaled physical models of real-world objects can be used as tangibles. Several research groups have also been working on the development of cube-based TUIs. Among the first who relied on cubes for TUI Suzuki et al. developed “AlgoBlocks” [SK95], a system that transforms the programming language “Logo” to the tangible domain. Blocks stand for commands, actions and arguments in physically connected sequences of cubes in order to define a program. After them, several works exploited the cube as a TUI volume, because of its proven cognitive abilities [SIW+02] and affordance for any user [SSVL+03]. The "Display Cube" introduced by Kranz et al. [KSHS05] uses the common shape of a cube that supports input by gesture recognition and output through six displays mounted at the sides of the cube. Zhi Ying et al. [ZCP04] explore the application of a 3D cube interface, complemented with augmented reality technology, to the field of interactive storytelling. Another example that uses cubes in an intuitive and direct way combined with a tangible playing area is the "reacTable" [Ser10]. This multiplayer tangible user interface enables the user to generate sound by moving physical objects across the table. Within this game each tangible has a dedicated function to generate or modulate sound, as can be seen in Figure 3.2.

Figure 3.2: **The Reactable.** [Ser10]

Tangibles could not only be used as input devices but also as output devices, for that purpose they require a certain kind of motor unit that can be controlled not only by the user but also by the interface itself. Brave et al. [SHA98] were the first in this field of actuated tangible user interfaces who introduced such a concept of synchronized distributed systems and their advantages for remote collaboration. They built a prototype consisting of two motorized chessboards, which control tangible objects placed on it and track objects that had been moved, this allows two participants to play with each other even if they are in different places. Another device, the "Actuated Workbench" [PMAI02], consists of electromagnets to move objects on a table in two dimensions. Some possible applications for this technology are in the field of entertainment or simulation and display for interacting objects.

A framework that offers an interface that enables researchers to easily extend and customize the principal structure of a tangible user interface is implemented by Vonach et al. [VGK14]. This project focuses on a flexible and modular design, which provides tracking, actuation mechanism and a proper communication protocol to allow the integration of different input and output devices. Therefore it is the basic concept for this master thesis and it's underlying system is described in detail in a later chapter where we concentrate on designing the tangibles (chapter 5.3.1).

Another field of application for TUIs is the usage of tangibles for entertainment purposes, like storytelling. Mazalek et al. [MWI01] created a tangible narrative system called "genieBottles" in which readers can open three glass bottles to release trapped genies which reveal fragments of narrative information. If more than one bottle is opened, the genies converse with each other. The physical bottles can be seen as a tangible interface for digital story information and wireless tag sensing technology is used to determine their open and closed states. Another example of a storytelling interface is the "Reading Glove" [TTA10]. Tanenbaum et al. present a wearable glove for tangible interactive storytelling, that focuses on the narrative meaning of physical objects. The "Reading Glove" allows interactors to extract stories from a collection of ten objects using natural grasping and gestures.

Furthermore there is research done to explore how playful tangible user interfaces can support the therapeutic progress of children with specific diseases. Li et al. [LFM08] present the design of a table-top game supporting the treatment of children with cerebral palsy. They aim to motivate children to practice specific skills and demonstrated that they are able to increase the duration of training sessions. TUIs can also offer advantages for people with autism. Sitdhisanguan et al. [SCDO08] evaluated the efficacy of tangible user interfaces for children with autism to support learning basic geometric shapes. The results show that the children who study with the TUI training system can learn more shapes than those studying with conventional treatment using window icon menus and pointing devices.

Shusong and Xia [SX10] developed a rehabilitation method for post-stroke patients by using the electrical signals transmitted to muscles to control a toy robot (Figure 3.3).

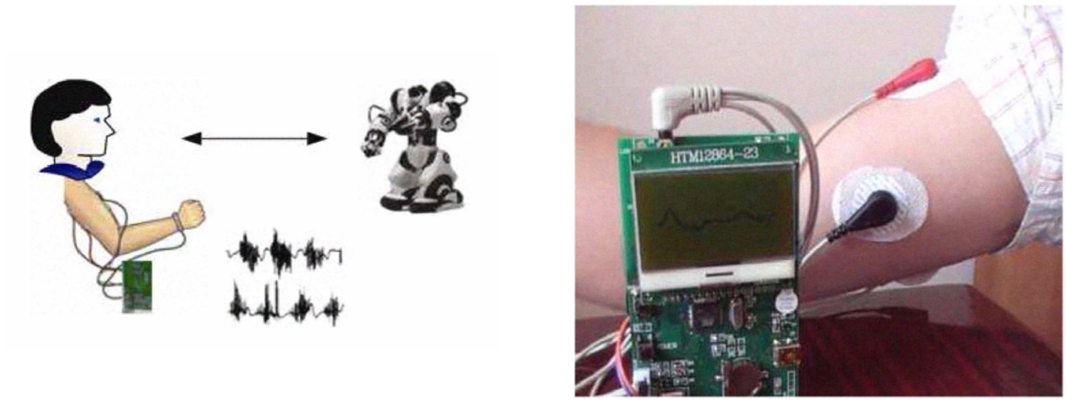


Figure 3.3: **Interaction between patient and computer game.** [SX10]

A similar method was discussed by Nenonen et al. [VAV^{+}07]. They took the heart rates of participants as input parameters for a physically interactive biathlon computer game. None of these examples consider health monitoring functionality.

In the field of medical sensors for home usage, the development goes far beyond blood pressure or temperature measurement devices. For example Lin et al. [YHLK11] mention a mobile blood pressure unit, which can be connected with common smartphones. For that matter the sensor is attached to the wrist and transmits the acquired data to the smartphone, which permanently saves the recordings and visualizes the results in a proper way.

Similar novel methods can be found in the domain of heart rate or temperature measurement. [DYFA11] or [VRS^{+}13] use cameras or microphones integrated in smartphones to recognize heart beats and produce results comparable to common medical devices.

There are also approaches that use TUIs in the field of clinical diagnosis of disease or injury. The "Cognitive Cubes" [SIW+02] for instance are an automated tool for examination of 3D spatial cognitive ability. Constructional deficits and disorders can be associated with brain lesion, Alzheimer's disease and other impairments. With "Cognitive Cubes" users attempt to construct a target 3D shape, while each change of shape they make is automatically recorded and scored for assessment.

A method to use medical sensors in an unperceived way, is to attach them to clothes or generally to the body. Jalaliniya et al. [ST12] designed a monitoring system for children to measure temperature and heart rate by so called "wearable sensors". However, they did not choose a suitable temperature sensor and were not able to estimate body core temperature.

One of the major drawbacks for wearable applications in the past has been the size of sensors and front-end electronics that made the hardware for gathering data too obtrusive to be suitable for long-term monitoring applications [PPB+12]. Recent developments in the field of micro-electronics allow the integration of sensing capability, front-end amplification, microcontroller functions and radio transmission in miniature circuits. The flexible circuit shown in Figure 3.4 is an example of such a technology [PPB+12].

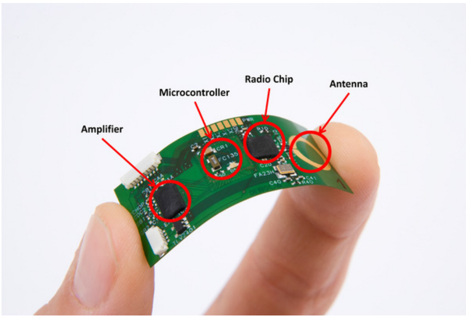


Figure 3.4: **Flexible wireless heart rate sensor.** [PPB+12]

CHAPTER 4

Medical considerations and sensing

On the following pages we present an overview of different medical devices, which can be integrated in game play. A main characteristic of the chosen sensors is their data-measuring ability in non-invasive ways to allow a mostly unnoticed medical examination. This means that during the measurement, it is not necessary to harm the skin and there is no contact with internal parts of the body. The identified vital signs, which comply with these requirements, and their possible measure methods will be discussed in this chapter.

4.1 Core body temperature and skin temperature

There is a variety of methods to measure body core temperature - it can be recorded from skin, oral, rectal or the eardrum [Jon10, Chapter 1]. Because of the fast and easy way of gathering temperature data by placing an infrared thermometer in the auditory canal, the latter has become very popular in recent years [CHH99]. Infrared (IR) sensors absorb and detect IR emissions given off by a heated surface. The main difficulty with this thermometry is to place the sensor on the warmest part of the ear to achieve an accurate reading of the body core temperature. This is an invasive measurement, so it is not applicable for the usage in a game play.

Nevertheless the acquiring of temperature data by infrared has considerable advantages for our envisioned goal compared to other technologies. For this reason our final approach is to measure the skin temperature on the hands and to estimate the core body temperature with that result.

4.1.1 Differences of skin and body core temperature

The human skin temperature is in general not equal to the core temperature. The most practical spot on the body giving the most reliable result, which is nearest to the body core temperature, is the area of the temporal artery. As a temperature measurement site, the temporal artery is easily accessible and usually quite visible. Because the temperature measured on the forehead is the temperature at the outer surface of the head, there has to be further calculations to approximate body core temperature. Therefore a technique that accounts for the radiated heat loss is employed by Pompei et al. [Pom10] known as arterial heat balance (AHB). The function includes a weighted difference of surface temperature T_s and ambient temperature T_a to calculate core temperature T_c:

$$T_c = k \cdot (T_s - T_a) + T_s \tag{4.1}$$

The constant coefficient *k* depends on the perfusion rate. In the area of the temporal artery *k* is about 0.09 to 0.13 [Pom10]. If hand perfusion also remains relatively constant, this equation can be adapted in a proper way to the palm of one's hand by adjusting the coefficient to the perfusion rate of hands or fingers.

The ambient temperature is not the only thing that can influence skin temperature and make it difficult to derive body core temperature. The skin radiates heat to control the internal temperature and is constantly adjusting the optimum balance between the physiologic demands of the body and external environmental conditions. Skin temperature is an effective indicator for objectively evaluating human sensations, because it is controlled by sympathetic nerve activity, which reflects the course of information processing in the brain. Generally speaking, human faces get hot from excitement and the fingertips get cold from tension [KKY$^+$98]. On the one hand these conditions have to be considered when measuring temperature on the base of skin temperature and on the other hand the recorded data can give additional information about psychological factors.

4.1.2 Suitability test

After comparing different infrared sensors, we finally choose the Melexis MLX90614 ESF DAA Infrared Sensor (Figure 4.2) as temperature measurement device for this project, which is suited for medical applications and has an accuracy of $\pm$ 0.1°C in a limited temperature range around the human body temperature. With infrared technology it is possible to acquire the surface temperature within seconds even if the sensor is not fully enclosed. The MLX90614 in particular takes one second to acquire the typical 33°C finger temperature. The field of view (FOV) of this sensor is 90°, which means that the sensor delivers the average temperature of a large area. Usually the field of view of infrared temperature devices is specified in a distance to spot ratio (D:S ratio). This ratio is the size of the area being evaluated by the infrared thermometer as it relates to distance. For example a 12:1 ratio, which is quite common for infrared temperature devices, means if the target is 1 cm in size the maximum distance to reliably measure the temperature of the target is 12 cm. The FOV information can be converted into the D:S ratio, for the MLX90614 this results in a 1:2 ratio. So with no further modifications the sensor will measure the mean temperature of an area of 2 cm if the target is just 1 cm away. The heat of objects very close to the sensor can influence the measured temperature. For that reason the hot target has to keep at a certain distance (2-3 cm) to avoid a bias of the measurements. This is why the FOV has to be narrowed to exclude the temperature of ambient surfaces in the recordings. To just measure a specific spot, a tube, lined with an infrared reflecting material (e.g. aluminum), is designed.

With this modification we measured different targets multiple times and compared the results with the infrared sensor Raytek Raynger ST30 as ground truth. The Raytek Raynger ST Pro models are common used noncontact thermometers and offer an accuracy of $\pm 1^{\circ}$ and a D:S ratio of 12:1. The average body core temperature of the test persons was measured by a commercially available digital thermometer under the armpit and was 36.4°C.

Target	MLX90614	Raytek Raynger ST30
Room ceiling	$26.1^{\circ}C$	$26.0^{\circ}C$
Palm of hand	$32.2^{\circ}C$	$33.1^{\circ}C$
Finger tip	$27.9^{\circ}C$	$28.9^{\circ}C$
Forehead	$34.1^{\circ}C$	$35.0^{\circ}C$

If we apply the arterial heat balance equation for the temperature measured with an infrared sensor on the forehead with a constant coefficient of 0.13 and an ambient temperature of 23.5°C, the measurement by infrared also results in 36.49°C body core temperature. This was the reason why we decided to use the MLX90614 infrared sensor for the estimation of body core temperature.

The ambient temperature used for the calculation of the arterial heat balance equation was measured by a digital contact temperature sensor (Dallas DS18B20) shown in Figure 4.1, which has been discarded for skin temperature readings. The reason for this was that due to the fact that contact sensors measure their own temperature, it takes up to 30 seconds until the observed temperature successively reaches its maximum. Because the sensor is not fully enclosed, even after this period of time, the measured temperature of the finger, which has a surface temperature of 33°C, does not get higher than 27°C. Nevertheless this digital sensor turned out to be ideal to measure the ambient temperature.

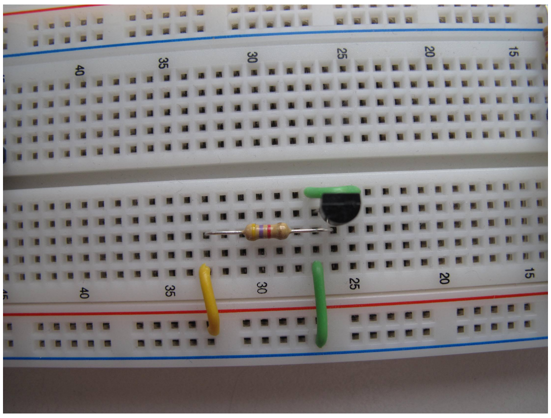


Figure 4.1: **Temperature Sensor DS18B20.**

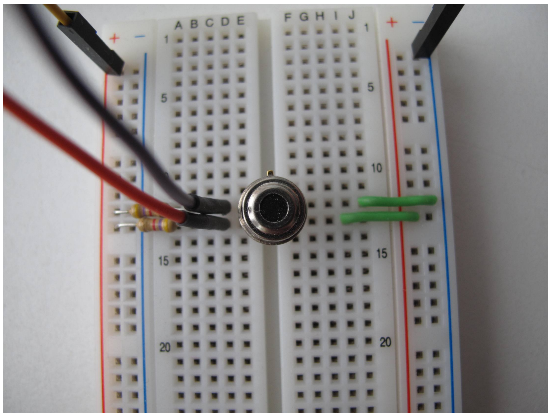


Figure 4.2: **Infrared Sensor MLX90614.**

4.2 Lung function

Spirometry is the most common way to measure the lung function of a patient, specifically the amount and speed of air that can be inhaled and exhaled. It is meant to illustrate the decline in function by asking the patient to breathe out the maximal volume possible with maximal effort. There are some parameters, which can be read from the shape of the resulting spirogram:

- Forced Vital Capacity (FVC): the total volume of air exhaled during the expiratory phase of the procedure.
- Forced Expiratory Volume After One Second (FEV1): the total volume of air exhaled after one second of the procedure.
- Peak Expiratory Flow (PEF): the maximum recorded flow during the course of the procedure.
- FEV1/FVC Ratio: the ratio of the FEV1 to the FVC of any procedure. An acceptable ratio for a healthy person is above 0.85.

With these values it is possible to detect the early onset of both restrictive and obstructive diseases (e.g. asthma) [SPNA11].

4.2.1 Measuring principles

There are different ways to monitor lung capacity. Turbine flowmeters for instance have a propeller built into the flow tube to record air flow by exciting the rotating elements and thereby interrupting or reflecting the light from a light-emitting diode (LED) [SK11]. One disadvantage of this approach is that the turbine is bearing a specific resistance, so it can only record data if a specific minimal speed is reached and additionally after exhalation the propeller is still spinning for a time distorting the resulting measurements.

Another possibility to measure PEF offer peak flowmeters. The classical mechanical peak flowmeter consists of a piston moving up in a flow tube when expiring. However, because of low accuracy in small dimensions, it is not suitable for our application [CTH+07].

A third alternative to record air flow is to deduce it from the measurement of the pressure drop in a tube during exhalation. These so called differential pressure flowmeters are cheap and easy to realize, because they require just a tube that creates a controlled pressure difference. This difference can be constituted by a inserted resistive element, like a bundle of capillaries (Fleisch Pneumotachometer) or a close-mesh screen (Lilly Pneumotachometer). These resistances aim to linearize the relationship between air flow and the differential pressure to facilitate simple and accurate pressure to flow calculations [FPP09]. Adversely with these flow-resistance elements the tube has to be cleaned after usage and needs frequent calibration.

It is also possible to achieve the required pressure drop by simply adjusting the form of the tube. This so called venturi tube is based on the observation made by Daniel Bernoulli, that if an annular restriction is placed in a pipeline, then the velocity of the fluid through the restriction is increased and the pressure at this section is decreased. Venturis have a quadratic pressure-flow relationship. One of the major advantages of the venturi tube is that the measurement uncertainty can be predicted without the need for calibration. In addition, this type of differential pressure flowmeter is simple, has no moving parts, and is therefore reliable [Tho99].

4.2.2 Bernoulli's Equation

The equation by Bernoulli defines the relationship between fluid velocity (v) and fluid pressure (p) above some fixed point for a fluid flowing through a pipe of varying cross-section. Bernoulli's equation states that [CTH+07]:

$$\frac{p_1}{\rho} + \frac{v_1^2}{2} + g \cdot z_1 = \frac{p_2}{\rho} + \frac{v_2^2}{2} + g \cdot z_2 \tag{4.2}$$

The gravitational acceleration (g) and the altitude of point i in respect to the sea (z_i) are constant. p_i is the pressure value in position i expressed in Pascal (Pa). v_i is the fluid speed in position i and ρ is the fluid density expressed in kg/m^3. After leaving parameters with constant values on both sides out, the equation looks like this:

$$\frac{v_2^2 - v_1^2}{2} = \frac{p_1 - p_2}{\rho} \tag{4.3}$$

Furthermore, for fluids like liquids and gases the volumetric flow rate q inside a closed tube with two different diameters d_1 and d_2 is defined as:

$$q = v_1 \cdot d_1^2 = v_2 \cdot d_2^2 \tag{4.4}$$

Combining the formula in 4.3 and 4.4 the flow rate can be calculated with the two different diameters of the venturi tube, a mean air fluid density of 1.3 kg/m^3 and the measured pressure difference:

$$q = d_1^2 \cdot \sqrt{\frac{2 \cdot (p_1 - p_2)}{\rho \cdot ((\frac{d_1}{d_2})^4 - 1)}} \tag{4.5}$$

4.2.3 Venturi Tube Design

After designing two prototypes of a venturi tube with modeling clay, we finally printed a 14.4 cm long venturi tube with a 3D printer. The 3D model (Figure 4.3) for this was created in the freeware modeling program SketchUp Make and complies with the standard specification of a venturi tube with the following additional modifications for spirometry:

- The diameter d_1 near the first tapping point is 2.1 cm and is chosen to fit standard spirometry mouthpieces. At the second point near the annular restriction the diameter d_2 is 1.6 cm. The angle values between the two diameters are 23° and 15° and were taken from standard venturi tube specifications (Figure 4.4).
- There is a small ridge before the first tapping point to ensure that the mouthpiece does not occlude the tapping point.
- The diameters of the two tapping points have the same size as the differential pressure sensor to simply connect the sensor via a flexible silicone tube.

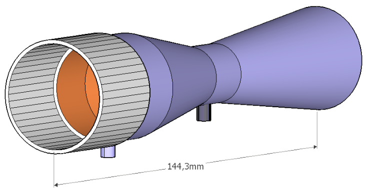


Figure 4.3: **Model of the 3D Tube.**

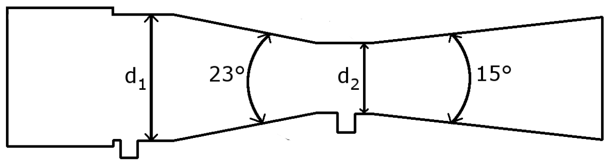


Figure 4.4: **Venturi Tube Cross Section.**

4.2.4 Differential pressure sensor

To record the pressure difference during exhalation the MPX5010 Pressure Sensor by Freescale Semiconducto is used. This sensor has an on-chip temperature compensation and calibration unit to overcome the problem of changing temperatures occurring while breathing through the tube. With the transfer function mentioned in the datasheet [MPX15] the sensor returns the pressure difference in kilopascal (kPa). After converting this value to pascal and inserting the resulting pressure in the equation 4.5, the fluid density in liter per second (L/s) can be computed allowing further analysis on lung functions. The pressure sensor (Figure 4.5) with its two incoming silicone lines of the venturi tube (Figure 4.6) is shown below.

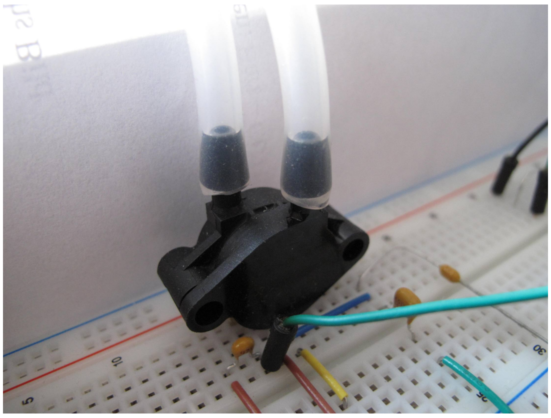


Figure 4.5: **Pressure Difference Sensor.**

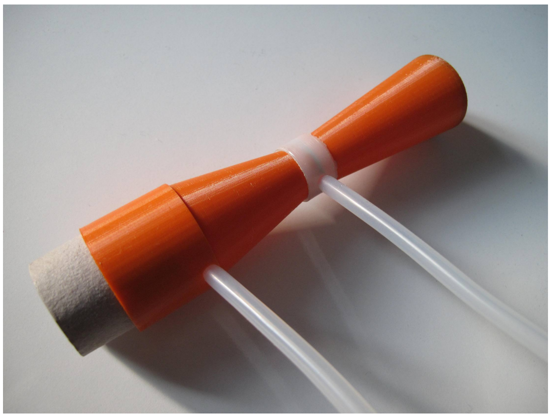


Figure 4.6: **3D print with mouthpiece.**

4.3 Skin conductance

The sweat glands as well as the skin blood vessels are exclusively innervated by the sympathetic nervous system, which forms part of the autonomic nervous system. The number of active sweat glands can be measured over skin conductance. This makes the skin an ideal measuring point for sympathetic activation and therefore for the stress reaction related with these emotions [SAS+10]. Accordingly, the skin conductance, also known as galvanic skin response or skin electrical conductance increases with enhanced arousal levels and is a significant indication of the emotional state identified with stress [NGFT04]. Skin conductance is also one of the signals used in the polygraph (popularly referred to as lie detector) test to recognize physiological responses that can be differentiated from those associated with truthful answers. With this method the emotional state identified with stress can be measured in a non-invasive way.

4.3.1 Electrical conductance sensor

The basic idea of a sensor, which can measure the electrical conductance of the skin, is to add the skin as a variable resistor to the electric circuit. It should be mentioned that there is no risk for users when they add their body to the circuit - the current flow stays minimal. Comparing a dry and cool skin with a sweating one, the skin resistance in the first case is high, while in the other case it is very low. Hence, the output voltage of this circuit is relatively high if a person is sweating. A good body part to measure this conductance is at the palmar sides of the hands or the feet where the density of sweat glands is the highest [SAS+10]. To connect the skin to the electric circuit, a conductive material has to be used (e.g. aluminum foil). This conductive material can then be used to measure the resistance between two fingers of one's hand (Figure 4.7). Furthermore a fixed resistor has to be added (at least 10 kiloohm (kOhm)) to create the appropriate pulldown to allow the voltage to drop to zero if the sensor is not in use - as shown in Figure 4.8 with two 4.7 kOhm resistors in series. This can be varied to increase or decrease sensitivity.

