Detecting air flow leakage in home spirometry

Using metaphors for children

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Abstract

Asthma is a chronic lung