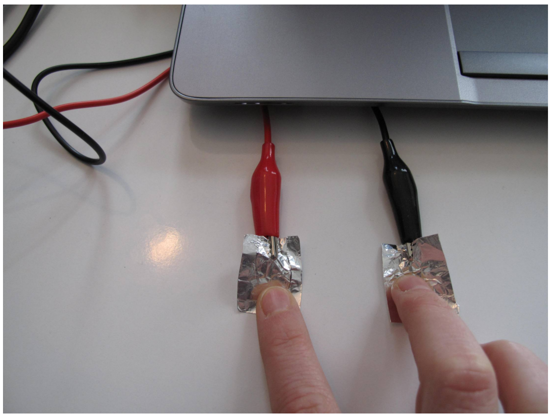


Figure 4.7: **Usage of the conductance sensor.**

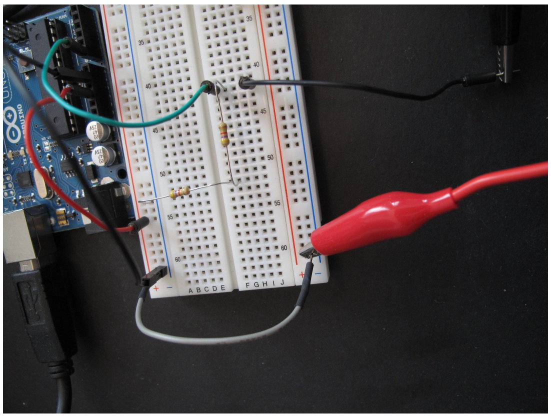


Figure 4.8: **Electrical circuit.**

4.3.2 Suitability test

For testing purposes we used the sensor on two test persons and just told them to think about something stressful. This activity doubled the output voltage in both cases as shown in Figure 4.9.

Figure 4.9: **Output of the sensor while a test person was thinking about a stressful situation.**

From these tests it follows that the developed skin conductance sensor could be used for our project to identify if a person is stressed or tensed in any kind of way.

4.4 Heart rate and blood oxygen saturation

Plenty of non-invasive methods for electronically sensing of the human heartbeat exist. This task can be done acoustically (stethoscope or doppler), mechanically (sphygmomanometer), electrically (EKG) or optically. The optical technique exploits the fact that tiny subcutaneous blood vessels (capillaries) in any patch of skin alternately expand and contract in time with the heartbeat. An ordinary infrared LED and infrared phototransistor can sense this rhythmic change as small but detectable variations in skin contrast. This persuasive method of measurement makes the optical technique the appropriate one for our project, because of the easy integration in a game play. Another advantage of this method is that the blood oxygen saturation can be recorded. This can be done by relating the absorbed/reflected red light with the absorbed/reflected infrared light and is described in detail in this chapter. Furthermore the architecture and possibilities of beat detection and oxygen saturation measurement are discussed in the following sections.

4.4.1 Principle of pulse oximetry

Pulse oximetry uses the technique of detecting transmitted or reflected light to monitor heart rate and peripheral oxygen saturation. In pulse oximetry, a part of the body is illuminated with two monochromatic light sources that have wavelengths in the red and infrared (IR) regions. Either the reflected or transmitted light from or through the body is detected to obtain red and IR photoplethysmographs (PPGs), which are waveforms produced by these sensors [RGMK09]. The PPG has two modes - transmission and reflectance. In transmission mode (Figure 4.10), the light transmitted through the medium is detected by a photodetector (PD) opposite to the source LED, while in reflectance mode (Figure 4.11), the photodetector detects light that is reflected from tissue, bone and blood vessels [TMSY14].

The transmission mode is capable of obtaining a relatively good signal, but the possible body locations for measurements may be limited, because the source and the detector have to be arranged on two opposite sides. Reflectance mode eliminates the problems associated with

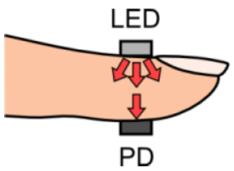


Figure 4.10: **Transmission mode.** [TMSY14].

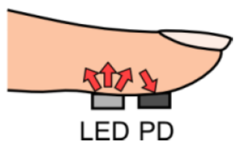


Figure 4.11: **Reflection mode.** [TMSY14].

sensor placement and the need of two surfaces. On the other hand, this method is affected by motion artifacts and pressure disturbances. Any movement, such as physical activity, may lead to motion artifacts that corrupt the PPG signal [TMSY14]. To minimize reading errors, which can occur with both techniques, signal de-noising can be done on the software side.

To integrate a mostly invisible heart beat measurement in a game play, we decided to use a sensor based on the reflection mode, so there is no need for two parallel surfaces, which have to be positioned in a specific way on body parts. The software adjustments for the described signal processing will be presented in the next section.

4.4.2 Heart beat detection

Only a small portion of the reflected light is responsible for sensing the arterial blood, which is used to calculate heart beats per minute (bpm). Nearly 90% of the light is reflected by skin and tissue.

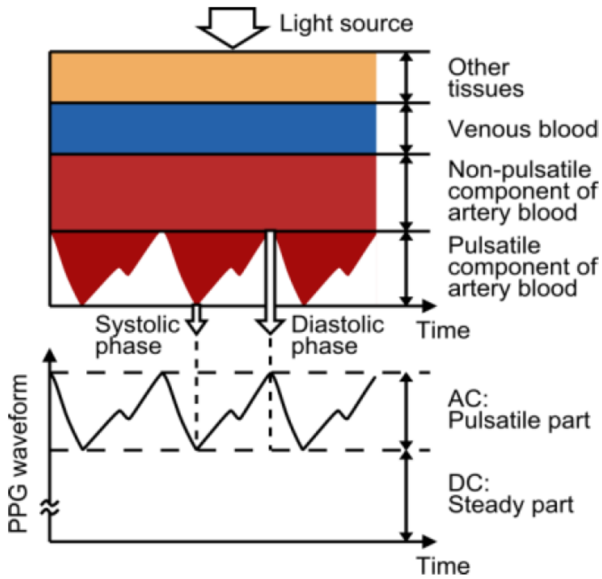


Figure 4.12: **Components of the reflected light.** [TMSY14]

Figure 4.12 shows on the bottom side an example of a photoplethysmographic waveform, consisting of direct current (DC) and alternating current (AC) components. The steady DC component of the PPG waveform corresponds to the detected reflected optical signal from the tissue and depends on the structure of the tissue and the average blood volume of both arterial and venous blood. The pulsatile AC component shows changes in the blood volume that occur between the systolic and diastolic phases of the cardiac cycle [TMSY14].

As explained above, arteries dilate and contract with each heartbeat so that during systole, the phase in which the ventricles of the heart contract and the blood pressure rises, the relatively thicker arteries increase the absorption of light. During diastole, the phase in which the ventricles of the heart relax and blood pressure falls, the relatively thinner arteries decrease the absorption of light. As can be seen in Figure 4.12 the time between two peaks in the pulsatile component of arterial blood - which are the valleys in the PPT - has to be measured to calculate the heart rate.

To detect these valleys in a proper way the following steps are necessary:

- **Sensor Hardware**: The major considerations for finding a suitable sensor are usability for a wide range of people and the amplification of the relatively small signal size in a proper way to detect the heart beat. After searching for different sensors which can accomplish this, we finally found the Pulse/SpO2 Sensor by Modern Device. It uses the Silicon Labs SI1143 chip, which was originally designed for proximity sensing, but provides digital control (I2C) over all its resources. The SI1143 was engineered to drive three LEDs at very high levels of current, and very short pulses. It also has some options regarding a couple of photo detectors. The Pulse/SpO2 sensor uses this chip in combination with red and infrared LEDs and an adequate parameter setting to sense the changes in skin contrast caused by the heart beat when putting a finger on the phototransistor of the chip.

- **Low and High Pass Filtering**: The sensor supplies two IR-LEDs and one red-LED. For each LED the sensor delivers the reflected light as an analog signal. The noise in the PPG signals (red and infrared) differs from subject to subject and also depends on the environment (ambient light or electromagnetic interferences). The DC residuals and noise in both raw signals are reduced through filtering with a high and low pass filter. In that way the blood pulsation signals can be extracted.

- **Separate AC part**: Because of motion artifacts the baseline of the pulsatile part of the signal drifts. With a drifting baseline it is complicated to find peaks and valleys. For that reason the baseline is computed by averaging the whole signal over time. By subtracting the baseline of the total signal the AC part is isolated.

- **Moving Average Filtering**: Additionally, to smooth the waveform further, a moving average filter is applied by averaging a number of consecutive samples from the input signal to replace corresponding samples in the output signal.

4.4.3 Calculation of blood oxygen saturation

Instead of summing up the reflected red and infrared light for heart beat detection, when calculating blood oxygen saturation (SpO_2) the two types of reflected light are set in relation. SpO_2

is defined as the percentage of the concentration of oxygenated blood cells (c_{HbO}) compared to the sum of the concentrations of reduced oxygenated blood cells (c_{Hb}) and oxygenated blood cells in arterial blood [RGMK09]:

$$SpO_2 = \frac{c_{HbO}}{c_{HbO} + c_{Hb}} \tag{4.6}$$

The usage of reflected light to measure these concentrations and to solve this equation is possible because of the hemoglobin molecules within red blood cells. They are essential for oxygen transport by blood since they carry about 97% of the blood's oxygen. Hemoglobins are able to bind oxygen reversibly - a fully saturated hemoglobin is referred to as oxyhemoglobin (HbO), whereas all other hemoglobins are called reduced hemoglobin (Hb) [RFW$^+$08]. This oxygenated hemoglobin can be detected over the reflection of red light [BG09]. By measuring the ratio of absorbance of light at two wavelengths $A_{\lambda 1}$ and $A_{\lambda 2}$ where oxyhemoglobin and reduced hemoglobin have different absorption coefficients, the ratio of oxygenated to total hemoglobin can be determined [MR06]:

$$R = \frac{A_{\lambda 1}}{A_{\lambda 2}} \tag{4.7}$$

The wavelengths of red and infrared light comply with these requirements. Figure 4.13 illustrates the different absorption spectra for oxyhemoglobin and deoxyhemoglibin at these two wavelengths.

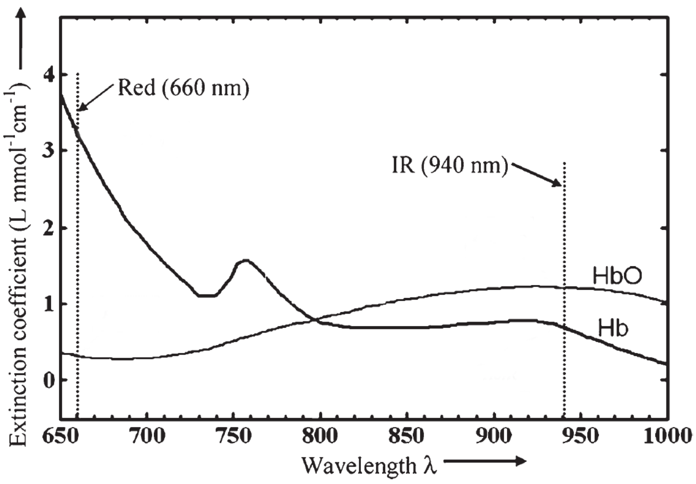


Figure 4.13: **Absorption spectra of Hb and HbO.** [RGMK09]

So as can be seen the ratio between the concentrations of deoxygenated blood and oxygenated blood is proportional to the ratio of red light absorption to infrared light absorption. To get the absorbance information $A_{\lambda 1}$ and $A_{\lambda 2}$ the Beer-Lambert law can be used. This law states that the absorbance A results from the relationship between the light of intensity I_0 and the emitted light I_1 after passing I_0 through an absorbing medium:

$$A = ln(\frac{I_0}{I_1}) = \varepsilon cd \tag{4.8}$$

Where ε is the extinction coefficient, which relates to the light absorption of the medium, d is the distance traveled by the light (cm) and c is the concentration of the absorbing medium (mol/L). By taking the ratio of the light measured by the photoreceptor at the peak ($I_{\lambda high}$) and trough ($I_{\lambda low}$) of a heartbeat cycle, we can obtain information that is independent of the absolute light intensity I_0 of the LED and independent of tissues that do not contain arterial blood.

Because of different absorbencies of HbO and Hb the Beer-Lambert law also determines that the total absorbance of a mixture of elements with varying absorbencies at a specific wavelength λ is the sum of the individual absorbencies:

$$A_\lambda = \varepsilon_{\lambda Hb} c_{Hb} d + \varepsilon_{\lambda HbO} c_{HbO} d \tag{4.9}$$

Combining equations 4.9 and 4.7 the ratio between red and infrared absorbencies can be written as:

$$R = \frac{A_R}{A_{IR}} = \frac{ln(\frac{I_{Rhigh}}{I_{Rlow}})}{ln(\frac{I_{IRhigh}}{I_{IRlow}})} = \frac{\varepsilon_{RHb} c_{Hb} d + \varepsilon_{RHbO} c_{HbO} d}{\varepsilon_{IRHb} c_{Hb} d + \varepsilon_{IRHbO} c_{HbO} d} \tag{4.10}$$

Substitute c_{Hb} and c_{HbO} by the function of arterial oxygen saturation by using 4.6 to derive R as a function of $SpO2$:

$$R = \frac{\varepsilon_{RHb} + (\varepsilon_{RHbO} - \varepsilon_{RHb}) SpO_2}{\varepsilon_{IRHb} + (\varepsilon_{IRHbO} - \varepsilon_{IRHb}) SpO_2} \tag{4.11}$$

Which allows us to rearrange, so we can finally calculate the theoretical saturation from the ratio of the measured, normalized absorptions we have in red and infrared:

$$SpO_2 = \frac{\varepsilon_{RHb} + \varepsilon_{IRHb} R}{\varepsilon_{RHb} - \varepsilon_{RHbO2} + (\varepsilon_{IRHbO} - \varepsilon_{IRHb}) R} \tag{4.12}$$

This ratio gives us information that is dependent only on the absorption coefficients of deoxygenated and oxygenated hemoglobin (λ) and on the percentage of hemoglobin that is oxygenated (R). All parameters in this equation are measurable and known values. The value of R is calculated from the four parameters derived from the photodetector and the values of the absorbencies are known and given as a function shown in Figure 4.13 and results in the values described on the next page. The values of the two wavelengths most commonly used in pulse oximetry are [Web97]:

Wavelength	ε_{Hb}	ε_{HbO}
660 nm	0.81	0.08
940 nm	0.18	0.29

As mentioned above, the Beer-Lambert law is based on the approximation concept that the sum of the transmitted and the absorbed light is equal to the incident light. But this incident light passing through human tissue is not only split into absorbed light and transmitted light. Some parts of the light are reflected and others are scattered. The Beer-Lambert law does not take these physical concepts into account and that is the reason why the theoretical oxygen saturation

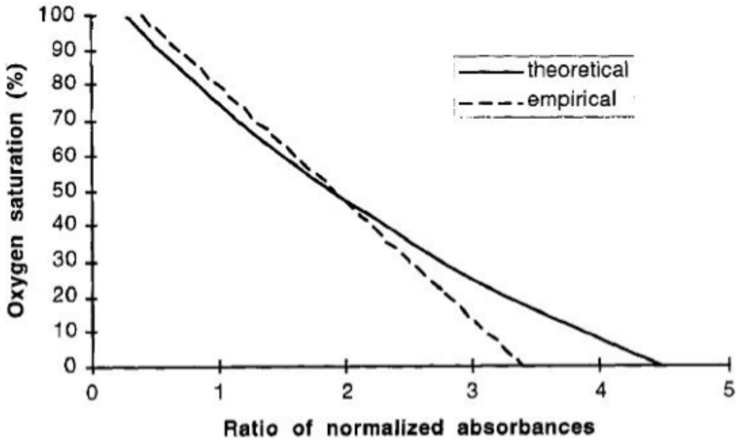


Figure 4.14: **Empirical and theoretical curves for pulse oximeters.** [Web97]

differs from the empirical one as can be seen in Figure 4.14. The solid line is the theoretical curve calculated by the Beer-Lambert law and the dashed line is the empirical curve [Web97].

The empirical calibration curve is derived by a second order polynomial and is calculated based on empirical data. As the oxygen saturation seldomly drops below 80%, a linear relationship with a slight offset can safely be assumed. For our purpose we took the theoretical approach by the Beer-Lambert law, thus no curve fitting data from volunteers is required.

4.5 Blood pressure

Blood pressure (BP) measurement devices have become increasingly popular during the last decade as prices for them dropped to an adequate level and they are now affordable for home usage. However, such devices are typically cuff based and measure the blood pressure indirectly using the detection of specific sounds [SI14]. To measure BP during a game the usage of an inflatable cuff is not suitable because of the long and mostly unpleasant measurement procedure. So we were looking for alternatives, which relay on other methods to calculate the blood pressure.

There are some techniques that measure BP through the combination of different parameters, like blood flow, electrocardiography (ECG), PPT or pulse wave velocity. These approaches employ a sensor network across the body as can be seen in Figure 4.15.

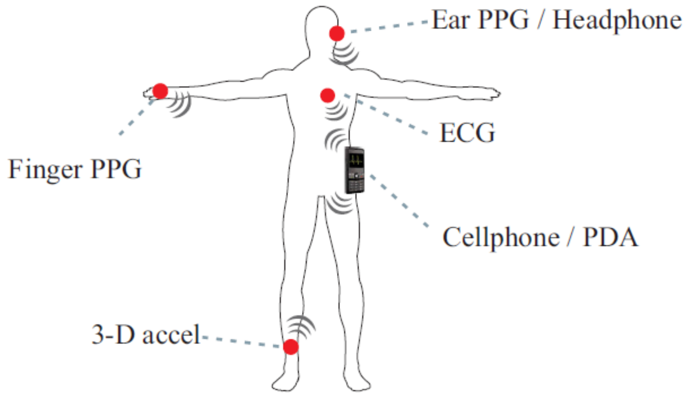


Figure 4.15: **Body Area Network Example.** [CG09]

Cattivelli and Garudadri [CG09] as well as Shriram et al. [SWDR10] presented a method to estimate BP by measuring the delay between the ECG peak and a point in the finger PPG waveform. With this measurement the synchronization of the sensors and an accurate and fixed position are essential because skew and jitter have effects on the estimation performance.

These sensor networks are also not suitable for our application, since there have to be several sensors on specific parts of the body and during the measurement only restricted body movements are allowed to avoid distortion of the results.

Sadao Omata of Nihon University exhibited a blood pressure meter that allows to measure blood pressure just by touching a small button-shaped area with one finger. The meter consists of LEDs and photo transistors. In [Oma12] they described their applied method with the picture shown in Figure 4.16 and called it "Phase Shift Method". Further details of the measurement method were not disclosed and the sensors are also not commercially available yet.

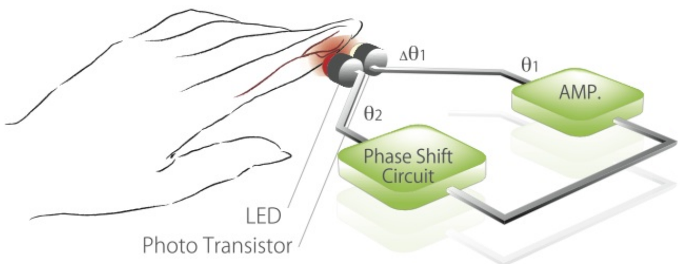


Figure 4.16: **Phase Shift Method.** [Oma12]

Because of blood pressure calculation by simply occluding a specific part of a sensor, this measurement technique could easily be integrated in a game. This brought us to the conclusion that for future projects, if such a sensor is commercially available or the technique of the measurement is published, blood pressure could also be monitored with a tangible user interface.

4.6 Brain activities

Electroencephalography (EEG) is a medical technique to measure voltage fluctuations to evaluate brain activity. EEG is most commonly used to diagnose epilepsy, which causes obvious aberrations in EEG readings. There are also approaches that try to detect depression [MMP+13] or Alzheimer's disease [DVC11] through EEG recordings.

Standard commercial EEG recording systems requires substantial preparation, because of the usage of a network of wet electrodes, which have to be placed on specific spots on the head depending on the user's head dimensions. This long and complex procedure seemed inapplicable for our usage. However, recently researchers developed dry electrodes and the results were comparable with standard EEG systems while requiring substantially less set-up time [GCB+10]. Several methods to realize such systems are presented in the following sections.

4.6.1 OpenEEG Project

The OpenEEG project [ope] offers hardware schematics and free software for building an EEG device. However, the hardware costs for acquiring the different parts are relatively high (about 200 USD), and there is not an easy plug-and-play implementation.

4.6.2 Hacking a toy EEG

Due to the recent availability of low-cost consumer EEG devices, EEG signals are used in devices for games and toys. There are many projects that hack these toys and extract the raw EEG data. One example is a tutorial about building a brain-computer interface via manipulating a ball game from Mattel called Mind Flex [min]. The authors solder one wire on the ground pin and one on the output pin and connect them with an Arduino [ard]. Exemplary construction steps and the final hardware modification are shown in Figure 4.17.

Nevertheless, none of these projects could derive any medical correlations corresponding to the recorded EEG signals. Therefore an integration of such a hacked toy with no further description on how to use the gathered data, is not suitable for our health monitoring tool.

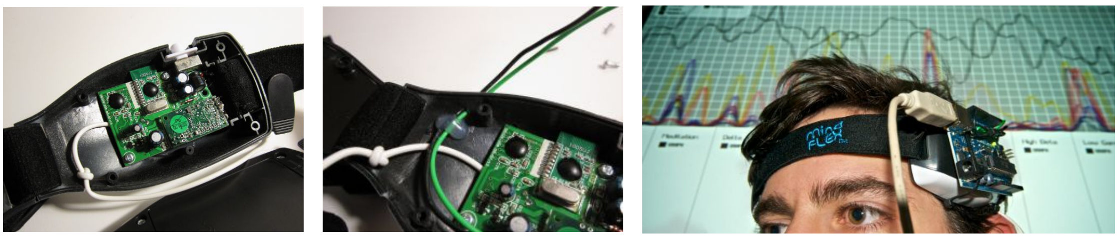


Figure 4.17: **Mindflex Hack.** [min].

4.6.3 TrueSense Sensor

Another affordable product to measure EEG signals is presented by OP Innovations - the TrueSense Kit [Tru]. The kit consists of one sensor, a memory module and a controller, as can be seen on the right side of Figure 4.18. The wireless sensor can capture bio-signals on multiple body locations. Consequently if the sensor is fixed on the head it can measure EEG signals. As with the hacked EEG toys, they describe in their manual that the kit is not considered to be a medical device and should not be used for monitoring or treating medical conditions. The sensor was tested during another student project at the institute, but no reliable EEG data could be extracted when positioned on the head.

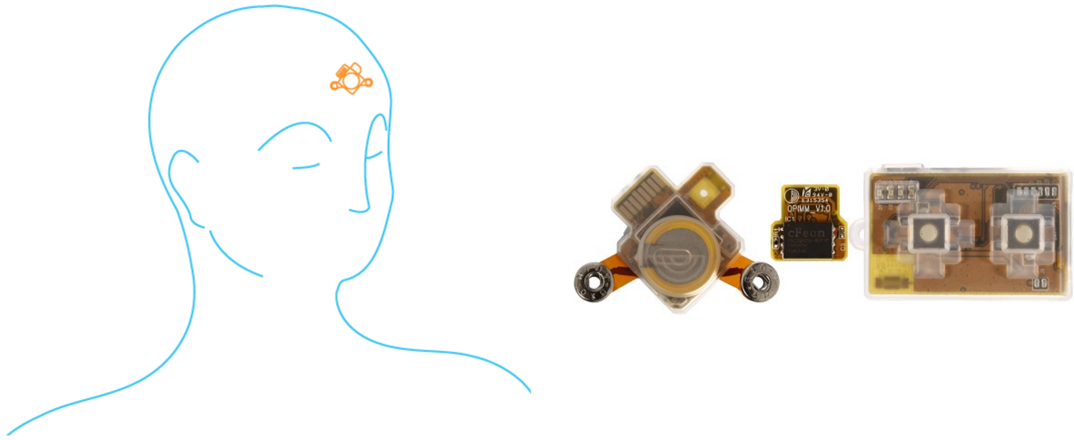


Figure 4.18: **TrueSense Kit.** [Tru].

EEG signals are highly polluted with various artifacts, like line interference or heart rate signals. These noise sources increase the difficulty in analysing the EEG and thus obtaining meaningful clinical information [MS09]. Furthermore since the measurement has to be taken from the head, the combination of EEG sensors and game play implicate some difficulties and there still has to be found a playful design to hide the EEG sensors.

However, we believe that with further research, this kind of sensors could deliver reliable EEG signals and could therefore be included in a health monitoring game to evaluate brain activity.

CHAPTER 5

Hardware Design

To measure vital signs in an unperceived way and to minimize the “White Coat Syndrome” we want to combine the medical sensors in a game-based setup and provide an easy to use and intuitive interface. To reach this envisioned goal the concepts of affordance, feedback and visibility should improve the interface’s intuitiveness and imply its functionality and usage.

Affordance was introduced to Human Computer Interaction by Donald A. Norman [Nor88] in the late 1980s. In one of his subsequent articles he distinguishes strictly between perceived and real affordance [Nor99]. The real affordance reflects the action opportunities that a physical object allows, whereas the perceived affordance is the one that actually is noticed by an observer and let someone determine how things could possibly be used. Furthermore the perceived affordance relies, among other things, on cultural conventions and could for instance be manipulated by visuals that advertise the real affordances. Real affordances on the other hand are closely related to physical constraints and could be manipulated by limiting possible operations.

With tangible user interfaces we have the opportunity to influence both affordances by designing the tangibles in a way that constrains the usage by physical properties and by creating perceived affordances by the implemented behaviour of the interface. To ensure that the desired, relevant actions are even more perceivable, the principle of feedback will also be paid a certain amount of attention during the design stage. Actions that have an immediate and obvious feedback effect can guide the user in a desired direction and help to decide which parts of an object have a dedicated functionality and which are solely for decoration purposes [Nor88].

It should be considered that the game offers similar operations and use similar elements for achieving similar tasks. Such consistent interfaces are easier to use and users have to learn only a single mode of operation that is applicable to all objects [RSP12].

So within this chapter we try to answer the question on how to design an interface that makes possible activities visible and drives the user behaviour in a specific direction to achieve a certain goal and on how their behaviour can be predicted.

5.1 Conceptual Design

5.1.1 Requirements

Beside appearance factors another main focus during the design phase is to ensure that the correct functionality of the medical sensors is not affected. For that reason there are some requirements for each sensor that may restrict the game play in a certain way:

- Skin conductance: At least two parts of the body have to touch the tangible, to measure skin conductance. If this measurement is repeated, the recordings could then also be used to discover stress development during the game.
- Lung capacity: The activity of breathing into a tube has to be integrated in the game play. The users should be motivated to breathe as long and as hard as possible into the device to compute the different parameters of lung functionality.
- Heart beat and oxygen saturation: To calculate the heart beats per minute, the pulse has to be measured for at least one minute without any interruption. For that reason one finger has to be placed directly on the photodetector of the pulse sensor and should be moved as little as possible to avoid movements beeing mistaken as pulse signals. Another restriction of this sensor is the fact that the photodetector has to be located at a maximal distance of 0.5 cm from the finger to correctly sense the rhythmic change in skin contrast.
- Temperature: The infrared sensor should be completely occluded by the hand or finger to avoid accidentally measuring the ambient temperature. Simultaneously the sensor should not be in direct contact with other body parts to avoid heating the sensor up and bias the measurements.

To realize the idea of a modular interface, every sensor should be located in one separate tangible. This is why each tangible has to measure at least 6 cm in length and width to provide sufficient space for all electrical components needed to record vital signs.

Furthermore in case of illness, chronic diseases or fatigue, to not affect the course of the illness or bias the measurements, the game should not be too stressful or exciting. Finally the game logic and design should be suitable for children aged 5 and older, for this reason it should be easily understandable and motivate them to play with it.

5.1.2 Cube affordance

The engagement and playfulness afforded by common or slightly modified cubes have been proven over the last decades, which convinced us to also implement our tangibles in a cube shape. Besides the popular Rubrik's Cube, blocks to construct buildings or simple dice, many researchers focused on the affordance of cube interfaces in the last years. "Audio Cubes" for instance is a tangible user interface to design sound [SV08], "Cognitive Cubes" are designed to assess cognitive ability [SIW+02] or the "Display Cube" introduced by Kranz et al. that supports input by gesture recognition [KSHS05], just to name a few. Sitdhisanguan et al. [SSVL+03] tried to identify the natural affordances of cubes during a user study. Their results suggest that there are some attributes that make one physical interface more desirable than another:

- Feedback prolongs interaction: Cubes with an appropriate feedback are used more often than others. Furthermore they can lead to a prolonged period of interaction time.
- Wider multi-sensory experience prolongs interaction: Cubes that offer more than visual aspects also extend interaction. For instance smell, texture or sound are such multi-sensory experiences that can sustain or even increase the attention for an interface.
- Weight trade-off: Interfaces must be heavy enough that users are aware of the object but light enough that they can be held for long periods of time. An adequate weight relies on application and user.
- Geometry: To securely hold them, cubes that fit naturally in the hand are preferred. For this reason cubes that had some curviness are found to be easier and more comfortable to grip.

Cube size

Since the grasping affordance of a cube does not lie only in the size per se, an even more relevant variable is its size in relation to body metrics [vdKZ07]. For that reason Cesari and Newell [CN00] studied grip configurations (2-finger, 3-finger, 4-finger, 5-finger, and 2-handed) used to pick up cubes of various lengths and masses and for instance found out that the transition for picking up an object with a two or three-finger grip happens at the same ratio of object size and hand width for small children and adults. They present a general equation that captures both the geometric and biodynamic constraints on prehension independently of the actor's sex or age:

$$K = lnL_c + \frac{lnM_c}{a + bM_h + cL_h} \tag{5.1}$$

Where L_c and M_c are the length and mass of a cube, L_h and M_h are the length and mass of the hand and a, b and c are empirically obtained constants. The resulting value K describes the relationship between cube length and mass that effectively constrains the grip configuration used to pick up a single cube.

So with the measurements of a participant's hand and possible cube sizes, the parameter K can be computed and according to their presented results the most used grip configuration and grip transition for this setup can be predicted as can be seen in Figure 5.1. For example, the switch between two and three fingers occurs at a mean value of 1.11 ± 0.15. This indicates that below this value all the grip configurations are predicted to be with two fingers whereas above this value the grip is predicted with three fingers.

To get an overview of weight and length of common children hands we used the measurements Cesari and Newell [CN00] made in their study to determine the cube size for our project. Figure 5.2 plots these measurements of all 30 participants, whereas the length is in centimetres and the mass in kilograms.

With an estimated cube size of 6 cm, a cube weight of 100 g, a children's hand size of 12 cm and the empirical coefficients used in the research of Cesari and Newell [CN00] of $a = 3.93$, $b = 0.016$ and $c = 0.142$, the computed value of K is 2.4. The estimation of the cube weight is

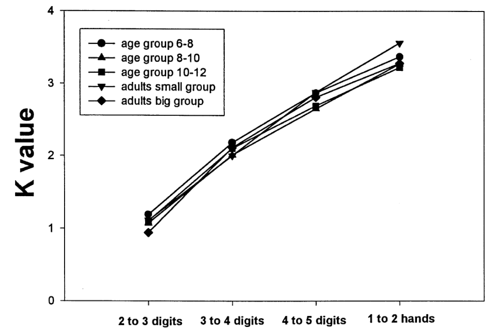


Figure 5.1: **Grip transitions.** [CN00].

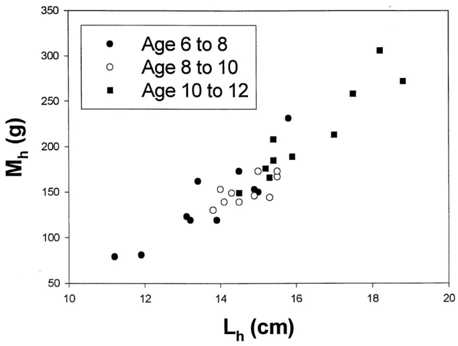


Figure 5.2: **Hand measurements.** [CN00].

computed by summing up the weight of the electrical components (50 g) and the approximated weight of a wooden housing (e.g. density of pine 0.41 g/cm^3).

This brought us to the conclusion that the tangibles we intend to develop will be held with four fingers in the majority of cases. This knowledge has to be included during designing the shape of the final cubes to assure that they lie well in the user's hand.

Cube position

How a cube is picked up and held also depends on the distance and rotation of it. Kamp et al. [vdKZ07] tested the reaching and grasping behaviour of eleven right-handed participants. Within their experiment the participants had to grasp objects on two predefined sides. For that reason the long axis of the object was positioned at an angle with the horizontal along the frontal plane (see Figure 5.3). To determine the angle that was most natural for the specific participant, they monitored each participant when grasping a cylindrical object. Angle α varied across participants from 5° to 40° (mostly 20° or 40°).

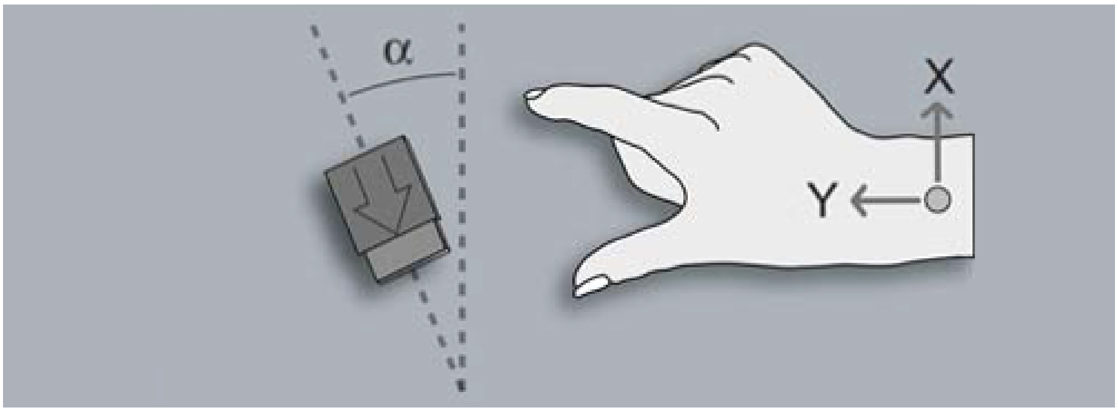


Figure 5.3: **Angle of object.** [vdKZ07]

To change the orientation of each tangible during the game to assure that they are grasped at the sides where the sensors are positioned, a motor unit could be used. In that way the tangibles could be arranged automatically depending on the users position.

5.1.3 Game logic and mechanics

In the next step, to comply with the described requirements and to include the previously gathered knowledge of cube affordances, we analyse different game ideas. After some sketching and research in games designed for children we describe our basic game concept illustrated in Figure 5.4:

- Several tangibles in cube shape with different symbolic pictures on top are positioned on a desk. Each tangible represents a specific part of a fairy tale or any other desired story.
- After expiration of a certain time, the cube, that stands for the first part of the story, plays a certain “pick me up”-tone to advise the user to pick it up.
- If this cube is then picked up and held “correctly”, the cube signals the correct handling with another tone, followed by replaying the story over the mobile phone’s speakers.
- After reaching the end of this part of the story an end-sound is played and the cube can be put down again.
- The pictures on the cubes are related to the part of the story hiding behind it. So the last sentences of each part of the story reveal which cube has to be grasped next. If the user takes to long to find the next cube, the same “pick me up”-tone as the one from the first cube, is played by the next cube.
- And again, when holding the cube correctly a tone plays and the next part of the story is played by the mobile phone. This procedure repeats until the end of the story is reached.

As described in section 6.2.7 during the implementation of the interface we replaced the “pick me up”-tone by rotating the tangibles, which turned out to be even more inviting than sound.

If the cube is not held correctly or is put down during the story telling, the story stops. This behaviour is needed to guarantee that the user is holding the tangible long enough to record the vital signs in an adequate way. If it is picked up again within a certain time, the story will start at the last position before releasing of the cube. Otherwise, when taking another cube or waiting too long, the story will start at the starting point of the current part of the story. It is also possible to hear parts of the story, that were already played back, by picking up a past cube. Picking up any other future cubes, apart from the one that is next in the sequence, will result in stopping any ongoing playback. The entire state diagram is shown in Figure 6.7 in chapter 6.

A special cube is the one with the breathing tube inside. To include breathing in the game play, the story has to contain a part that prompts the user to breathe into a tube. A possible fairy tale that includes such elements is for instance the “Three Little Pigs” in which a wolf blows down the first two pigs’ houses, made of straw and wood respectively, but is unable to destroy the third pig's house, made of bricks. Another example is the story of the "Pied Piper of Hamelin", who lures rats away by playing his magic pipe. By arriving these or similar parts of the story, the story stops and the user has to breathe into the tube mounted in the tangible. If the measurement is not successful, the prompting sentence (e.g. "Then I'll huff and I'll puff and I'll blow your house in") is played again and the user has to breathe another time into the tangible. Additional to stopping the story when breathing is required, the tangible could vibrate in the user's hand to make the action even clearer.

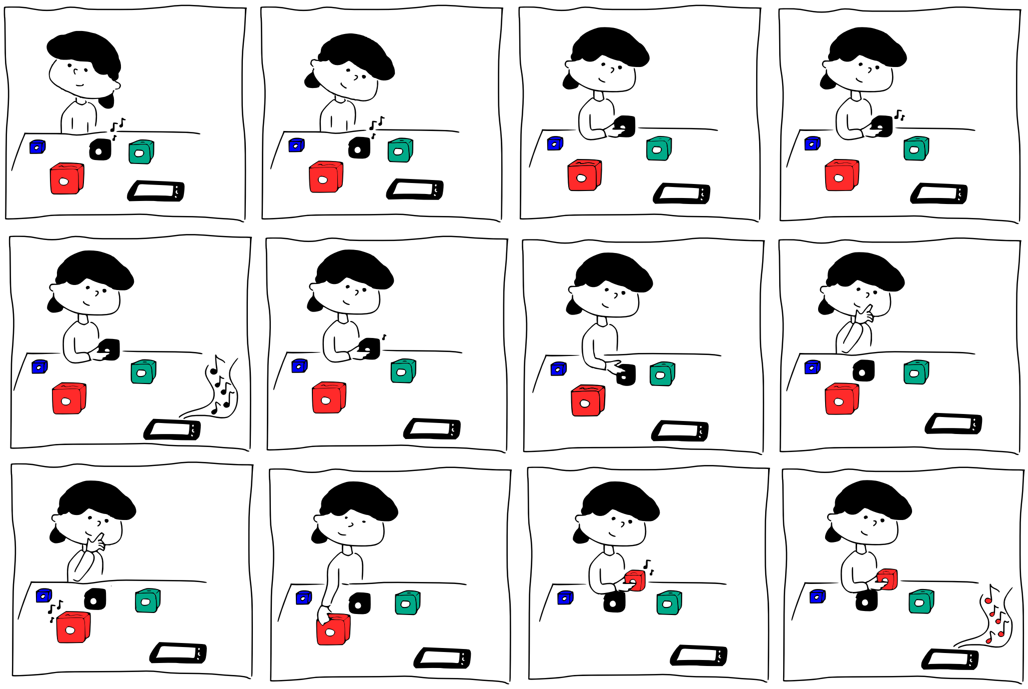


Figure 5.4: **Game concept.**

5.2 Mock-up testing

With the conceptual design of the medical story cubes, we built some mock-ups for first interface tests. Like with classical graphical user interfaces we started with sketching and prototyping on paper. But due to the fact that TUIs are not only consisting of digital objects, we needed to build real physical mock-ups to test their handling. Therefore we tested some tangibles with other modalities of interaction such as gesture, sound or voice.

5.2.1 Building a mock-up

Our first static TUI mock-up made out of paper is shown in Figure 5.5 on the left side. The cubes have a length of 7.2 cm and follow our first idea, in which each cube can be activated with a certain action (rotating, pressing, breathing, lifting). After testing these cubes we found out that they are too big, especially for children's hands. So we built smaller ones with edge lengths of only 5.5 cm (right side of Figure 5.5). Furthermore we changed the design in a way that the sensors are occluded by left- and right-handed users.

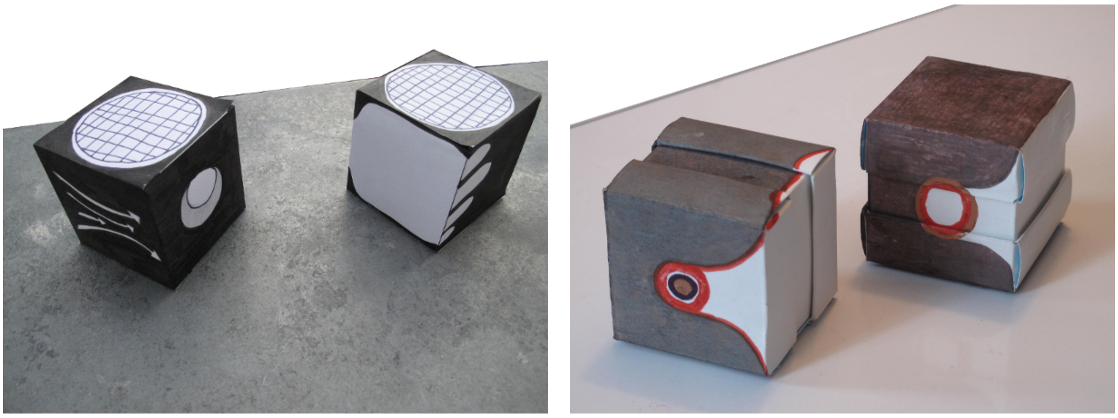


Figure 5.5: **First mock-ups.**

After this first testing phase we decided to activate the cubes simply by holding them in the correct way and for that purpose we dropped the idea of certain gestures. We added the story telling concept and put pictures on the top of each cube. In Figure 5.6 the different parts of the story of the "Three Little Pigs" can be seen, where the start cube is the one with the three little pigs on it, followed by "going out into the big wide world", "building houses", "the appearance of the big bad wolf" and the last cube, which includes the part of the story where the wolf finally climbs down the chimney and falls into the hot pot of water on the fire.

Figure 5.6: **Mock-ups for story telling concept.**

5.2.2 First user inquiries

With these "Three Little Pigs" mock-ups we tested our story telling concept with the help of a notebook that replays the story by manually selecting the corresponding audio files. We decided to evaluate the concept with adults instead of children, because we hoped to get more information out of verbal feedback and adults could better imagine how the real interface should work in the end whereas children can get quite fretful with semi-finished interfaces. For that purpose we asked 5 participants aged between 28 and 38 years to interact with the TUI mock-up. Each user realized the core concept of the story telling cubes within a few minutes and all listened to the entire story - some by testing every enabled action (e.g. holding two cubes simultaneously or picking up past cubes) and others in the intended, direct way. After each testing sequence the participants summarized their experiences, concerning the usability and playfulness of the interface. We got interesting findings out of this verbal feedback: two participants were quite irritated by the design of the tangibles, which indicates to use just two finger to pick up the cube, and would intuitively use four fingers for this action. Another user had concerns regarding the size of the cubes and if they weren't too big for children's hands. A third one would have hoped for more cubes and was bored by parts of the story that were longer than one minute. Generally speaking, as a result of this test we adapted the design of the tangibles for the usage of more than two fingers. Furthermore the number of cubes should not be limited, since it may be that in the final interface more than 5 cubes are desired to entertain children. Relating to cube size we had already enquired that a cube with a size of 5 cm to 6 cm will be grasped with one hand by a typical child (chapter 5.1.2), so we kept this calculated size.

5.3 Designing the tangibles

5.3.1 Modular design

The actuated tangible user interface objects (ACTOs) [VGK14], which were developed at the same institute as this thesis, use a modular and flexible design strategy that allows quick adaptations for different scenarios and setups on tabletops and are therefore the foundation for this project. One ACTO consists of a "Base Modul" (Figure 5.7), which includes a customized microcontroller inspired by the Arduino Pro Mini, and an optional "Motor Module" (Figure 5.8), which enables the tangible to change position or rotate. These existing modules can be easily extended by adding a custom module on top of them. Some examples can be seen in Figure 5.9.

Figure 5.7: **ACTO Base Modul [VGK14].**

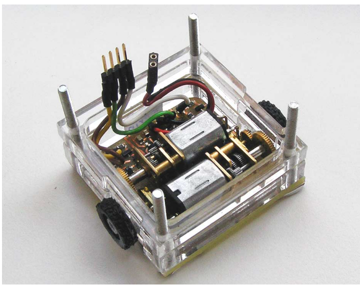


Figure 5.8: **ACTO Motor Modul [VGK14].**

Figure 5.9: **ACTO Extensions [VGK14].**

This concept makes it easy to use the ACTO as base for each tangible and design extensions for the different medical sensors. The complete ACTO hardware structure composed of extension module, base module with RF unit, motor module and marker panel for identification of each ACTO is shown in Figure 5.10. How these markers are used is described in detail in the implementation chapter (chapter 6).

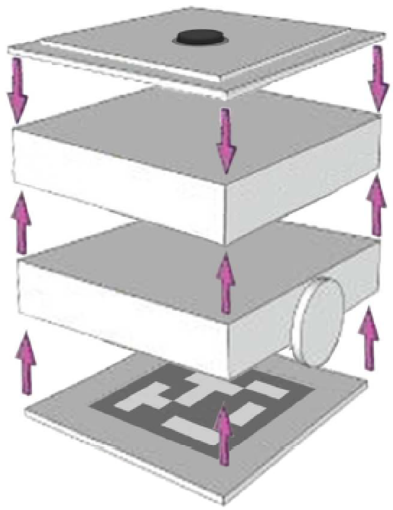


Figure 5.10: **ACTO hardware structure [VGK14].**

5.3.2 Circuit board and circuit diagram design

In this section the developed circuit boards and related circuit diagrams needed for the ACTO extensions are described. Each extension encapsulates one or two medical sensors and along with the housing of the ACTO hardware represents the hardware setup for the tangibles. Due to the number of medical sensors and the available ACTO base modules, we limited our interface to three tangibles and therefore designed three different circuit boards.

The lung functionality tangible (Figure 5.11) has to include the breathing tube, the pressure sensor and additional contact sensors placed on the side walls of the housing to recognize if the cube is held or not. The need of these contact sensors brought us to the idea of integrating the skin conductance sensor in this tangible. This sensor can be used because of the change in resistance when touching the conductive material and therefore no fourth tangible is needed. Furthermore the tangible for lung functionality measurements needs additional electronic components for the vibrating unit to prompt the user of breathing in the tube. For this purpose a vibration motor by Precision Microdrives, a diode as protector against voltage spikes that the motor may produce, a NPN transistor to output enough current, a $0.1\mu F$ capacitor to absorb voltage spikes and some resistors are added. Finally an additional piezo element is placed in every tangible for generating simple sounds.

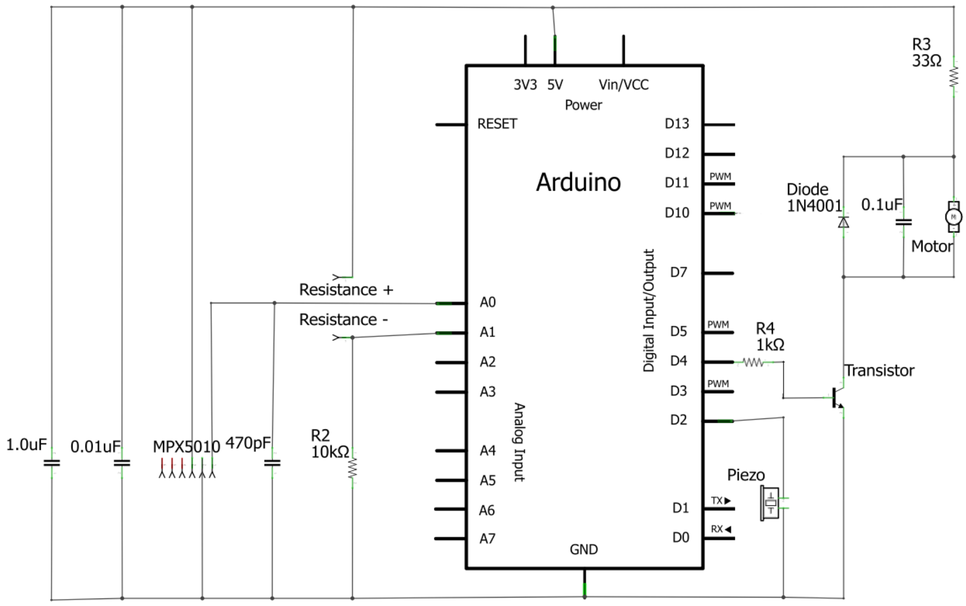


Figure 5.11: **Lung functionality unit.**

With the help of the second tangible the temperature can be measured (Figure 5.12). This unit consists of the infrared sensor MLX90614, which could also be used to find out when the tangible is held. The temperature sensor will not be mounted on the circuit board itself, but on the front side wall of the tangible housing to allow a direct view to the user's hand.

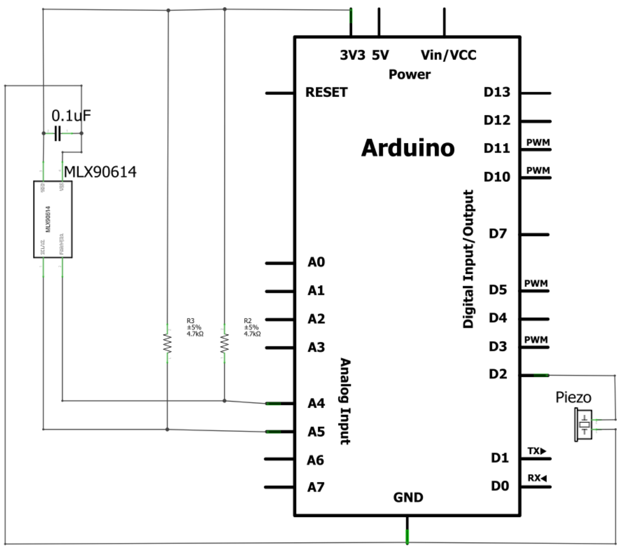


Figure 5.12: **Temperature unit.**

The tangible for pulse and oxygen saturation measurements is the third and last one (Figure 5.13). This tangible, just as the temperature tangible, does not need further electrical components to detect contact, because the implementation for this sensor also includes finger recognition. So the pulse sensor has to be placed in the side wall of the housing in the same way as the temperature sensor for the second tangible.

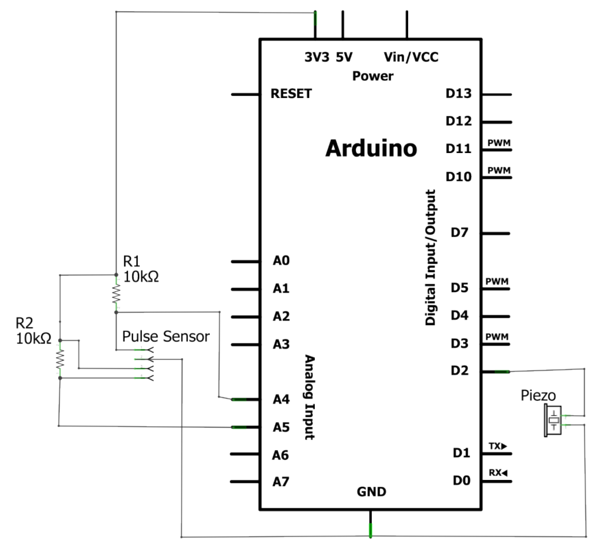


Figure 5.13: **Pulse and oxygen saturation unit.**

The resulting circuit board layouts (Figure 5.14) are mirrored and printed out on a transparent foil. This foil is then put on a blank printed circuit board (PCB) with the printed side facing towards the board, so the ink is as close to the PCB as possible. This has to be done to ensure in the next step when exposing the PCB to ultra violet light that there is no possibility of light leaking in sideways and causing unsharp edges, which can result in a poor etching result. Afterwards, to wash off the parts of the PCB that were exposed to ultra violet light, the PCB is put inside a fixation base consisting of natriumhydroxide and water. Within this step the PCB structures that will stay are getting golden, while the rest is washed of. Finally the cooper traces on the PCB are etched in a heated etching tank filled with natriumpersulfate until the opaque pink parts, which were exposed to ultra violet light, turn to a transparent yellow.

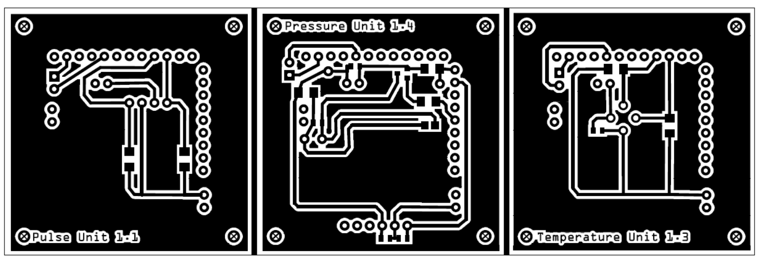


Figure 5.14: **Circuit board layouts for the three final tangibles.**

5.3.3 Housing

The main restriction for the housing of the tangibles is the size of the ACTO base and motor module, which is around 50 x 50 x 40 mm. Additionally on the top of it there has to be some free room for the extension and the sensors. Furthermore some sensors have to be placed in the side walls of the housing and the inclusion of a tube has to be considered in an adequate way. One opportunity for a possible housing would be the use of a 3D printed plastic housing. With this solution three 3D models for the different tangibles have to be created and it would be easy to reproduce them by simply reprinting them. On the other hand plastic has an unnatural, artificial surface and its flat texture doesn't offer any multi-sensory experience as mentioned in the cube affordance subchapter 5.1.2. Wood on the other side features all these positive affordance characteristics. As mentioned in Donald A. Normans book about emotional design [Nor04] attractive things work better and evoke better brainstorming when feeling good holding them. Furthermore toys for children often consist of natural materials and a wooden housing would probably remind oneself of toys of one's childhood and so the affordance to pick them up is even more present.

Another challenge of the tangible design is the weight. The ACTO base and motor module weighs 100 g, so a light weighted housing material has to be found which does not tempt the user to pick up the cube with two hands. The perfect choice to solve this issue is the very lightweighted balsa wood with a density of around 0.2 g/cm^3. If the walls have a thickness of 5 mm, this would result in an additional weight of about 18 g for the housing. The final three housings constructed with this balsa wood are shown in Figure 5.15. The top of each housing is replaceable to cover different stories with the same cubes. The two tangibles with the temperature sensor and the pulse sensor inside have a size of 60 x 60 x 60 mm. The third tangible needs additional space for the tube and is therefore 20 mm higher. Inside of the walls there is additional space for different sensors and appropriate cut-outs for the wires connecting the sensor with the ACTO extension.

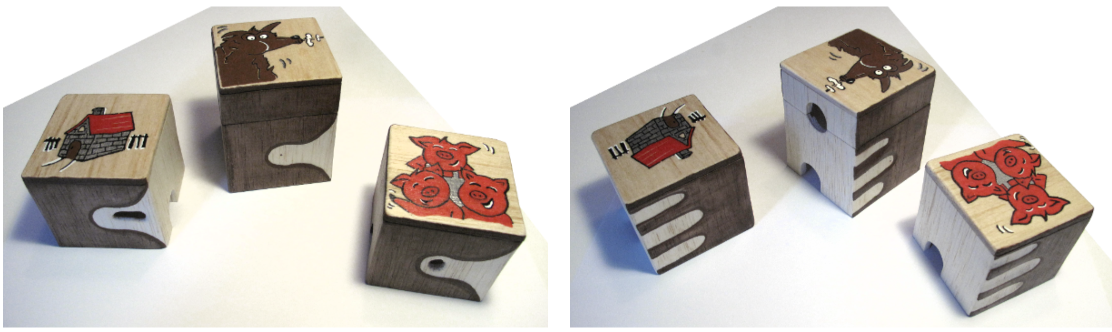


Figure 5.15: **Back and front of the final wooden housings.**

5.3.4 Tube Design

Since the housings of the tangibles have external dimensions of 60 x 60 x 50 mm the tube had to be redesigned. The original diameter and length of the 3D model of the tube for measurement of lung capacity are 3 cm and 14.4 cm, which does not fit in the previously designed tangible cubes. Ah Kim et al. [AKSLJC05] measured the pressure of respiratory tubes with diameters of 10, 15 and 20 mm and came to the conclusion that the minimum tube diameter that satisfies the internationally accepted standards is 15 mm. So the tube was scaled down to this smaller diameter, which does not influence the measurements in a negative way and therefore is a great advantage for a portable medical device. For that purpose another 3D model of a venturi tube with a total length of 8 cm and a diameter on the front side of 16 mm was printed and is shown in Figure 5.16. To design a replaceable mouth piece for the tube a wooden mouth piece was designed in the first place. For an easier use, reproduction and especially for hygiene factors additionally a separate 3D model of the mouth piece was designed and printed out (Figure 5.17). Furthermore the common single-use paper mouth pieces with a diameter of 16 mm could also be used.

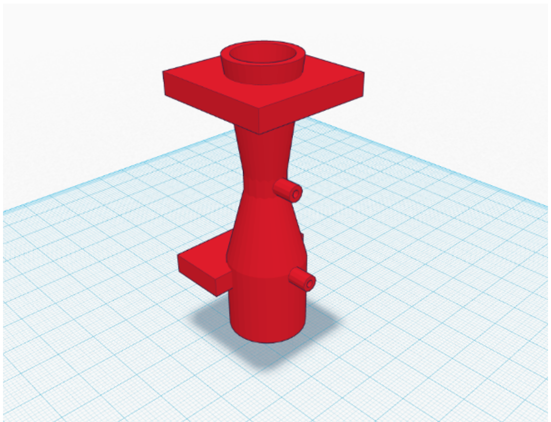


Figure 5.16: **Venturi tube 3D model.**

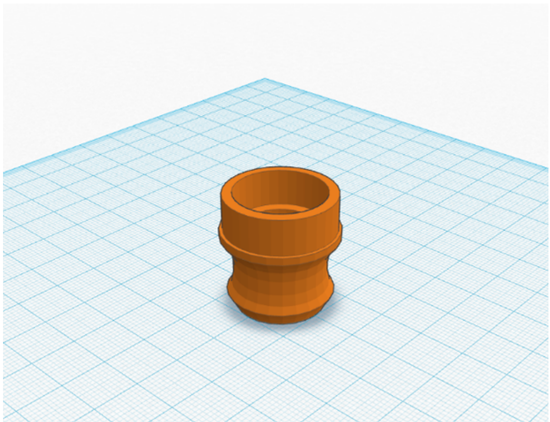


Figure 5.17: **Mouth piece 3D model.**

5.3.5 Wiring

Another goal of the tangible design, as already mentioned in chapter 5.3.1, is a modular concept to support the different components to be separated and recombined. For that reason there should be an easy way to disconnect all the electrical components related to one housing as well as the ACTO extensions from the ACTO base module. So we integrated a 6-pin connector in each tangible to link the electrical elements mounted in the housing (like the sensors, the piezos or the vibration motor) with the ACTO extension. The different wire setups for each tangible are pictured in Figure 5.18.

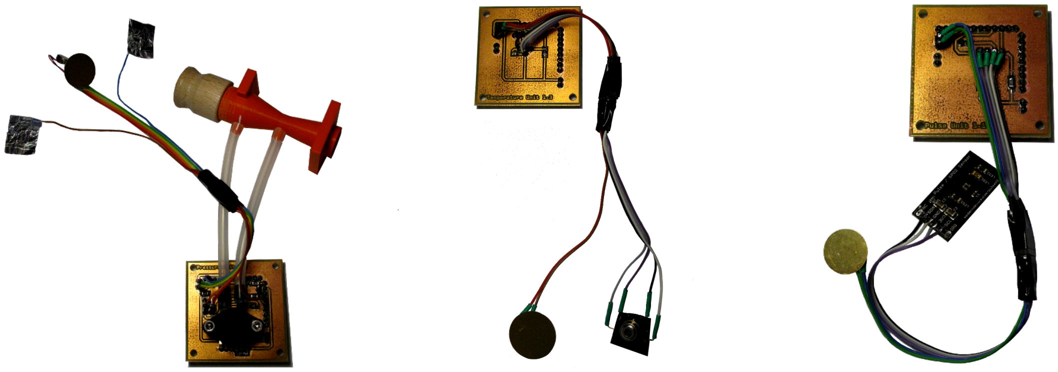


Figure 5.18: **Wiring for lung functionality unit, temperature unit and pulse unit.**

One tangible can then be simply assembled by attaching the ACTO extension onto the ACTO base and motor module, putting the housing containing all the needed components for measurement and feedback over the ACTO parts and finally connecting everything by plugging in the 6-pin connector.

CHAPTER 6

Implementation

The ACTO project, which is used as base for the hardware setup (chapter 5.3.1), also defines a software layer, which describes how the tangibles communicate with each other. The ACTO itself is operated over an Arduino code, that handles the different input and output signals related to a specific ACTO extension. This Arduino code can be implemented in the corresponding open-source Arduino environment, which, as can be seen on the right side of Figure 6.1, enables the developer to easily upload a written program over a USB connection to the ACTOs.

With the help of an integrated radio frequency (RF) unit each ACTO can communicate with an “Arduino Server”, which itself is an Arduino with RF communication capabilities and is linked with an Android smartphone. With this concept the incoming data from a sensor connected with an ACTO is sent wirelessly to the “Arduino Server”, which in turn transfers it to an application running on the smartphone (Figure 6.1). This application called “ACTO Server App” handles the whole processing and graphical interface part and is also able to send signals back to the ACTOs.

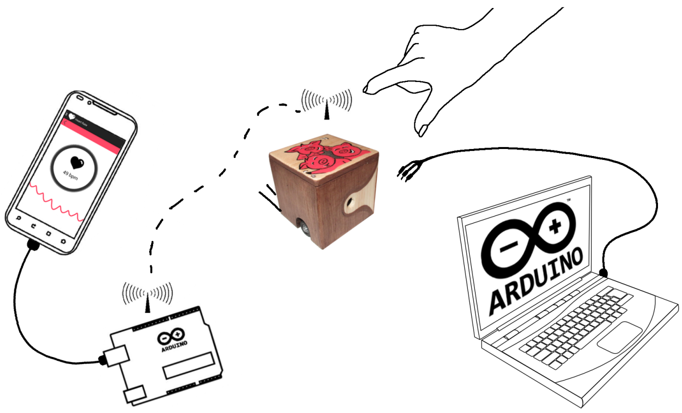


Figure 6.1: **Schematic communication layout.**

Furthermore to recognize the position of the ACTOs the smartphone's front camera is used for tracking. Therefore a fiducial marker is mounted on the bottom side of each ACTO identifies it when placed on top of a glass table with the smartphone lying underneath.

This identification of every ACTO positioned in the range of the camera's view angle makes it possible to send specific translation and rotation data to the tracked ACTOs to drive them to desired positions. Each of these mentioned features needs specific adaptions and support in all involved components of the communication layout, which is provided by the ACTO framework itself. During the implementation for this master thesis this framework was extended and customized for our purposes and is therefore explained in detail in the following subchapters.

6.1 Arduino Code and Setup

The source code for the ACTOs and the "Arduino Server" is written in the Arduino programming language, which is an implementation of $Wiring$ [wirb], a similar physical computing platform, which is based on the $Processing$ [pro] multimedia programming environment. The Arduino code has to process incoming data from the sensors, write output signals to the motor unit, the piezos and to the vibration motor for adequate feedback, provide wireless communication between the two different Arduino systems of the ACTO and the "Arduino Server" unit and exchange data with the "ACTO Server App" running on the smartphone. An overview on how these features are implemented is part of the following subchapters.

6.1.1 Server Arduino

There was no need to modify the Arduino code for the "Arduino Server" used in the ACTO framework for our purposes, because it is just responsible for forwarding two different kinds of incoming data:

- the data received from the ACTOs over the RF unit has to be forwarded to the smartphone over the serial interface.
- the same has to be ensured in the other direction for incoming messages of the smarthpone that should be transmitted to the ACTOs.

6.1.2 Wireless connection between ACTOs and "Arduino Server"

The communication between one ACTO and the "Arduino Server" is realised via the particular RF units. Therefore the RF transceivers are directly connected to the microcontroller via **Serial Peripheral Interface (SPI)**. Within this synchronous connection data can travel in both directions at the same time, but on separate lines (full-duplex bus). This is accomplished by defining one master device - in our case this is the Arduino itself - which is linked by four wires with one or more peripheral devices: One line for sending data from the SPI-controlled device to the Arduino (Master in Slave out - MISO), one line for the opposite direction (Master Out Slave In - MOSI), one line that carries clock pulses to provide synchronisation (Serial Clock - SCK) and a fourth one that has to be specified for each SPI-controlled device to enable or disable it (Slave Select - SS), because SPI has no addressing capability.

There are predefined hardware pins for the different Arduino boards to handle the SPI communication. In our case with a slightly adjusted Arduino Pro Mini for the ACTOs and a Arduino Diecimila for the “Arduino Server” these are the digital pins 11, 12 and 13 for MOSI, MISO and SCK. For the pin that handles the slave selection (SS) any digital pin could be used, the ACTO framework therefore uses pin 9. The whole connection diagram is shown in Figure 6.2.

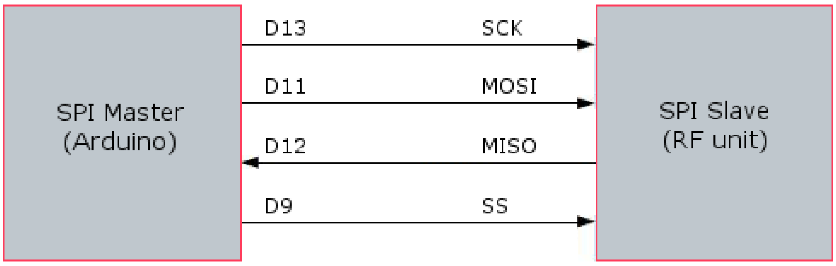


Figure 6.2: **Connection diagram for SPI communication.**

There are different Arduino libraries, which can be used to send data over the integrated RF unit (Nordic nRF24L01+ RF transceiver) and simultaneously take care of the SPI communication. For that purpose the ACTO framework uses the *MIRF library*, which can be downloaded on different websites (e.g. [mir]). With this library after initializing the module by setting the configurable pins, the size of the transmitted bytes, the receiving and sending address, the exchange of data bytes can easily be initiated with a few lines of code.

To identify each message, the ACTO framework determines that the first byte of each message contains a unique command ID which is declared in the Arduino code of the ACTOs and in the one of the “Arduino Server” and reflects the type of the transmitted message (e.g. a message to move the ACTO to a desired position or to set an analog pin to a specific value).

While testing the communication between the ACTOs and the “Arduino Server” we noticed that messages which were explicitly sent to the address of the “Arduino Server” were also received by the ACTOs, which led us to the assumption that the configuration of the receiving and sending address in the MIRF library was not handled in a proper way. This assumption was proven to be right as we took a closer look at the function, which is called when the transmitting address is set. The function does not only set the address to which the message should be sent, but also registers this address as receiving address. The reason for this additional setting is described in the specification of the RF units: By defining the transmitting address as one of the receiving addresses, the receiver of the message is able to send back an acknowledgement message to this same address. For our setup this meant that all ACTOs which set the sending address to the address of the “Arduino Server”, register this address as own receiving address, which leads to the effect that a message which is intended for the “Arduino Server” is additionally sent to all ACTOs. To avoid this behaviour, we set the sending address manually without using the predefined library function.

6.1.3 ACTO Extensions

The three designed ACTO extensions for pulse, lung volume and temperature measurement along with the related sensors also require additional Arduino code on the ACTO side to communicate with the connected sensors and output devices.

Communicating with the medical sensors

The sensors for skin conductance and for the differential pressure are connected directly to the analog pins A0 and A1 on the Arduino board and therefore deliver values between 0 and 1023:

```
int   mpxPin = 0;                    //pin for pressure sensor
mpx = (float)analogRead(mpxPin);
flow = ((mpx/float(1023)-0.04)/0.09);//flow in kilopascal
                                     //transfer function from datasheet
...
int skinPin = 1;                     //pin for skin conductance sensor
skin_conductance = (float)analogRead(skinPin);
```

In contrast to this, the pulse sensor has an **Inter-Integrated Circuit (I2C)** interface, that allows to send data from the sensor in a specific digital format. I2C like SPI is a serial communication protocol, with some fundamental differences:

- I2C supports multiple devices on the same bus without additional select signal lines, like the SS wire with SPI. This is possible, because each device on the bus is independently addressable.
- Furthermore each device can be connected to the bus in any order and devices can be master or slave - so with I2C it is possible to use more than one master. However, for our purposes the Arduino is always the master and the sensors are the slaves.
- I2C only requires two bidirectional signal lines: one for the data (Serial Data Line - SDA) and one for synchronisation purposes (Serial Clock Line - SCL). Like for SPI there are also hardware pins predefined that should be used for I2C communication: on the Arduino Pro Mini these are the pins A4 for SDA and A5 for SCL.
- I2C has been established as an official standard, which provides good compatibility among different I2C implementations.
- I2C ensures that data sent is received by the slave device while SPI does not verify that data is received correctly. That is also the reason why I2C is less susceptible to noise than SPI.
- SPI supports higher speed, while I2C is slower.

Both SCL and SDA lines are “open drain” drivers. This means that the chip can drive its output low, but it cannot drive it high. For the line to be able to go high, there has to be provided a pull-up resistor to the 5v supply from the SCL line and another from the SDA line.

The reason why I2C only uses two wires to communicate with a number of devices lies in the way how communication is handled. Each I2C communication is initiated by the master, that also drives the SCL clock line. It starts with a start sequence on the I2C bus, followed by the 7- or 10-bit address, that calls out the address of the peripheral device, and one bit that defines the direction (0 for write, and 1 for read). Afterwards the master lets the data line float, which means, it is set to high because of the pull-up resistor. If there actually is a device on the bus, that has this particular address, that device will write the next bit as a zero by pulling the data line down.

After this acknowledge bit sent by the slave the data transfer begins and one byte after the other is sent or received, until a special stop sequence or a repeated start sequence is sent by the master.

To differentiate between data transfer and the start and stop sequence, the data line only changes state during the normal transfer of data (from 0 to 1 or from 1 to 0) when the clock is low. This means there are two states left that could be used for the synchronisation events: the transition from 0 to 1 (stop sequence) while the clock is high and the transition from 1 to 0 (start sequence) while the clock is high. An example of the whole procedure is shown in Figure 6.3, with the start sequence followed by the 7-bit address 1100110, the direction bit, the acknowledge bit and the data bytes.

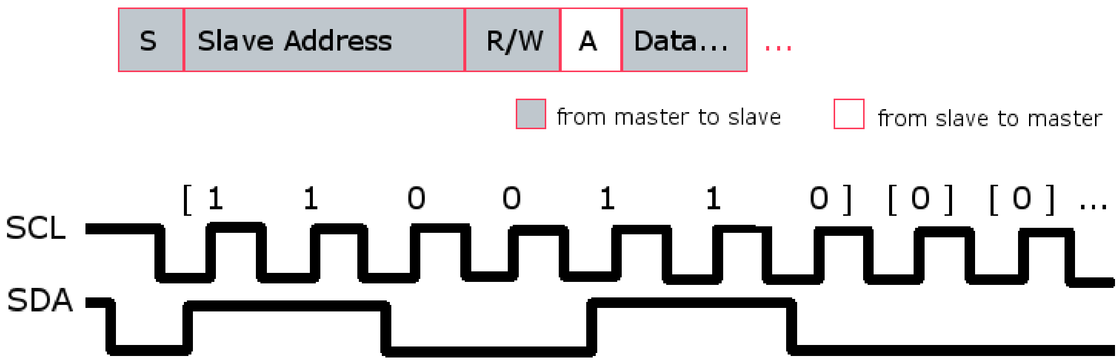


Figure 6.3: **Start bit, address bits, direction bit and acknowledge bit.**

Usually this communication is managed by the Arduino *Wire library* [Wira] and enables the user to apply a few specific methods that take care of the described specification formats. However, in the case of the pulse sensor, we do not need this library, because the developers of the sensor did not only provide the sensor hardware but also an Arduino library for that purpose (*SI1143 library* [SI1]). With the provided library the incoming values of the phototransistor can be retrieved with a few lines of code (beside the initialisation of the pulse sensor):

```
const int portForSI114 = 0;     // port 0 for 18 (A5) and 19 (A4)
PortI2C myBus (portForSI114);
PulsePlug pulse (myBus);

pulse.fetchLedData();           //read the LED registers
red = pulse.ps1;                //emitted red light
IR1 = pulse.ps2;                //emitted infrared light of IR Led 1
IR2 = pulse.ps3;                //emitted infrared light of IR Led 1
```

Although the infrared sensor (MLX90614) also has a 2-wire digital interface it is slightly different to I2C and is called **System Management Bus (SMBus)**. In general, the I2C bus and the SMBus are compatible and act identically in the majority of cases. The most important and for our purpose relevant differences are the minimum clock speed and the defined timeout within the SMBus specification. The I2C bus has no timeout and therefore the slave device never resets its interface. On the other hand the SMBus slaves are expected to reset their interface whenever the clock is low for longer than 35 ms [SMB]. Because of this divergent behaviour in the case of our infrared sensor the standard I2C library for Arduino could not be used. To solve this problem developers who also needed to communicate with this infrared sensor created different libraries. Finally we chose a library called *I2CMaster* [I2Cb] that was adapted from an I2C software library, written in assembler [I2Ca]. The exchange of data over SMBus to read the temperature in celsius then was implemented as shown below:

```
float MLX_temperatureCelcius(int address) {
  int dev = address;
  int data_low = 0,data_high = 0,pec = 0;

  i2c_start_wait(dev+I2C_WRITE);  //write address and write/read bit
  i2c_write(0x07);                //set RAM address
  i2c_rep_start(dev+I2C_READ);    //start reading
  data_low = i2c_readAck();       // Read 1 byte and then send ack.
  data_high = i2c_readAck();      // Read 1 byte and then send ack.
  pec = i2c_readNak();
  i2c_stop();

  double tempFactor = 0.02;       // 0.02 degrees per LSB (measurement
                                  // resolution of the MLX90614).
  double tempData = 0x0000;       // Zero out the data
  int frac;                       // Data past the decimal point

  // This masks off the error bit of the high byte, then moves it left
  // 8 bits and adds the low byte.
  tempData = (double)(((data_high & 0x007F) << 8) + data_low);
  tempData = (tempData * tempFactor)-0.01;
  float celcius = tempData - 273.15; //convert from fahrenheit
  return celcius;
}
```

To avoid any unnecessary overhead some data like the signals of the skin conductance sensor, which are changed very often, are just sent in a predefined reduced frequency. Furthermore, in case of the pulse sensor, an average value of the last incoming signals is computed and the final forwarded value is then a combination of the last computed average and the currently observed value to skip outliers.

Processing the incoming data of the medical sensors

The incoming data of the differential pressure sensor, the skin conductance sensor, the infrared sensor and the sensor for pulse and oxygen saturation has to be processed in an adequate way and sent over the SPI connection to the RF unit. To comply with the ACTO communication protocol this has to be done by fitting each finally computed value with a unique command id for transmitting float values and sending the resulting message via SPI as mentioned in chapter 6.1.2 wirelessly to the "Arduino Server", which relays the incoming message to the smartphone app:

```
const int sizeOfFloatData = 2;
...
void loop()  {
  ...
  setFloatData(0,flow);            //value of venturi tube on index 0
  ...
  setFloatData(1,skin_conductance); //value of skin conductance on index 1
  ...
}

boolean setFloatData(byte id, float val) {
  if (id < sizeOfFloatData) {
      writeFloatMsg(USB_SET_FLOAT, id, val);  //create a new MIRF message
                                              //and send it to ACTO Server
      return true;
  }
  else return false;
}
```

Write output for feedback

To provide feedback when the tangible is held correctly, a sound is played as soon as the sensors are able to read user data and another sound as soon as the signal is lost. For that purpose the standard Arduino library has included some functions to generate waves:

```
#define SPEAKER 2

//play sound for correct holding
tone(SPEAKER,392,35);  //generates a wave of the specified frequency
                       //and duration in milliseconds on the speaker pin
```

```
actoDelay(35);
tone(SPEAKER,784,35);
actoDelay(35);
tone(SPEAKER,1568,35);
actoDelay(35);
noTone(SPEAKER);          //stops the generation of a wave triggered
                          //by tone()

//play sound for lost user signal
// Run through the notes one at a time
for (int note = 1; note < (freqs[0] * 2 + 1); note = note + 2) {
  tone(SPEAKER, freqs[note], (1000/freqs[note + 1])); //play the note
  actoDelay((1000/freqs[note + 1]) * 1.30);            //delay
  noTone(SPEAKER);
}
```

During the game play the vibration motor for prompting the user to blow into the venturi tube should be controlled by the "ACTO Server App". To comply with such requirements the ACTO framework also provides some predefined methods to easily write output sent from the "ACTO Server App" to specific ACTO pins. If a message, that contains the unique command ID for setting a digital output pin as first byte, is received from the "Arduino Server", it is verified in the next step if the second transmitted byte equals one output pin in a predefined list. If that is the case, the third byte is written to the output pin:

```
const int digitalOutputPins[] = {4};//4=vibrator motor
...
if(Mirf.dataReady()){
  Mirf.getData((byte *)&inMirfBuffer);      //read message
  switch (inMirfBuffer[0]) {
    ...
    case USB_SET_DI_UNIT: //5- format: CMD,ID,dataID(byte),data(byte),SEP
      if (inMirfBuffer[2] < sizeOfDigitalOutput) {
          digitalWrite(digitalOutputPins[(int)inMirfBuffer[2]],
          (int)inMirfBuffer[3]);
      }
      else writeMirfAck(false);
        break;
    ...
  }
}
```

With this concept the output pins for different extensions can easily be modified in each template and no further code has to be changed. The corresponding code in the "ACTO Server App", that is responsible for sending such messages, will be explained in subsection 6.2.5.

Motor unit

Beside the code for communicating over the RF units and the adaptions for the used extensions, the Arduino template for the ACTOs also contains an additional code section that controls the motor unit. The motor unit is originally connected with the ACTO base module over the analog pins A4 and A5, which are actually also the hardware pins for SDA and SCL for the I2C bus and SMBus and therefore needed for the pulse and infrared sensor as explained above. So in the template code and the hardware setup, the pins used for the left and right motor had to be changed from A4 and A5 to A2 and A3.

6.2 Implementation of the game play

Our whole implementation of the game logic, the graphical user interface, the visualization of the recordings and the communication with the "Arduino Server" is integrated in a smartphone application, written in Java and compatible with Android 4.0 and higher.

6.2.1 ACTO Server App

The "ACTO Server App" of the framework takes care of tracking the ACTOs and handling the incoming and outcoming messages. For tracking the framework integrates the *Metaio SDK 5.3* [Met], a free to use development toolkit that supports Augmented Reality applications with various optical tracking and visualization methods.

Furthermore the framework manages the communication with the "Arduino Server", therefore it processes incoming messages from the ACTOs and sends different commands back to them, like moving to a specific position or writing an output to a desired pin. The "ACTO Server App" also handles collision avoidance of the different ACTOs and implements calibration algorithms for the interactive surface. All these functionalities are already implemented in the framework and just have been extended in a way to fulfil our requirements for a medical game.

6.2.2 Database connection

One major extension to the existing framework was to establish a database connection to save the measured recordings for different users. Android provides full support for SQLite databases, to store structured data in a private database. Therefore the database is accessible by name to any class in the application, but not outside the application. For that purpose we created a new SQLite database with three tables, that contain all the data that has to be saved persistently, and is described in detail in the next section.

Data representation

To save "games", which represent one tracking and data acquiring session with the help of the tangibles, for different users along with the measured values, three database tables are necessary (Figure 6.4).

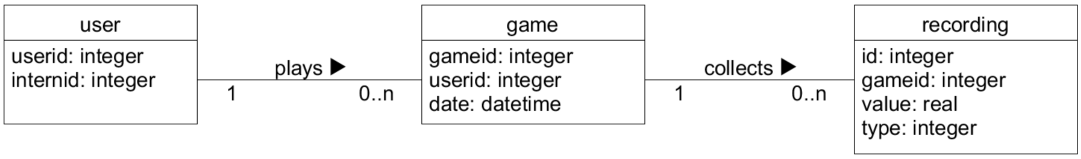


Figure 6.4: **Entity Relationship Diagram for the “StoryCubes” application.**

The $internid$ in the table $user$ corresponds with the id of the contacts in the “people” application installed on every Android smartphone. This reference makes it possible to add users to our application by choosing one of the existing contacts saved on the smartphone. The benefit of this approach is to automatically transfer the name and an optional image without entering it another time, especially for people that are already saved as contacts.

To differentiate between games, each game has an additional field $date$, consisting of date and time when the game was started. A recorded measured value is then identified by an id, a $gameid$ and a $type$. The integer value of the attribute $type$ corresponds to the ordinal value of an enum data type:

```
public enum ValueType {vtheart, vtoxygen, vtlung, vttemperature,
                       vtskinConductance, vtheartRaw};
```

The reason for a second type of heart measurement is, that $vtheart$ is related to the computed beats per minute and $vtheartRaw$ to the raw values of the reflected light to present the process of heart beating also in a visual way.

This database tables are represented by three different classes in the source code called $MedicalUser$, $MedicalGame$ and $MedicalData$.

Database access

To create a new database a subclass of $SQLiteOpenHelper$ called $DatabaseReaderHelper$ is created and as well as the $onCreate()$ method, in which an SQLite command to create tables in the database is executed, is overridden with the execution of the SQL statements that creates our database. Additionally this helper class controls version management. This is done by incrementing the database version stored in a static field called $DATABASE\_VERSION$ every time the database schema needs to be changed. For that purpose also the $onUpgrade()$ method has to be overridden with the execution of the sql statements for deleting the whole database structure and the ones that recreate it. These sql statements are stored in the separate $MedicalDatabase$ class, which also contains the names of the whole database structure:

```
public class DatabaseReaderHelper extends SQLiteOpenHelper {
  public static final int DATABASE_VERSION = 5;
  public static final String DATABASE_NAME = "medicalmonitor.db";
```

```
    public DatabaseReaderHelper(Context context) {
        super(context, DATABASE_NAME, null, DATABASE_VERSION);
    }

    @Override
    public void onCreate(SQLiteDatabase db) {
        //sql statements that creates the three tables
        db.execSQL(MedicalDatabase.SQL_CREATE_USER_ENTRY);
        db.execSQL(MedicalDatabase.SQL_CREATE_GAME_ENTRY);
        db.execSQL(MedicalDatabase.SQL_CREATE_RECORDING_ENTRY);
    }
    @Override
    public void onUpgrade(SQLiteDatabase db,int oldVersion,int newVersion){
        //if the database version is higher than the last time
        //first delete all tables and then recreate them
        db.execSQL(MedicalDatabase.SQL_DELETE_USER_ENTRY);
        db.execSQL(MedicalDatabase.SQL_DELETE_GAME_ENTRY);
        db.execSQL(MedicalDatabase.SQL_DELETE_RECORDING_ENTRY);
        onCreate(db);
    }
}
```

To use the $DatabaseReaderHelper$ class the $SQLiteOpenHelper$ provides two different methods: $getWritableDatabase()$ and $getReadableDatabase()$ for writing to and reading from the database. These methods return an $SQLiteDatabase$ object that represents the database and provides methods for SQLite operations. For example all stored games related to one specific user are read and added one by one - capsulated in a $MedicalGame$ object - to a list with the following code lines:

```
public List<MedicalGame> getAllGames(long aUserID) {
    List<MedicalGame> gamelist = new ArrayList<MedicalGame>();
    DatabaseReaderHelper mDbHelper = new DatabaseReaderHelper(getBaseContext()
        );
    SQLiteDatabase db = mDbHelper.getReadableDatabase();

    Cursor cursor = db.query(GameEntity.TABLE_GAME,
                             new String[] { GameEntity.COLUMN_GAME_ID,
                                            GameEntity.COLUMN_GAME_DATE },
                             GameEntity.COLUMN_GAME_USERID + "=?",
                             new String[] { String.valueOf(aUserID) },
                             GameEntity.COLUMN_GAME_ID, null, null, null);

    // looping through all rows and adding to list
    if (cursor.moveToFirst()) {
        do {
            MedicalGame game = new MedicalGame(getBaseContext());
            game.setID(Integer.parseInt(cursor.getString(0)));
            game.setDate(cursor.getString(1));
```

```
            // Adding contact to list
            gamelist.add(game);
        } while (cursor.moveToNext());
    }
    cursor.close();
    db.close();
    return gamelist;
}
```

In SQLite databases when deleting a record that has an "on delete cascade reference" in another table, the enforcement of foreign key constraints has to be activated by executing this statement:

```
db.execSQL("PRAGMA foreign_keys=ON");
```

Otherwise if a user is deleted, the records in the tables *game* and *recording*, which are connected with the *user* table over an "on delete cascade reference", would still remain in the database.

Another challenge regarding database access came up when we first tried to save the recorded medical values. Caused by the huge amount of generated records, the creation of the database helper class and the required sql statements for each single value was very time-consuming. Even when the records were summed up in a list and only saved all together after the recording stopped, the storage process took up to two minutes, caused by the $insert()$ method of the database helper class, which has to be executed for every record. After taking a look at this method we found out, that every $insert()$ starts and ends a transaction, which leads to this long processing time. So instead of using the predefined methods of the helper class for this large number of records, we create our own $SQLiteStatement$ object, execute it for every record and add a single transaction for all these inserts. This adaption reduced the saving time of all generated records from 10 seconds to under one second and can be seen in the next code snippet:

```
db.beginTransaction();
try {
    SQLiteStatement insert = db.compileStatement(sql_insert);
    for (int i = 0; i < data_list.size(); i++) {
        valType=data_list.get(i).getvalType();
        fData=data_list.get(i).getValue();
        insert.bindLong(1, gameid);
        insert.bindLong(2, valType.ordinal());
        insert.bindString(3, Float.toString(fData));
        insert.executeInsert();
    }
    db.setTransactionSuccessful();
} finally {
    db.endTransaction();
}
```

Database debugging

To debug and monitor the database content while inserting or deleting during the development phase we used a free to use *Database Manager library for Android SQLite databases* [DMA14]. This library consists of just one single activity class, that can easily be embedded in every application with a few lines of code. With the help of this library the database can be managed directly inside the implemented application itself. With a few clicks rows can be updated, deleted or inserted, even custom queries can be executed. Furthermore we used it to verify if the "on delete cascade reference" foreign keys work in a proper way, for example when users were deleted. One screen that shows the content of the table $recording$ is shown in Figure 6.5.

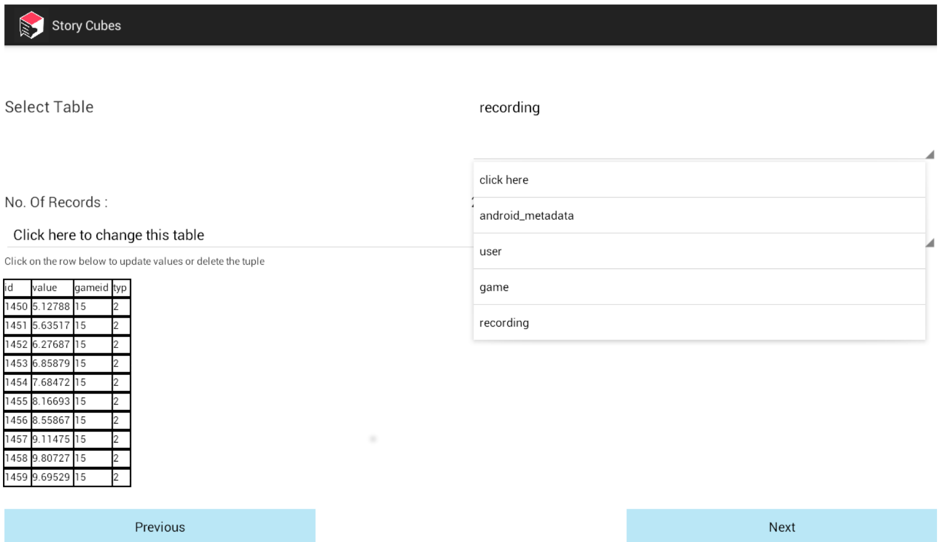


Figure 6.5: **DatabaseManager for Android.**

6.2.3 Sensor values

The incoming messages in the ACTO framework sent from the ACTOs are received as USB messages. As described in section 6.1.3 the medical values are fitted with a unique command id for transmitting float values and therefore can be defined as such when they arrive in the ACTO framework. With this unique command, the three subsequent bytes in the message can be parsed as:

- id: The first byte contains the ID of the sending ACTO to differentiate between our three tangibles.
- dataid: The second byte is an index value that is needed to distinguish different float values sent by one ACTO. In our project just the cube with the venturi tube inside delivers two such different float values and therefore needs one index for the measured values of the venturi tube and a different one for the values from the skin conductance sensor, which is also part of this tangible.

- fdata: Finally the last byte contains the measured float value.

With these three parameters each incoming float message can be clearly assigned to one medical sensor.

6.2.4 Structures for the game logic

Since the theoretical background of the game mechanics and logic were already described in chapter 5.1.3, this section is about the implementation of the described concept.

The main implementation of the game logic is managed in the class $ACTOGUI$, which contains a $playList$ filled with $MedicalGamePlay$ items (Figure 6.6). This list is processed step by step, by incrementing the variable $playIndex$. Therefore the current item defines which medical value needs to be recorded and which audio file is correlated with it. So if an incoming value of one of the ACTOs is received, the method $isRightTangible$ verifies if the corresponding medical sensor equals the one defined in the $playList$ and if that is the case the playback of the corresponding audio file is started.

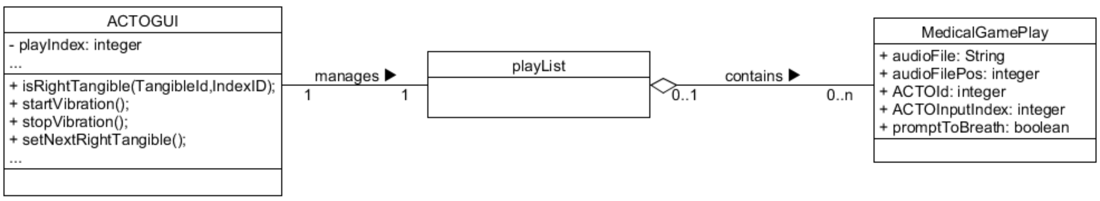


Figure 6.6: **List of *MedicalGamePlay* items.**

As already mentioned each $MedicalGamePlay$ object corresponds to one audio file and to one medical sensor connected to a tangible on a specific input pin. Thereby the assigned tangible is specified in the field $ACTOId$ and the input pin in the field $ACTOInputIndex$. Such a $MedicalGamePlay$ object has different states during the game play: At the beginning each $MedicalGamePlay$ object has the state “untold” and reflects the situation that the audio file of this $playList$ item will be set to the very beginning. Afterwards if the “correct” cube is held, the object state moves to “telling” and the playback of the audio file begins. When the part of the story corresponding to this list object is over and the cube was held the whole time, the state switches to “told”. Otherwise if the cube is released before the part of the story is over, the story is paused, the object gets in a “waiting” state and after another 30 seconds is set back to the start state “untold”. When the cube is held again before the 30 seconds expire, the audio file will be continued from the position where it was paused until the story is over and the state switches to “told”. In the $entry()$ function of the state “told” the next $MedicalGamePlay$ object in the list will be set as the current one. If the next object is the one with the breathing tube, the vibration motor will start to vibrate after 10 without no incoming data, to prompt the user to breathe into the tube. The entire state diagram of the $MedicalGamePlay$ items is shown in Figure 6.7.

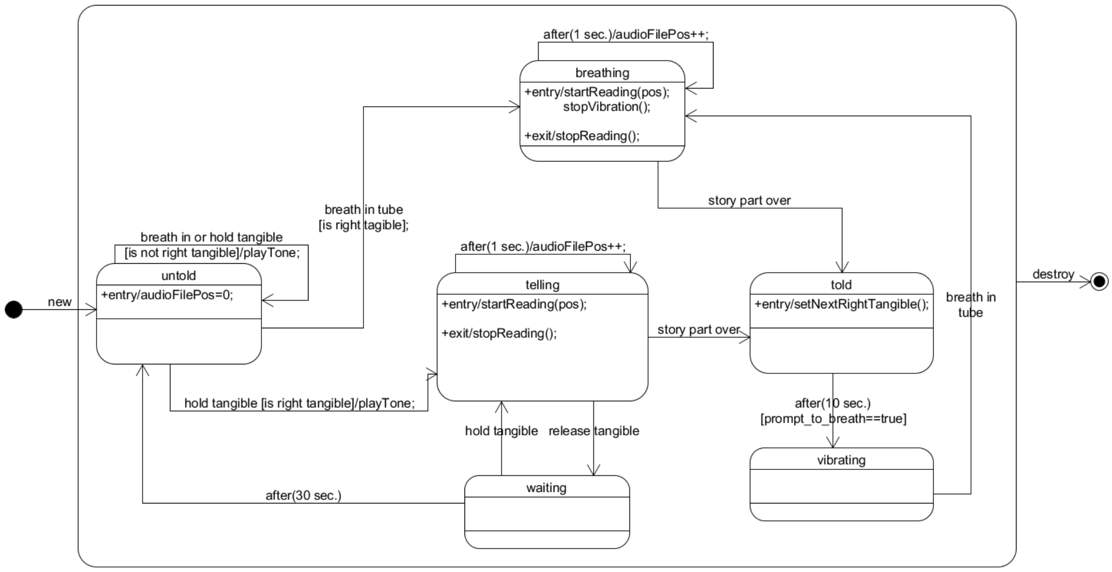


Figure 6.7: **State diagram of a *MedicalGamePlay* object.**

6.2.5 Controlling the vibration motor

The vibration motor is controlled over a scheduled task which first fires after 10 seconds and then every other 10 seconds. When creating this task with a $ScheduledExecutorService$ the result is a $ScheduledFuture$ object that can easily be cancelled by calling the method $cancel()$ when the motor should stop vibrating. To make the motor periodically vibrate in this task it is set to high and low by sending a USB message to the "Arduino Server". This message includes a unique id for setting a digital output on the ACTOs, the id of the targeted tangible, the index of the digital output that should be changed and if the output should be set to low or high:

```
motorthread =   VibrationgScheduler.scheduleAtFixedRate(new Runnable() {
  public void run() {
    setTuioExt(ACTOConst.USB_SET_DI_UNIT,
               new ACTOData(ACTOData.DATA_BYTE,(byte)'1',(byte)0,(byte)1));
    try {
      Thread.sleep(500);
    } catch (InterruptedException ex) {
      System.err.println(ex.toString());
    }
    setTuioExt(ACTOConst.USB_SET_DI_UNIT,
               new ACTOData(ACTOData.DATA_BYTE,(byte)'1',(byte)0,(byte)0));
  }
}, 10, 10, TimeUnit.SECONDS);
```

6.2.6 Playback of the audio parts

To illustrate the playback of the audio files the state diagram in Figure 6.7 shows the incrementation of the counter $audioFilePos$ for each audio file. This is just a simplified schematic representation of the implementation behind it. In our implemented $ACTOGUI$ the whole audio playback is controlled by the $MediaPlayer$ class provided by the Android API. Within this class, a $MediaPlayer$ object changes between different states driven by the supported playback control operations. An excerpt of the whole life cycle diagram is shown in Figure 6.8, which contains the states and operations that are relevant for our game.

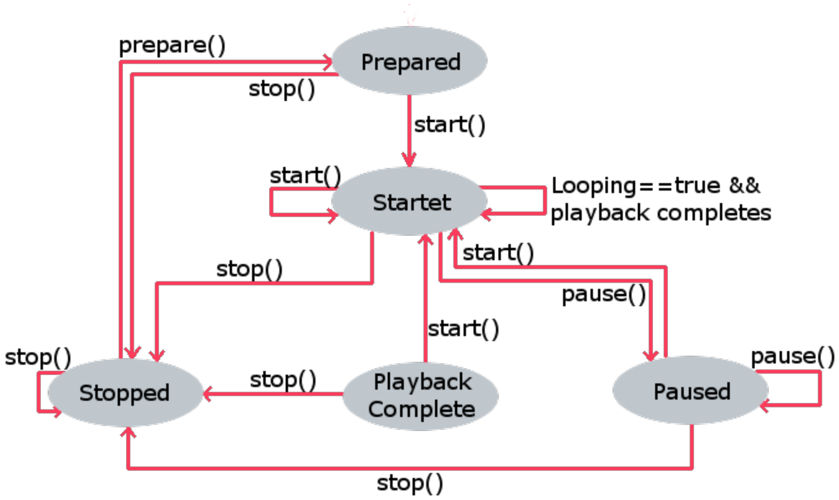


Figure 6.8: ***MediaPlayer* state diagram.**

To pause and stop the currently playing audio file the methods $pause()$ and $stop()$ are called in two separated $CountDownTimer$ objects. The first timer pauses the audio file in its $onfinish()$ method after one second and the second timer stops the audio file after 30 seconds without incoming data.

For our setup we created nine audio files to tell the story of a German version of the fairy tale “Three Little Pigs”. The original material for these audio files was broadcasted on the german/french TV station ARTE as part of a documentary intended for children [ART11]. To comply with our game mechanics and the use of three different tangibles, the original story was shortened, split into appropriate parts and compressed as MP3 file. The compression was an essential step, because it reduced the size of the application package from over 75 MB with the previously used WAV files to around 25 MB.

There are different download platforms, which also offer free audio books, that could be used for further stories (e.g. `http://vorleser.net`). The sound that is played when the breathing tube is used is downloaded from the free sound portal *SoundBible* [sou].

6.2.7 Rotation of the tangibles

Instead of using sound to advise the user to pick up a certain cube, we decided to slightly shake the cubes from left to right, because we think that movement is even more inviting than sound.

To assure that the tangibles are grasped at the sides, where the sensors are positioned, the orientation of them can be changed after this shaking during the game. Therefore at the beginning of each game the rotation of every tangible is stored and the motor unit can be triggered at any time to resume these memorized rotation coordinates. To request all current positions when calibrating, the function $getFullPose()$ is called, which results in incoming asynchronous messages containing the position and rotation of each tangible. These incoming messages are handled in the method $onTuioPoseUpdate()$ of the $ACTOActivity$, which updates the stored position of the particular tangibles.

In that way, the tangibles can be rearranged automatically, if the user has released a cube and put it down on the table. To rotate the tangibles to the stored values, the framework provides the function $setTuioRot()$, which sends the rotation array to the passed id of the tangible, that should be moved:

```
for (int i = 0; i < cube_poses.size(); i++) {
  ACTOData pose = cube_poses.get(i);
  setTuioRot((byte)+pose.id, pose.rotation);
}
```

6.3 Visualization of the recordings

To visualize the medical measurements, the implemented application on the one hand offers an overview of the measured values recorded during all played games and on the other hand a detail view of a specific medical value that illustrates the progress between and during the different games.

To provide such a progress illustration we were searching for a graph view library that could easily be filled with hundreds of values and can be adapted to match the design of our application. Finally we found an open source library for Android called *MPAndroidChart* [Cha14] that supports customizable line charts, as well as scaling, dragging and selecting but furthermore provided all functionalities that are needed for our purpose. With the help of this library all recorded values of one sensor can be loaded into the graph at one time, several labels, lines or borders can be enabled and the line color and width can be manually set.

To reach the overview page (Figure 6.9) in the first screen of the implemented application a user has to be selected. Therefore either an already added user can be chosen or a new one can be searched in the contact list of the smartphone. Then the contact photo of the chosen user is shown in the overview page on the top right, next to the button for starting a new game. When starting a new game the previously described game starts and the values measured by the sensors will be stored permanently.

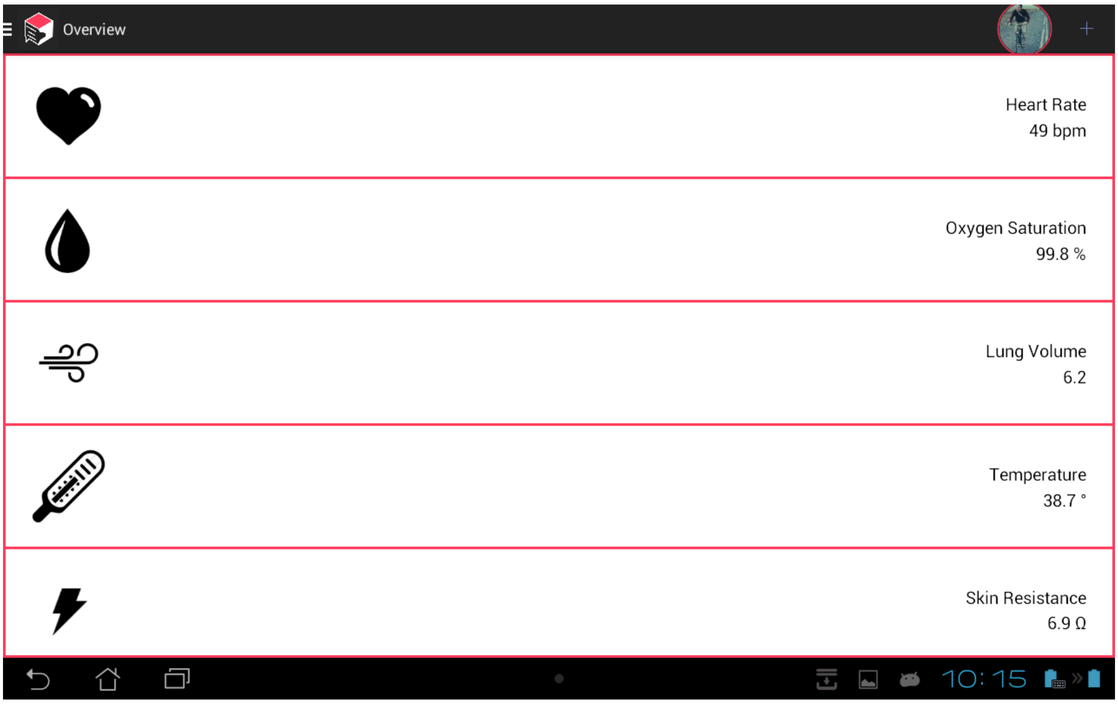


Figure 6.9: **Overview page.**

The icons used as symbols for heart rate, blood oxygen, temperature, lung volume and skin conductance are slightly adapted versions of free to use icons [ico].

After finishing the game, the overview page computes the overall average of each medical indicator. By selecting one of these averaged values a graph visualization can be loaded (Figure 6.10).

Figure 6.10: **Detail pages.**

Within this detail view the user can look through all played games by swiping to the right or left side and has therefore a detailed breakdown of this specific medical value over a specific time. The complete path to all windows inside the application is shown in detail in Figure 6.11.

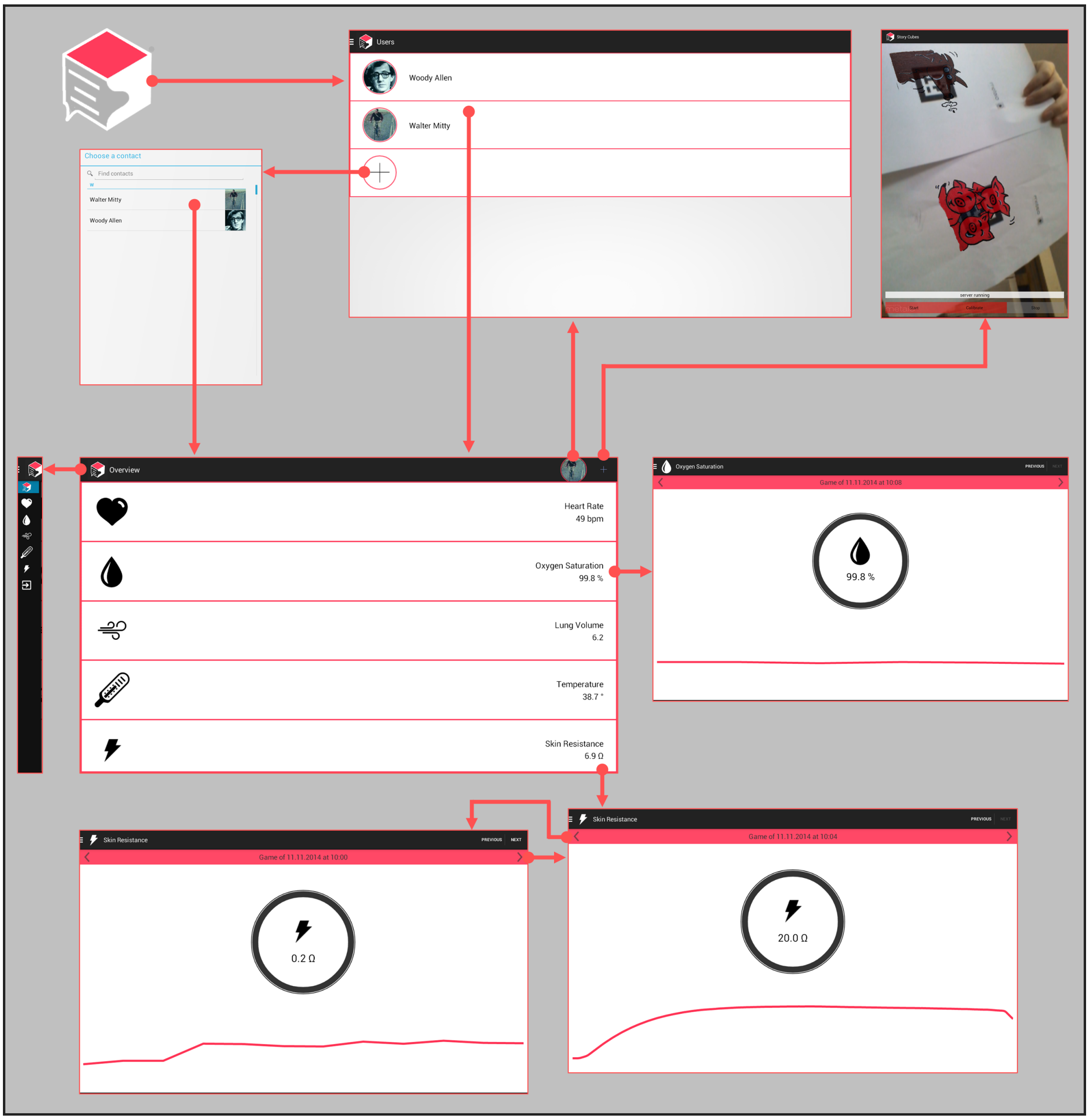


Figure 6.11: **Path to the different application windows.**

CHAPTER 7

Evaluation

Testing the interactivity of a product is more than the look and feel or the functionality of it. So one way to analyse the usability and to see if our concept also works with children is to watch them interact with the cubes. According to Markopoulos et al. [MRMH08] the goal of such an unstructured passive observation, where interaction with the participant should be as minimal as possible, is to uncover unexpected issues and usage patterns. They also describe that interactivity of a product can only be really discovered by observing it in use or predicting its use [MRMH08, p. 22].

On the other hand an observation with no structured observation guide can produce data that is too diverse or too hard to analyse [MRMH08]. But due to our game logic and the fact that there is just one possible sequence of actions to reach the end of the story, an unstructured observation would not produce too widely spread results. Furthermore such a non-task-based testing leaves more room for free exploration, which offers a good user experience and verifies if the game itself can guide the children's action [MRMH08, p. 98].

Therefore, after completing the hardware and software, we evaluated our implemented design by observing children and adults playing with the story cubes and with a subsequent questionnaire with the observed users and the parents of the younger participants.

7.1 Participants and evaluation method

Before evaluating the interface with children, we decided to test the usability of the game and the accuracy of the measured medical values recorded during a game play, with 14 adults. Two of them were used as a pilot study to identify possible problems regarding the design of the interface and the test setup.

The monitored values can be compared to the data of a conventional pulse oximeter and a infrared temperature device to identify a possible deviation of these two methods. An additional advantage of this prior testing with adults is that it is possible to fix some potential problems and adjust some parameters to improve the game play before the children's test takes place.

Finally, after this evaluation with adult participants, we started an observation study with 8 children aged between 5 and 12 to see if the game is also understandable and easy to use for younger users, which should be the target audience for our developed concept. The age distribution of all participants can be seen in Figure 7.1.

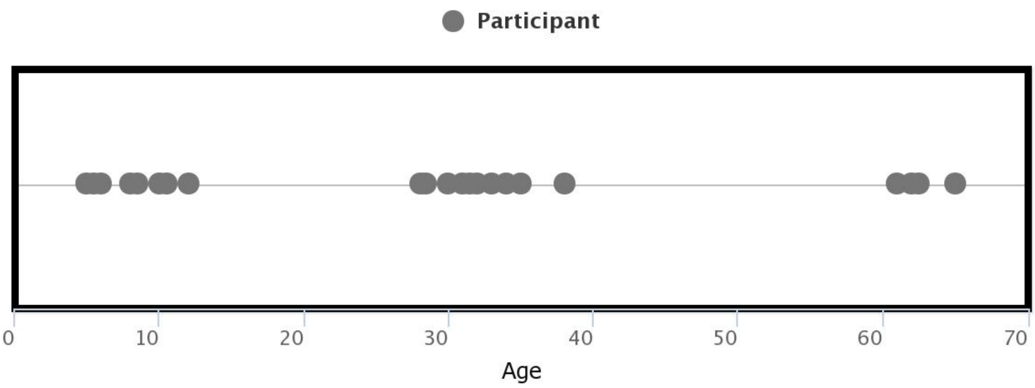


Figure 7.1: **Participants age distribution.**

7.2 Location and Setup

An important decision, especially when children are involved, is the location for the test setting [MRMH08]. To avoid a formal setup and to reduce the stress factor for children and also for adult participants we chose to test in familiar environments, like their homes or other places where they often spend their time. The setup for all participants was the same and consists mainly of the following components:

- A well-lit glass table with a tablet laying underneath, with the "StoryCubes" application installed. The tablet's camera is directed to the bottom side of the glass table to track the cubes when they are positioned on the table (Figure 7.2)
- A chair for the user to sit in front of the glass table.
- The three story cubes positioned on the table in a specific order, as can be seen in Figure 7.3.
- Audio speakers, to grant a good sound experience and also to easily adjust the volume of the story.
- A video camera to record the session.
- An evaluator, who introduces the test procedure and helps filling out the questionnaires.
- An additional team member, whose function is to manage the recording of the camera, to activate the "StoryCubes" application and to switch on the story cubes.

Furthermore to guarantee the playback of the story even when the sensors do not work in a normal way (e.g. if the participant has too cold fingers, the temperature sensor does not recognize if the cube is held) a fourth cube is used by the evaluator or the second team member to simulate the correct functionality to avoid distracting the tested person.

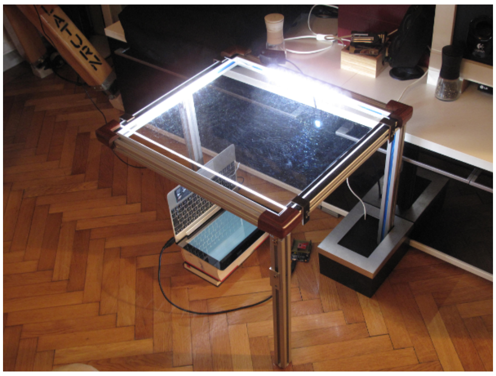


Figure 7.2: **Interactive table.**

Figure 7.3: **Initial cube positions.**

7.3 Procedure

Prior to beginning, participants or in the case of children their parents are asked to sign a consent form and complete the first page of a survey with questions about their current emotional state (the questionnaires are discussed in detail on the next page and can be found in the appendix in section A.2). The parents or the evaluator helped the younger participants with this task.

Afterwards a team member starts the camera and the evaluator introduces the participant to the setup. For the pilot study with two adult participants we decided to give as few hints as possible how to handle the cubes and just said that the three cubes positioned on the table can tell a story if they are handled correctly. Based on the results of this pilot study, which are described in detail in section 7.5, we extended the introduction for the remaining adults and children and included the information that the cubes tell a story as long as the cubes were held correctly.

After the introduction part, the first 10 seconds of the story are played back automatically and stop with the words "the three little pigs". These words should provide an indication to pick up the cube with an illustration of the three little pigs on the top. Furthermore this cube starts to slightly shake from left to right to emphasize the desired action even more. If the cube is then picked up and held correctly the story goes on until the story stops another time with the word "house" and the cube relating to this part of the story starts to shake. Again, if this cube is held correctly the next part of the story is played back. This way, each part of the story is played back after the other by holding different cubes at specific times.

Finally with the last cube, the story stops with the words "Then I'll huff and I'll puff and I'll blow your house in", which should motivate the participant to blow into the tube of the third cube.

If any of these actions is not recognized by the participants after a specific time, the evaluator gives some hints on what to do next. Furthermore after every shaking action the cubes rotate to a predefined position, so they can be grasped more easily.

After the game is finished and the story has ended, the participants are asked to fill out the remaining questions of their questionnaire and the team members are thanking them for the participation and help. The game duration along with the time that is needed for completing the questionnaire lasts about 15 minutes.

In the case of the children's tests they are rewarded with a printed certificate (shown in section A.1 in the appendix) stating how helpful they were and personalized the certificates with the child's name.

After their first round of play two adult participants were asked to play another time after 3 minutes of physical exercise to test if the recorded values vary after this workout. As a comparison another two adults played the game a second time without workout in between to see if the recorded values of both rounds were consistent.

7.4 Data collection

Data for evaluation is collected in different ways. On the one hand by recording the measured medical values and the behaviour while playing and on the other hand by analysing the questionnaires.

7.4.1 Video Analysis

As already mentioned the whole game play session of every participant is recorded via video camera. Afterwards the recordings of all participants are manually analysed by specific criteria, like:

- Did they know which cube was to be held next? When did they realize that?
- Was the cube held correctly to allow recording the medical data? If not, which hints did they need to hold it correctly?
- Did they use their left hand to pick up and hold a cube?
- Did they hold the cubes mainly with two hands?
- Did they use the breathing tube correctly?
- How fast did they switch between the different cubes?

7.4.2 Questionnaires

As described by Markopoulos et al. [MRMH08] designing surveys for children needs even more effort than for adult participants. Children are often affected by the person who asks the questions and stressed by unknown situations. For that purpose questions that are just answerable with "Yes" or "No" should be used as little as possible, because children would take mostly "Yes" to please the evaluator and to quickly finish the questionnaire. So we decided to include some free-recall questions, since they are more useful with children and offer more analysable results, especially with spoken surveys [RM06].

Furthermore to get a rating of some of the asked questions we, integrated pictorial representations that children can use to identify their feelings or opinions. Such representations are a widely used question format and an alternative to the traditional open-ended and closed question formats.

Therefore we used a scale based on the Smileyometer, which is part of a known toolkit to measure enjoyment and fun developed by Read and MacFarlane [RM06]. The set of five pictorial representations shown in Figure 7.4 depicts a range of feelings from awful to brilliant.

Figure 7.4: **Smileyometer.**

To get an overview of the perceived desirability while interacting with our game design, we utilized a toolkit developed by Microsoft called "Product Reaction Cards" [BM02]. This method to measure desirability consists of a set of adjectives participants could use to describe their reactions to a user interface. In our questionnaire for adults and parents we asked to look at these adjectives and to select five words that matches their personal reactions to the system they had just used most closely.

With these different question formats combined in three surveys for the different participant groups we tried to analyse and to better understand the user experience while playing and what possible challenges and problems could come with it. Since all participants are German native speakers, the three questionnaires are also in German and can be found in the appendix in section A.2.

7.5 Pilot study

As already mentioned we conducted a pre-test with two adults to identify possible problems. During these tests a few minor issues were recognized, which were improved prior to the actual user study:

- The time that had to expire before the next cube is shaking was too long. The first participants were quite irritated which cube should be held next. So we reduced the time from 6 to 2 seconds, which led to much better results with the remaining adults and children.

- We often used a bluetooth receiver for the playback of the audio signals. Occasionally there were delays with this setup, which resulted in absence of the first 2 seconds of each audio track. This was fixed by adding 2 seconds of silence at the beginning of every part of the story.

- Furthermore, we extended the introductory words at the beginning of each test. By just saying that the cubes are able to tell a story, the participants needed almost the entire playing time to understand the game concept. These participants all thought that just by touching the cubes the story starts and they did not recognize that they had to hold them the whole time. So for the remaining participants we added the information that the cubes tell a story as long as they were held correctly.

7.6 Results

The information gathered from the different data sources during our evaluation, namely video analyses, questionnaires and recorded medical values, can be structured in two main categories: the accuracy and comparability of the measurements as well as the usability of the developed interface. They are discussed in the following subchapters.

7.6.1 Interface usability

Due to the adaptations after the pilot study, the remaining 11 adult participants needed nearly no further hints when interacting with the cubes and they intuitively held the cubes in a correct way, as shown in Figure 7.5. Except for two elderly participants all users recognized where to hold the cubes and which cube comes next. Only with the blowing part some participants needed advice on what to do next or a simple confirmation that their guess was right. However, all participants used the tube the right way, meaning they blew into the mouth piece. Subsequent blowing story parts were solved without further assistance (Figure 7.6).

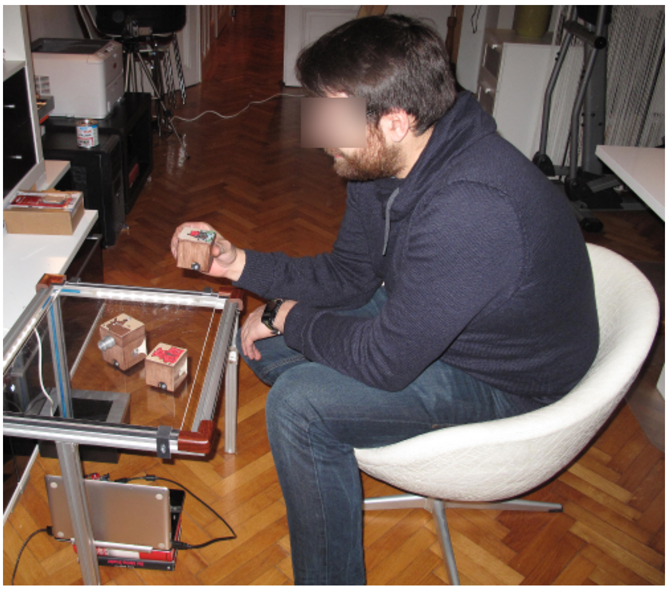


Figure 7.5: **Correct holding of the cubes.**

Figure 7.6: **Tube interaction.**

After the usability test with adults the evaluation with children on the one hand confirmed the positive feedback and on the other hand showed some new issues that did not appear with adults.

The observation of the 8 children while playing and the analysis of the recorded video material with the help of predefined questions brought us to these main findings:

- Picking up action: For all children the shaking of the cube was sufficient to hint them to pick the correct cube next. Just two of them were looking to the evaluator to get a confirmation for their guess. For further cubes half of the participants were waiting until the next cube was shaking and the other half knew which cube they had to pick next because of the picture on the top side of it and therefore picked them up before they started shaking.

- Picking up grip configuration: One interesting observation was the fact that slightly over 35% of the children were picking up a cube with the left hand, if this hand was closer to the cube (Figure 7.7). Because the cubes were constructed to be handled with the right hand, this behaviour lead to some complications regarding the coverage of the sensors on these cubes. The same problem occured with one participant who was the only left-handed child.

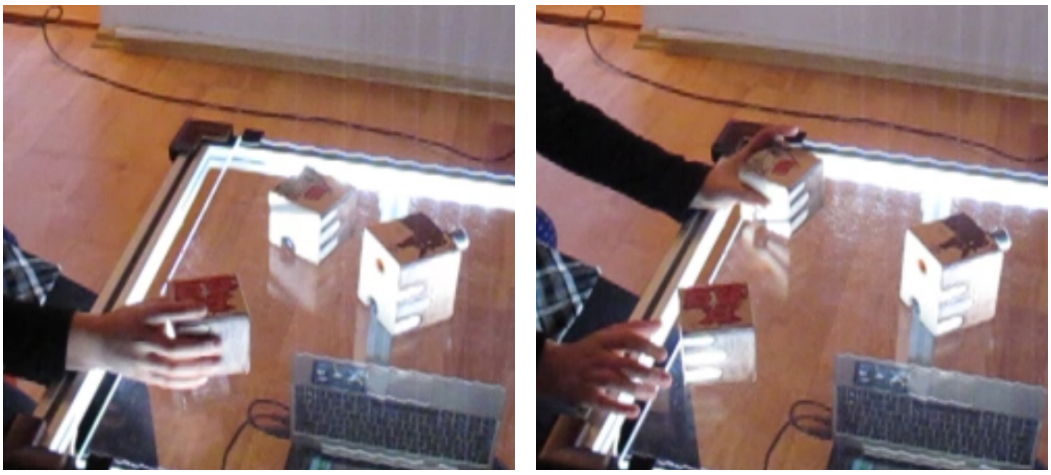


Figure 7.7: **Pick-up behaviour when cube is closer to right hand or to left hand.**

- Cube holding: With the exception of the two youngest participants, the cubes were all held with just one hand. One of these youngest children used the left hand just in a supportive way, while the other child used both hands in an equivalent way. Two other participants put down one or more cubes before the part of the story was over. But both realized that they had to pick up these cubes again, since they were starting to shake, and that they should hold them for the entire part of the story.

- Using the breathing tube: As already observed during the adult usability testing, also the children did not intuitively know that they should breathe into the tube. But with the additional information that they should blow the house away, all participants, with the exception of of one child, breathed instantly into the correct side of the tube. For the remaining three times where participants had to use the tube, just the youngest participant needed further advice, the others realized the usage on their own. Since this cube was standing in the middle of the table just one participant was holding it initially with the left hand and therefore needed more time to find the correct handling of the breathing tube. Figure 7.8 is showing this circumstance in the second row and fourth column: Although the participant had switched the cube to the right hand, it was not held on the sides with the skin conductance sensor and therefore the participant had to reposition her fingers a couple of times to be able to continue the playback. As can be seen on the other seven images, the remaining participants were holding the cube on the front and back side of the cube and could therefore easily interact with the tube, while still touching the skin conductance sensor.

Figure 7.8: **Different interactions with the breathing tube.**

- Finger position while holding the temperature cube (first cube): Since this cube was initially standing on the right side of the table all children were picking it up with the right hand. Furthermore 75% of all children were holding the cube intuitively in the way the cube was designed for (thumb at the side of the cube where the sensor is positioned). If the sensor was not occluded by the thumb, a little hint on this issue motivated all children to reposition their thumb to fully occlude the temperature sensor. During the game this cube was then held correctly by all participants without any further instructions.

- Finger position while holding the pulse cube (second cube): After realising the main game concept by using the first cube, when interacting with the second cube, which contains the pulse measuring sensor, all participants were searching for an equivalent sensor as the one on the temperature cube. With the exception of two participants, who were part of the ones who picked up this cube with their left hand, all children understood that the pulse sensor is used in an equal way as the temperature sensor and therefore positioned their thumb in a correct way over the sensor. The two remaining participants had huge problems with this cube, because after picking it up with the left hand they did not switch it over to the right hand and consequently did not find the right position for their fingers as can also be seen in Figure 7.7 on the right side.

- Finger position while holding the skin conductance cube (third cube): No participant had problems with the correct holding of the third cube. Everyone intuitively put the fingers on the aluminium areas on the front and back side of the cube. However, during listening to the part of the story corresponding to this cube and the subsequent breathing into the cube while holding it, some participants lost their grip on the aluminium areas, so the story stopped and they had to reposition their fingers to continue the playback.

7.6.2 Questionnaire analysis

In addtion to observing the participants while interacting with the cubes we also handed out questionnaires regarding the usability and applicability of the developed cubes. The three different surveys for adults, children and parents provided us with an insight in the opinion of the participants.

By analysing the five words chosen by the participants from the "Product Reaction Cards", which were part of the survey for parents and adults, we recognized that due to the combination of positive as well as negative adjectives, participants felt more comfortable also choosing negative words. Since some participants might hesitate to state such things in a face-to-face interview, this question format allows them to also express their negative opinions. A summary of the selected words is illustrated in the word cloud in Figure 7.9, where the size and position of each word reflects the number of times a word was chosen by participants.

Figure 7.9: **Frequency of chosen words that fits the developed interface best.**

The majority of participants was impressed by the idea that medical values could be measured during a game and expressed this by selecting words like “Creative”, “Sophisticated” or “Novel”. They also liked the concept that children could play with it and described this as “Fun”, “Entertaining” and “Friendly”. Two parents were concerned about the time that is needed for the setup and the measuring procedure itself and stated that a conventional measurement of temperature or pulse is less time-consuming. Another two parents found that the cubes and the corresponding story are a good distraction, so children are not bothered about the medical examination. One adult participant had doubts if the game concept is understandable for children and if the story would be too boring for some of them. In contrast to this all other adult participants were satisfied with the game and had the opinion that the story is perfect and very entertaining, especially for children, and would suggest to construct more cubes and different stories.

Nearly two-thirds of the adult participants did not recognize that the cubes are measuring medical values while playing. The other third was only thinking about medical devices while blowing in the respiratory tube. Furthermore during the children observations no signs of fear were recognized, which led us to the conclusion that the children also did not notice any medical devices.

All of the questioned parents could imagine to use the developed game instead of conventional measurement techniques. We also asked one paediatrics specialist in a children’s hospital about the usage of the cubes in hospitals and she thinks that the cubes are highly capable of being integrated in doctor’s offices and that they would save time, especially with children, who are afraid of examination.

The survey also included questions on the entertainment factor and the design of the cubes, which were determined using the previously described pictorial representations of feelings. The results of these questions are shown in the two bar charts shown in Figure 7.10 and Figure 7.11, which summarize the answers of all participants.

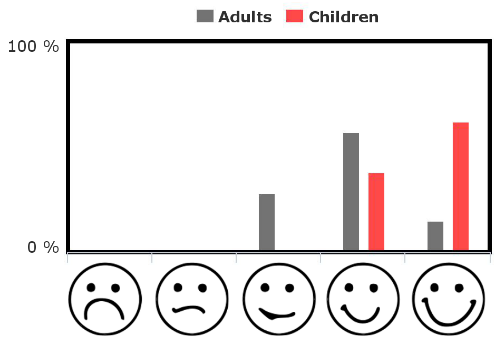


Figure 7.10: **How much fun while playing?**

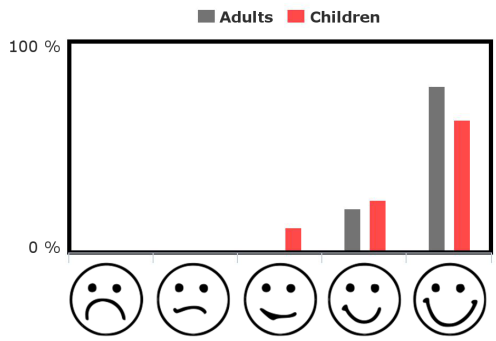


Figure 7.11: **How appealing is the design?**

All adults stated, that they were quite entertained by the game, although they assumed that this would be even more the case with younger users. Their assumption proved to be right, since over 60% of the children chose the right-most smiley.

Furthermore all adult participants liked the wooden design of the cubes and only chose one of the two right-most smileys. Nearly the same distribution of smileys was chosen by the children.

Except one child which had no explicit opinion regarding the design, all children were satisfied by the cubes and the drawn pictures on the top of it.

Finally the questionnaire tried to verify if the children were listening to the story or if they just wanted to reach the end of the story to "pass" the test. The results concerning the attention span of the participating children were quite surprising. With the exception of the youngest participant all children remembered the whole story and were able to reconstruct every part of it. Especially one participant was satisfied so much that she was able to retell the whole story mostly word for word, although she was not part of half of the children, who had known the story before the testing session.

7.6.3 Accuracy of measurement

To compare the measured values recorded during the game with conventional medical devices, we measured the forehead temperature after each game with a traditional infrared thermometer produced by Sanitas (Figure 7.12) and the oxygen saturation and heart rate with a fingertip pulse oximeter produced by AVAX (Figure 7.13).

Figure 7.12: **Infrared thermometer [san15].**

Figure 7.13: **Pulse oximeter [ava15].**

Since the employed sensors provide different accuracy and comparability with common medical devices we describe the results of each medical parameter separately:

Pulse and oxygen saturation

We compared the recordings of 12 adults and 3 children with a conventional fingertip pulse oximeter. The other 5 children did not produce valid measurements because of their more frequent switching of finger and hand position. This was the case because of our decision to not explicitly advise the children on the handling of the medical devices, to avoid distorting the usability study.

Figure 7.14 and Figure 7.15 show the direct comparison between the measured pulse and oxygen saturation recorded with the story cubes and with the fingertip pulse oximeter. The closer the points are located to the gray diagonal, the smaller the gap between the two measuring methods.

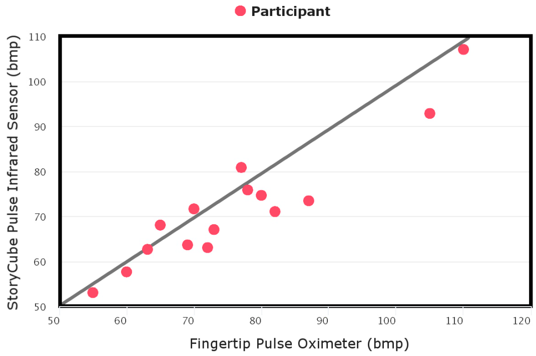


Figure 7.14: **Pulse measurements.**

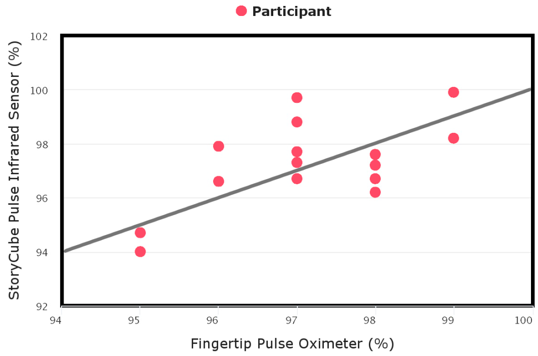


Figure 7.15: **Oxygen measurements.**

As can be seen in the charts above, except some outliers, both methods produce quite similar results. The average value of the computed proportional differences with the calculated heart beat lies at 6.5%, whereas the mean proportional difference of the calculated oxygen saturation lies at 1.14%. The participants, which had a greater difference between the two methods, were the same, who set down the pulse cube and picked it up again repeatedly and therefore their measuring time without interruptions was below the suggested one minute.

Furthermore two participants were tested with the game a second time after a three minute workout, with the result of an increased pulse of 11.7% and 12.6%. Quite the same differences occurred with two participants, which both said that they were very nervous about the test and had a 12.8% and 11.9% higher pulse during the first test than they had in a following game. Two more participants were chosen, which neither made some sport between the games nor were noticeably nervous. Consequently, these two adults had just changes of 3.4% and 0.8% in the measured pulse values.

Temperature

The similarities between the infrared sensor in the temperature cube and the commercially available infrared thermometer were not as consistent as with the pulse sensor. The average temperature measured on the forehead of the participants was around 36.8 degrees, whereas in most cases the body core temperature estimated with the story cubes by measuring the finger temperature lay far apart. Several circumstances were the reason for the differences between the two methods:

- The threshold of a valid finger temperature was set to 30 degree for the detection of holding the cube to avoid beeing mistaken for example with a passing person. This restriction was a problem for four participants, whose finger temperature measured on the thumb was under this threshold or just barely above it. This led to nearly 20% of all measurements to be under 33 degrees.

- On the other hand two participants emitted such a high temperature just by sitting in front of the temperature cube, that it was constantly in the state of beeing held and recorded this as finger temperature.
- Due to implementation requirements we could not comply with the suggested distance between finger and sensor. Caused by the almost direct contact of the thumb with the temperature sensor, the sensor was heated up while holding and the measured temperature was getting higher and higher during the game. This heat was the reason, why more than 25% of all recorded temperature values were above 40 degrees.

Nevertheless the design of our temperature cube could be informative for future projects. A possible solution for the three problems, that occurred with the current placing of the sensor, could be to relocate it from the front side of the cube to its right side. So the sensor would not measure the thumb temperature, but the temperature of the hand's palm. For one thing, the temperature of someone's hand palm is closer to the body core temperature than the one measured on the fingers and for another there would not be a direct contact between the user and the sensor. Another approach could be the usage of an additional contact sensor to avoid defining a threshold to detect holding of a cube.

Lung volume

The measurements of lung capacity were highly dependent on the way of using the breathing tube. Some of the participants were not blowing as much and as long in the respiratory tube as it would have been necessary in a medical observation. Furthermore some children were afraid of placing the mouth piece too near to their mouth and were just blowing from a specific distance towards the tube.

Although some participants did not produce valid flow-volume recordings, which could be compared with medical measurements, others did. For future projects we believe that if the users are getting an introduction on how to use a respiratory tube, our developed tube could be a mobile and cheaper version of the currently available products. In comparison to typical examples of commonly encountered flow-volume recordings illustrated in the standardisation of spirometry [MHB$^+$05], our recordings show some significant similarities. The first row of Figure 7.16 shows three flow-volume examples printed in this standardisation article:

The first illustration is a visual pattern of a normal subject, the one next to it is of a person with a airflow limitation and the last one has a more curved end, which can be seen with ageing. Under each of these figures a flow-volume recorded by the story cubes is shown. The first one is a curve monitored in the measurements of most of the participants, the second one is of a child who currently suffers from a mild kind of asthma and the last curve shows the recordings of a 62 years old participant.

The result did not only show marked similarities in the curve form but also in the recorded liters per second. This is illustrated in Figure 7.16 by adding the y-axis to our generated graphs corresponding to the raw values saved in the SQLite database in the developed Android application.

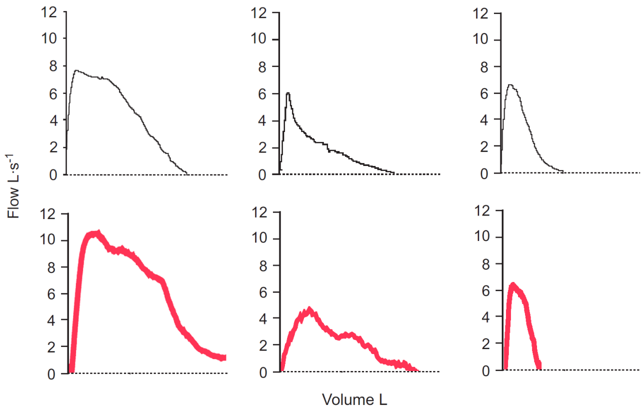


Figure 7.16: **Comparison of flow volume recordings.**

Skin conductance

We are not aware of any known possibilities to verify skin conductance measurements. However, our goal for this medical parameter was to monitor the development of the skin conductance during a longer period of time relating to one specific user. These recordings should then point out changes of stress levels between the different games.

The stress levels of the different participants during one game were constant as can be seen on the example graph shown in Figure 7.17. Such graphical illustrations of values recorded over weeks or months could help to represent the emotional state of the patient.

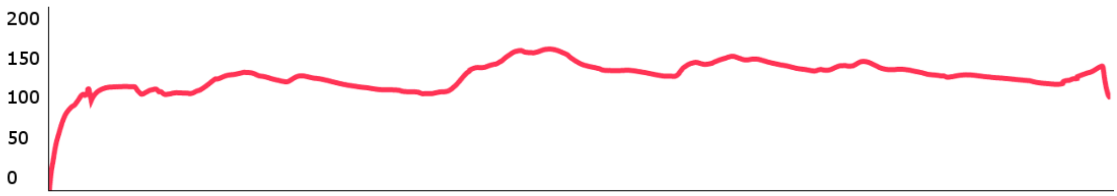


Figure 7.17: **Recorded skin conductance during one game.**

Furthermore we were able to confirm the validity of the recorded skin conductance values by observing the increase after some workout.

CHAPTER 8

Conclusion and Future Work

During the implementation of this master thesis we developed a tangible user interface constituting a game for storytelling on the one hand and a monitoring tool for specific medical values on the other hand. To combine these two different kinds of applications, which were never used together before, to one novel interface, we invested plenty of time in research. We studied possible sensors for the medical measurements and ways to provide affordance, feedback and visibility through the design of our interface. The conclusion drawn from this research lead us to read values recorded from medical sensors, process their signals in an adequate way and integrate them in suitable tangible objects. These tangibles were designed to comply with the requirements of the sensors as well as the needs of an easy and understandable interface for children.

Furthermore, we developed an Android application that connects the tangibles wirelessly and tracks them over the smartphone's camera to be able to control their position throughout the game. Additionally, this application can store the recorded values for multiple users and present the results of every played game.

After the implementation of the user interface, the conducted evaluation showed that we achieved our envisioned goal of a playful interface that simultaneously is able to record comparable health values. Nevertheless, the observed handling during the tests also revealed some open issues and ideas for future projects, which will be described in the following sections.

Setup time

Since the interface needs a tracking system to rotate the tangibles to a desired position, the testing location has to provide specific lighting conditions to work properly. On the one hand the markers on the bottom side of the tangibles need to be illuminated to be visible for the camera and on the other hand it has to be ensured that the glass table does not reflect this additional light. Although, integrating an indirect lighting inside of the interactive table improved the tracking, it still requires quite a long time fine tuning, which makes the setup at different locations more difficult. The interface would highly benefit from a better lighting or tracking system that also reliably identifies the markers under poor lighting conditions.

Bi-manual handling

It turned out that children often use the hand that is closer to an object they wanted to pick up. Since the currently developed design was made for a handling with the right hand, this makes the correct usage of the tangibles with the left hand even more difficult. Therefore in future projects the design has to be either adapted to a bi-manual handling or the user has to be advised to just use their right hand to hold the tangibles.

Sensor placement and size

As already mentioned the placement of the temperature sensor in the housing of the tangible was suboptimal. Due to the almost direct contact of thumb and sensor caused by the thin walls of the housing, the sensor does not work reliably. To resolve this issue, the sensor could be placed in the sidewall of the housing, where direct contact while holding is minimized.

Furthermore the aluminium areas for the skin resistance sensor could be enlarged to cover the entire side of the cube. The possibility of touching these wider areas instead of small specific spots would simplify the interaction with this cube.

Response time

Some participants had initial problems to understand the game concept regarding the response time of the different tangibles. Especially the tangible containing the pulse sensor took up to 3 seconds until a pulse was detected. This led to a specific latency in story telling. Such delays have to be avoided by starting the story immediately after a finger is detected and not until the first beat is received.

Demonstrate the usage of the breathing tube

For valid measurements of the lung volume the users have to handle the respiratory tube in a specific way. For that purpose a health professional has to demonstrate or at least describe how to use the tube correctly before the game starts.

Charging

Every two games the battery of each tangible has to be recharged. Since the charging of all three tangibles needs up to 40 minutes, the battery capacity has to be increased to employ the interface not only for test scenarios but also in medical offices, where they would have to be operated for several hours. Another difficulty with the charging procedure, was the fact that the wooden housing has to be removed every time the tangibles needed recharging, to switch of the tangible and reach the connectors for the charger. This additional setup time could be minimized if the switches and plugs were accessible with the housing still on top of the tangibles.

More cubes and different stories

The concept of different cubes that can tell a story would work even better, if more than three cubes were involved. More cubes would make the choice, which cube to pick up next, more challenging. Furthermore, if a child had to use the interface frequently, several participants mentioned that they would appreciate different stories with variable sets of illustrations, which could be exchanged with the currently existing pictures on top of the tangibles. Since the cover plate of every tangible is removable our developed design already supports this application and could easily be modified for additional stories.

Nevertheless, this master thesis showed that there is a high degree of acceptance for this new way of health monitoring. Children, parents as well as health professionals would benefit from such a tangible user interface. By offering a stress-reducing distraction by applying a storytelling game, our developed cubes would simplify medical examinations not only in doctor's offices but also at patients' homes.

APPENDIX A

German questionnaires

A.1 Children certificate

A.2 Survey questionnaires

The next pages contain the three different questionnaires: first the one for children, then the one for the adult participants and finally the consent form and conclusive questions for parents.

Danke, dass du mir beim Ausprobieren meines Spiels behilflich bist!

Das Ausfüllen dieses Fragebogens dauert in etwa 5 Minuten. Nachdem du dann eine Runde gespielt hast, gibt es einen weiteren Fragebogen der ebenfalls 5 Minuten dauern wird.
Es gibt weder richtige noch falsche Antworten, deshalb bitte ich dich mir einfach ehrlich und aus dem Bauch heraus zu antworten.

Über dich

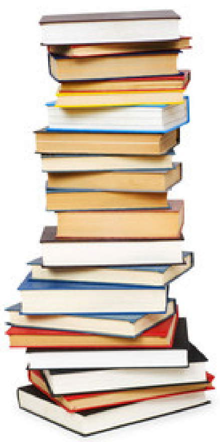
1. **Dein Vorname**: ____________________
2. **Wie alt bist du?** Ich bin ________ Jahre alt.
3. **Wie fühlst du dich gerade?**

4. **Mit welchem der folgenden Dinge würdest du am ehesten deine Zeit verbringen (falls du dich nicht entscheiden kannst, kannst du auch mehrere auswählen)?**

☐ 

☐ 

☐ 

☐ 

☐ 

☐ 

☐ 

☐ 

Spiel

5. **Was fällt dir spontan ein, wenn du an die Würfel denkst, mit denen du gerade gespielt hast?**

6. **Wie viel Spaß hattest du beim Spielen?**

7. **Um was ging es in der erzählten Geschichte?**

8. **Hast du diese Geschichte zuvor schon einmal gehört?** ☐ Ja ☐ Nein

9. **Wie gefallen dir die Würfel?**

10. **Gibt es etwas, dass dir beim Spielen besonders gut gefallen hat?**

11. **Gibt es etwas, dass dir überhaupt nicht gefallen hat?**

Danke, dass du dich mit der Teilnahme an diesem Fragebogen bereit erklärst, mir bei der Evaluierung meines im Rahmen der Diplomarbeit entwickelten Spiels namens "StoryCubes" behilflich zu sein. Deine Angaben und eventuelle Fotoaufnahmen oder Videoaufzeichnungen werden nur innerhalb meiner Diplomarbeit oder in wissenschaftlichen Artikeln, die sich auf meine Arbeit beziehen, verwendet. Selbstverständlich werden alle Abbildungen und Aussagen anonymisiert.
Das Ausfüllen dieses Fragebogens dauert ca. 5 bis 10 Minuten. Deine investierte Zeit und Bereitschaft an meinem Projekt mitzuwirken, schätze ich sehr. Dankeschön!

Datum: ____________ Unterschrift: ______________________________

Fragen zu deiner Person

1. **Dein Vorname:** ______________________________
2. **Alter:** ________
3. **Welches Bild trifft am ehesten deine momentane Gefühlslage (Mehrfachauswahl möglich)?**

Fragen zu dem Spiel

4. **Wie unterhaltsam war das Spiel für dich?**

5. **Wie unterhaltsam würdest du dieses Spiel für ein 5- bis 10-jähriges Kind einstufen?**

6. **Gab es für dich während des Spielens ein Indiz, dass es sich bei den Würfeln um medizinische Geräte handelt? Falls ja, welches?** ☐ Nein ☐ Ja

____
____
____

7. Welche 5 Begriffe treffen aus deiner Sicht am ehesten auf das Spiel zu?

- ☐ ablenkend
- ☐ alt
- ☐ altmodisch
- ☐ anfällig
- ☐ angenehm
- ☐ anmaßend
- ☐ anpassbar
- ☐ anregend
- ☐ ansprechend
- ☐ attraktiv
- ☐ auf dem neuesten Stand
- ☐ aufregend
- ☐ ausgeklügelt
- ☐ außergewöhnlich
- ☐ bedeutsam
- ☐ beeindruckend
- ☐ befriedigend
- ☐ begehrenswert
- ☐ beschäftigt
- ☐ beschützend
- ☐ direkt
- ☐ dynamisch
- ☐ effektiv
- ☐ effizient
- ☐ einfach zu verwenden
- ☐ eingebunden
- ☐ einheitlich
- ☐ einladend
- ☐ einschüchternd
- ☐ entsprechend
- ☐ erwartungsgemäß
- ☐ essenziell
- ☐ fesselnd
- ☐ flexibel
- ☐ fortgeschritten
- ☐ freundlich
- ☐ frisch
- ☐ frustrierend
- ☐ gemeinschaftlich
- ☐ geschäftlich
- ☐ gewöhnlich
- ☐ hilfreich
- ☐ hochwertig
- ☐ ineffektiv
- ☐ innovativ
- ☐ inspirierend
- ☐ intuitiv
- ☐ irrelevant
- ☐ klar
- ☐ komplex
- ☐ kontrollierbar
- ☐ kreativ
- ☐ langsam
- ☐ langweilig
- ☐ lustig
- ☐ mächtig
- ☐ mitreißend
- ☐ motivierend
- ☐ mühelos
- ☐ nervig
- ☐ neuartig
- ☐ nicht kontrollierbar
- ☐ nicht sicher
- ☐ nicht wertvoll
- ☐ nicht wünschenswert
- ☐ nicht zusammenhängend
- ☐ nützlich
- ☐ optimistisch
- ☐ organisiert
- ☐ persönlich
- ☐ praktisch
- ☐ professionell
- ☐ reaktionsfähig
- ☐ reizlos
- ☐ ruhig
- ☐ sauber
- ☐ schlechte Qualität
- ☐ schnell
- ☐ schwer zu benutzen
- ☐ schwierig
- ☐ sicher
- ☐ stabil
- ☐ stärkend
- ☐ steif
- ☐ steril
- ☐ störend
- ☐ stressig
- ☐ überwältigend
- ☐ überzeugend
- ☐ umfangreich
- ☐ umgänglich
- ☐ uneinheitlich
- ☐ unfein
- ☐ uninteressant
- ☐ unkonventionell
- ☐ unpersönlich
- ☐ unpraktisch
- ☐ unterhaltsam
- ☐ unverständlich
- ☐ unvorhersehbar
- ☐ unwiderstehlich
- ☐ unzugänglich
- ☐ vereinbar
- ☐ verlässlich
- ☐ verständlich
- ☐ vertrauenswürdig
- ☐ vertraut
- ☐ verwendbar
- ☐ verwirrend
- ☐ vorhersehbar
- ☐ wartungsarm
- ☐ wertvoll
- ☐ zeitaufwendig
- ☐ zeitsparend
- ☐ zu einfach
- ☐ zu technisch
- ☐ zugänglich
- ☐ zusammenhängend

8. Wie ansprechend findest du das Design der Würfel?

9. Wie könnte deiner Meinung nach der Spielverlauf noch verbessert werden?

10. Sonstige Anmerkungen:

Danke, dass du dich gemeinsam mit deinem/n Kind/ern bereit erklärst, mir bei der Evaluierung meines im Rahmen der Diplomarbeit entwickelten Spiels namens "StoryCubes" behilflich zu sein. Eure Angaben und eventuelle Fotoaufnahmen oder Videoaufzeichnungen werden nur innerhalb meiner Diplomarbeit oder in wissenschaftlichen Artikeln, die sich auf meine Arbeit beziehen, verwendet. Selbstverständlich werden alle Abbildungen und Aussagen anonymisiert.
Das Ausfüllen dieses Fragebogens dauert ca. 5 bis 10 Minuten. Eure investierte Zeit und Bereitschaft an meinem Projekt mitzuwirken, schätze ich sehr. Dankeschön!

Datum: ____________ Unterschrift: ______________________________

Fragen zu deiner Person

1. **Dein Vorname**: ______________________________

2. **Kinderanzahl:** ______

Fragen zu deinen Kindern

3. **Hat eines deiner Kinder Angst vor dem Arztbesuch?** ☐ Ja ☐ Nein

4. **Welche medizinischen Werte erfasst ihr zu Hause ohne ärztliche Hilfe?**
   - ☐ Temperatur
   - ☐ Puls
   - ☐ Blutdruck
   - ☐ Atemvolumen
   - ☐ Weitere: ______________________________

5. **Wie oft kommen solche Untersuchungen in eurem Haushalt pro Kind innerhalb eines Jahres vor?** Ungefähr ______ Mal.

6. **Wäre es für dich eine Erleichterung, wenn solche Untersuchungen innerhalb eines Spiels durchgeführt werden könnten?** ☐ Ja ☐ Nein, weil:
   ____
   ____
   ____

7. **Kannst du dir vorstellen, dass deine Kinder gerne mit StoryCubes spielen anstelle eines Arztbesuchs?** ☐ Ja ☐ Nein, weil:
   ____
   ____
   ____

8. **Kannst du dir vorstellen, dass deine Kinder gerne mit StoryCubes spielen anstelle einer herkömmlichen Messung zu Hause?** ☐ Ja ☐ Nein, weil:

____

____

Fragen zum Spiel

9. **Welche 5 Begriffe treffen aus deiner Sicht am ehesten auf das Spiel zu?**

- ☐ ablenkend
- ☐ alt
- ☐ altmodisch
- ☐ anfällig
- ☐ angenehm
- ☐ anmaßend
- ☐ anpassbar
- ☐ anregend
- ☐ ansprechend
- ☐ attraktiv
- ☐ auf dem neuesten Stand
- ☐ aufregend
- ☐ ausgeklügelt
- ☐ außergewöhnlich
- ☐ bedeutsam
- ☐ beeindruckend
- ☐ befriedigend
- ☐ begehrenswert
- ☐ beschäftigt
- ☐ beschützend
- ☐ direkt
- ☐ dynamisch
- ☐ effektiv
- ☐ effizient
- ☐ einfach zu verwenden
- ☐ eingebunden
- ☐ einheitlich
- ☐ einladend
- ☐ einschüchternd
- ☐ entsprechend
- ☐ erwartungsgemäß
- ☐ essenziell
- ☐ fesselnd
- ☐ flexibel
- ☐ fortgeschritten
- ☐ freundlich
- ☐ frisch
- ☐ frustrierend
- ☐ gemeinschaftlich
- ☐ geschäftlich
- ☐ gewöhnlich
- ☐ hilfreich
- ☐ hochwertig
- ☐ ineffektiv
- ☐ innovativ
- ☐ inspirierend
- ☐ intuitiv
- ☐ irrelevant
- ☐ klar
- ☐ komplex
- ☐ kontrollierbar
- ☐ kreativ
- ☐ langsam
- ☐ langweilig
- ☐ lustig
- ☐ mächtig
- ☐ mitreißend
- ☐ motivierend
- ☐ mühelos
- ☐ nervig
- ☐ neuartig
- ☐ nicht kontrollierbar
- ☐ nicht sicher
- ☐ nicht wertvoll
- ☐ nicht wünschenswert
- ☐ nicht zusammenhängend
- ☐ nützlich
- ☐ optimistisch
- ☐ organisiert
- ☐ persönlich
- ☐ praktisch
- ☐ professionell
- ☐ reaktionsfähig
- ☐ reizlos
- ☐ ruhig
- ☐ sauber
- ☐ schlechte Qualität
- ☐ schnell
- ☐ schwer zu benutzen
- ☐ schwierig
- ☐ sicher
- ☐ stabil
- ☐ stärkend
- ☐ steif
- ☐ steril
- ☐ störend
- ☐ stressig
- ☐ überwältigend
- ☐ überzeugend
- ☐ umfangreich
- ☐ umgänglich
- ☐ uneinheitlich
- ☐ unfein
- ☐ uninteressant
- ☐ unkonventionell
- ☐ unpersönlich
- ☐ unpraktisch
- ☐ unterhaltsam
- ☐ unverständlich
- ☐ unvorhersehbar
- ☐ unwiderstehlich
- ☐ unzugänglich
- ☐ vereinbar
- ☐ verlässlich
- ☐ verständlich
- ☐ vertrauenswürdig
- ☐ vertraut
- ☐ verwendbar
- ☐ verwirrend
- ☐ vorhersehbar
- ☐ wartungsarm
- ☐ wertvoll
- ☐ zeitaufwendig
- ☐ zeitsparend
- ☐ zu einfach
- ☐ zu technisch
- ☐ zugänglich
- ☐ zusammenhängend

10. **Sonstige Anmerkungen:**

Bibliography

[AKSLJC05] Kyung Ah Kim, Tae Soo Lee, and Eun Jong Cha. Minimum diameter of the velocity type respiratory air flow transducer. *Conf Proc IEEE Eng Med Biol Soc*, 6:6619–22, 2005.

[ard] Arduino platform. `http://www.arduino.cc/`. [Online; accessed 17-Januar-2015].

[ART11] Mal mir ein märchen - die drei kleinen schweinchen, 2011. Premiered on ARTE.

[ava15] Cms-50dl pulse oximeter. `http://www.amazon.com/50-DL-Pulse-Oximeter-Neck-Wrist/dp/B004BJT9OE/ref=pd_sim_sbs_pc_1?ie=UTF8&refRID=1242NMJS1HEWFJGSGMTJ`, 2015. [Online; accessed 04-January-2015].

[BG09] Pawan K. Baheti and H. Garudadri. An ultra low power pulse oximeter sensor based on compressed sensing. In *Wearable and Implantable Body Sensor Networks, 2009. BSN 2009. Sixth International Workshop on*, pages 144–148, June 2009.

[BLRL11] C.A Boano, M. Lasagni, K. Ro?mer, and T. Lange. Accurate temperature measurements for medical research using body sensor networks. In *Object/Component/Service-Oriented Real-Time Distributed Computing Workshops (ISORCW), 2011 14th IEEE International Symposium on*, pages 189–198, 2011.

[BM02] Joey Benedek and Trish Miner. Measuring desirability: New methods for evaluating desirability in a usability lab setting. In *Proceedings of UPA 2002 Conference*, 2002.

[CG09] F.S. Cattivelli and H. Garudadri. Noninvasive cuffless estimation of blood pressure from pulse arrival time and heart rate with adaptive calibration. In *Wearable and Implantable Body Sensor Networks, 2009. BSN 2009. Sixth International Workshop on*, pages 114–119, June 2009.

[Cha14] Charting library for android. `https://github.com/PhilJay/MPAndroidChart`, 2014. [Online; accessed 28-November-2014].

[CHH99] Charmaine Childs, Ruth Harrison, and Claire Hodkinson. Tympanic membrane temperature as a measure of core temperature. *Arch Dis Child*, 80(3):262–6, 1999.

[CN00] P Cesari and Karl M. Newell. Body scaling of grip configurations in children aged 6-12 years. *Dev Psychobiol*, 36(4):301–10, 2000.

[CTH+07] R. Carta, D. Turgis, B. Hermans, P. Jourand, R. Onclin, and R. Puers. A differential pressure approach to spirometry. In *Biomedical Circuits and Systems Conference, 2007. BIOCAS 2007. IEEE*, pages 5–8, 2007.

[DMA14] DatabaseManager for Android. `https://github.com/sanathp/DatabaseManager_For_Android`, 2014. [Online; accessed 20-November-2014].

[DSN+11] Sebastian Deterding, Miguel Sicart, Lennart Nacke, Kenton O'Hara, and Dan Dixon. Gamification. using game-design elements in non-gaming contexts. In *CHI '11 Extended Abstracts on Human Factors in Computing Systems*, pages 2425–2428. ACM, 2011.

[DVC11] Justin Dauwels, François-Benoît Vialatte, and Andrzej Cichocki. On the early diagnosis of alzheimer's disease from eeg signals: A mini-review. In Rubin Wang and Fanji Gu, editors, *Advances in Cognitive Neurodynamics (II)*, pages 709–716. Springer Netherlands, 2011.

[DYFA11] Grimaldi Domenico, Kurylyak Yuriy, Lamonaca Francesco, and Nastro Alfonso. Photoplethysmography detection by smartphone's videocamera. In *IDAACS (1)*, pages 488–491. IEEE, 2011.

[FPP09] Jr. Frank P. Primiano. Measurements of the respiratory system. In John G. Webster, editor, *Medical Instrumentation Application and Design, 4th Edition*, chapter 9, pages 377–448. Wiley Global Education, 2009.

[GCB+10] Gaetano Gargiulo, Rafael A Calvo, Paolo Bifulco, Mario Cesarelli, Craig Jin, Armin Mohamed, and Andre van Schaik. A new eeg recording system for passive dry electrodes. *Clin Neurophysiol*, 121(5):686–93, 2010.

[I2Ca] I2C Master Interface for AVR devices. `http://homepage.hispeed.ch/peterfleury/avr-software.html`. [Online; accessed 18-November-2014].

[I2Cb] I2C Master Library. `http://bildr.org/2011/02/mlx90614-arduino/`. [Online; accessed 15-November-2014].

[ico] Iconfinder. `www.iconfinder.com`. [Online; accessed 17-Januar-2015].

[Jon10] D.P. Jones. *Biomedical Sensors*. Sensor technology series. Momentum Press, 2010.

[KKY+98] Hisanori Kataoka, Hiroshi Kano, Hiroaki Yoshida, Atsuo Saijo, Masashi Yasuda, and Masato Osumi. Development of a skin temperature measuring system for non-contact stress evaluation. In *IEEE Annual Conference on Engineering Medicine Biology Society*, pages 940–943, 1998.

[KSHS05] Matthias Kranz, Dominik Schmidt, Paul Holleis, and Albrecht Schmidt. A display cube as a tangible user interface. adj. In *Proc. of UbiComp 2005*. Springer, 2005.

[LFM08] Ying Li, Willem Fontijn, and Panos Markopoulos. A tangible tabletop game supporting therapy of children with cerebral palsy. In *Proceedings of the 2Nd International Conference on Fun and Games*, pages 182–193. Springer-Verlag, 2008.

[Met] Metaio Augmented Reality SDK. `http://www.metaio.com/products/sdk/`. [Online; accessed 19-November-2014].

[MHB+05] M. R. Miller, J. Hankinson, V. Brusasco, F. Burgos, R. Casaburi, A. Coates, R. Crapo, P. Enright, C. P. M. van der Grinten, P. Gustafsson, R. Jensen, D. C. Johnson, N. MacIntyre, R. McKay, D. Navajas, O. F. Pedersen, R. Pellegrino, G. Viegi, and J. Wanger. Standardisation of spirometry. *European Respiratory Journal*, 25(2):319–338, 2005.

[min] How to Hack Toy EEGs. `http://frontiernerds.com/brain-hack`. [Online; accessed 22-July-2014].

[mir] MIRF Library. `https://github.com/stanleyseow/arduino-nrf24l01`. [Online; accessed 15-November-2014].

[MMP+13] K. Morikawa, A Matsumoto, S. Patki, B. Grundlehner, A Verwegen, Jiawei Xu, S. Mitra, and J. Fenders. Compact wireless eeg system with active electrodes for daily healthcare monitoring. In *Consumer Electronics (ICCE), 2013 IEEE International Conference on*, pages 204–205, 2013.

[MPX15] Mpx5010 datasheet. `http://www.freescale.com/files/sensors/doc/data_sheet/MPX5010.pdf`, 2015. [Online; accessed 16-January-2015].

[MR06] Mark McEwen and Karen Reynolds. Noninvasive detection of bilirubin using pulsatile absorption. *Australas Phys Eng Sci Med*, 29(1):78–83, 2006.

[MRMH08] Panos Markopoulos, Janet C Read, Stuart MacFarlane, and Johanna Hoysniemi. *Evaluating Children's Interactive Products: Principles and Practices for Interaction Designers*. Morgan Kaufmann Publishers Inc., 2008.

[MS09] M. Murugesan and R. Sukanesh. Towards detection of brain tumor in electroencephalogram signals using support vector machines. *International Journal of Computer Theory and Engineering*, 1(5):622–631, 2009.

[MWI01] Ali Mazalek, Ali Wood, and Hiroshi Ishii. Geniebottles: An interactive narrative in bottles. In *Conference Abstracts and Applications SIGGRAPH*, page 189, 2001.

[NGFT04] Yoko Nagai, Laura H. Goldstein, Peter B. C. Fenwick, and Michael R. Trimble. Clinical efficacy of galvanic skin response biofeedback training in reducing seizures in adult epilepsy: a preliminary randomized controlled study. *Epilepsy & Behavior*, 5(2):216–223, 2004.

[Nor88] Donald A. Norman. *The Psychology of Everyday Things*. Basic Books, New York, 1988.

[Nor99] Donald A. Norman. Affordance, conventions, and design. *interactions*, 6(3):38–43, 1999.

[Nor04] Donald A. Norman. Emotional design. *Ubiquity*, 2004(January):1–1, January 2004.

[Oma12] Sadao Omata. Novel Blood Pressure Monitor. `http://www.ee.ce.nihon-u.ac.jp/~omata/file/BP.pdf`, 2012. [Online; accessed 19-July-2014].

[ope] OpenEEG Project. `http://openeeg.sourceforge.net/doc/`. [Online; accessed 22-July-2014].

[PMAI02] Gian Pangaro, Dan Maynes-Aminzade, and Hiroshi Ishii. The actuated workbench: Computer-controlled actuation in tabletop tangible interfaces. In *Proceedings of the 15th Annual ACM Symposium on User Interface Software and Technology*, UIST '02, pages 181–190. ACM, 2002.

[Pom10] F. Pompei. Temporal artery temperature detector, August 31 2010. US Patent 7,787,938.

[PPB+12] Shyamal Patel, Hyung Park, Paolo Bonato, Leighton Chan, and Mary Rodgers. A review of wearable sensors and systems with application in rehabilitation. *Journal of neuroengineering and rehabilitation*, 9:21+, 2012.

[pro] Processing. `https://processing.org/`. [Online; accessed 17-Januar-2015].

[RFW+08] S. Reichelt, J. Fiala, A. Werber, K. Forster, C. Heilmann, R. Klemm, and H. Zappe. Development of an implantable pulse oximeter. *Biomedical Engineering, IEEE Transactions on*, 55(2):581–588, Feb 2008.

[RGMK09] K. A. Reddy, B. George, N. M. Mohan, and V. J. Kumar. A Novel Calibration-Free Method of Measurement of Oxygen Saturation in Arterial Blood. 58(5):1699–1705, 2009.

[RM06] Janet C. Read and Stuart MacFarlane. Using the fun toolkit and other survey methods to gather opinions in child computer interaction. In *Proceedings of the 2006 Conference on Interaction Design and Children*, IDC '06, pages 81–88. ACM, 2006.

[RSP12] Yvonne Rogers, Helen Sharp, and Jenny Preece. *Interaction Design - Beyond Human-Computer Interaction, 3rd Edition.* Wiley, 2012.

[san15] Sanitas sft 65 - multi-function thermometer. `http://www.sanitas-online.de/web/en/products/bodytemperature/SFT65.php`, 2015. [Online; accessed 04-January-2015].

[SAS+10] C. Setz, B. Arnrich, J. Schumm, R. La Marca, G. Troster, and U. Ehlert. Discriminating stress from cognitive load using a wearable eda device. *Information Technology in Biomedicine, IEEE Transactions on*, 14(2):410–417, March 2010.

[SCDO08] K. Sitdhisanguan, N. Chotikakamthorn, A Dechaboon, and P. Out. Evaluation the efficacy of computer - based training using tangible user interface for low-function children with autism. In *Digital Games and Intelligent Toys Based Education, 2008 Second IEEE International Conference on*, pages 70–74, 2008.

[Ser10] Jordà Sergi. The reactable: tangible and tabletop music performance. In *CHI Extended Abstracts*, pages 2989–2994. ACM, 2010.

[SH10] Orit Shaer and Eva Hornecker. Tangible user interfaces: Past, present, and future directions. *Found. Trends Hum.-Comput. Interact.*, 3(1–2):1–137, January 2010.

[SHA98] Brave Scott, Ishii Hiroshi, and Dahley Andrew. Tangible interfaces for remote collaboration and communication. In *CSCW*, pages 169–178. ACM, 1998.

[SI1] Pulse Sensor Library. `https://github.com/moderndevice/SI1143_Pulse-Prox_Sensors`. [Online; accessed 16-November-2014].

[SI14] Pooja Sridhar Shivaraman Ilango. A non-invasive blood pressure measurement using android smart phones. *IOSR Journal of Dental and Medical Sciences*, 13(1):28–31, 2014.

[SIW+02] Ehud Sharlin, Yuichi Itoh, Benjamin Watson, Yoshifumi Kitamura, Steve Sutphen, and Lili Liu. Cognitive cubes: A tangible user interface for cognitive assessment. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '02, pages 347–354. ACM, 2002.

[SK95] Hideyuki Suzuki and Hiroshi Kato. Interaction-level support for collaborative learning: Algoblock - an open programming language. In *The First International Conference on Computer Support for Collaborative Learning*, CSCL '95, pages 349–355. L. Erlbaum Associates Inc., 1995.

[SK11] Rolf M. Schlegelmilch and Rüdiger Kramme. Pulmonary function testing. In Kramme; Hoffmann; Pozos, editor, *Handbook of Medical Technology*, chapter 8, pages 95–117. Springer, Heidelberg u.a., 2011.

[SMB] SMBus Specification. `http://www.smbus.org/specs/smbus20.pdf`. [Online; accessed 16-November-2014].

[sou] Soundbible sound portal. `http://soundbible.com`. [Online; accessed 17-Januar-2015].

[SPNA11] Gupta Siddharth, Chang Peter, Anyigbo Nonso, and Sabharwal Ashutosh. mobilespiro: Accurate mobile spirometry for self-management of asthma. In *Proceedings of the First ACM Workshop on Mobile Systems, Applications, and Services for Healthcare*, mHealthSys '11, pages 1:1–1:6, New York, NY, USA, 2011. ACM.

[SSVL+03] J.G. Sheridan, B. W. Short, K. Van Laerhoven, N. Villar, and G. Kortuem. Exploring cube affordance: towards a classification of non-verbal dynamics of physical interfaces for wearable computing. In *Eurowearable, 2003. IEE*, pages 113–118, 2003.

[ST12] Jalaliniya Shahram and Pederson Thomas. A wearable kids' health monitoring system on smartphone. In *Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design*, NordiCHI '12, pages 791–792. ACM, 2012.

[SV08] Bert Schiettecatte and Jean Vanderdonckt. Audiocubes: A distributed cube tangible interface based on interaction range for sound design. In *Proceedings of the 2Nd International Conference on Tangible and Embedded Interaction*, TEI '08, pages 3–10. ACM, 2008.

[SWDR10] R. Shriram, A Wakankar, Nivedita Daimiwal, and D. Ramdasi. Continuous cuffless blood pressure monitoring based on ptt. In *Bioinformatics and Biomedical Technology (ICBBT), 2010 International Conference on*, pages 51–55, April 2010.

[SX10] Xing Shusong and Zhang Xia. Emg-driven computer game for post-stroke rehabilitation. In *Proceeding of: Robotics Automation and Mechatronics (RAM)*. IEEE, 2010.

[Tho99] Richard Thorn. Differential pressure flowmeters. In John G. Webster, editor, *The Measurement, Instrumentation and Sensors Handbook*, Electrical engineering handbook series, chapter 28-1. CRC Press, 1999.

[TMSY14] Toshiyo Tamura, Yuka Maeda, Masaki Sekine, and Masaki Yoshida. Wearable photoplethysmographic sensors - past and present. *Electronics*, 3(2):282–302, 2014.

[Tru] TrueSense Kit. `http://www.op-innovations.com/sites/op-innovations.com/files/OPI-Truesense-brochure3.pdf`. [Online; accessed 22-July-2014].

[TTA10] Joshua Tanenbaum, Karen Tanenbaum, and Alissa Nicole Antle. The reading glove: designing interactions for object-based tangible storytelling. ACM, 2010.

[UI99] John Underkoffler and Hiroshi Ishii. Urp: A luminous-tangible workbench for urban planning and design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '99, pages 386–393. ACM, 1999.

[VAV+07] Nenonen Ville, Lindblad Aleksi, Häkkinen Ville, Laitinen Toni, Jouhtio Mikko, and Hämäläinen Perttu. Using heart rate to control an interactive game. In *CHI*, pages 853–856. ACM, 2007.

[vdKZ07] Cornelis van de Kamp and FrankT.J.M. Zaal. Prehension is really reaching and grasping. *Experimental Brain Research*, 182(1):27–34, 2007.

[VGK14] Emanuel Vonach, Georg Gerstweiler, and Hannes Kaufmann. Acto: A modular actuated tangible user interface object. pages 259–268, 2014.

[VRS+13] Chandrasekaran Vikram, Dantu Ram, Jonnada Srikanth, Thiyagaraja Shanti, and Subbu Kalyan Pathapati. Cuffless differential blood pressure estimation using smart phones. *IEEE Trans. Biomed. Engineering*, 60(4):1080–1089, 2013.

[Web97] J.G. Webster. *Design of Pulse Oximeters*. Series in Medical Physics and Biomedical Engineering. Taylor & Francis, 1997.

[Wira] Wire Library. `http://www.arduino.cc/en/Reference/Wire`. [Online; accessed 16-November-2014].

[wirb] Wiring framework. `http://wiring.org.co`. [Online; accessed 17-Januar-2015].

[YHLK11] Ya-Ting Hsu Yuan-Hsiang Lin, Zhe-Min Lin and Hau-Ying Ku. A mobile intelligent blood pressure monitor based on the android smartphone. *Security-Enriched Urban Computing and Smart Grid*, 223:178–187, 2011.

[ZAR05] Oren Zuckerman, Saeed Arida, and Mitchel Resnick. Extending tangible interfaces for education: Digital montessori-inspired manipulatives. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '05, pages 859–868. ACM, 2005.

[ZCP04] ZhiYing Zhou, Adrian David Cheok, and JiunHorng Pan. 3d story cube: An interactive tangible user interface for storytelling with 3d graphics and audio. *Personal Ubiquitous Comput.*, 8(5):374–376, 2004.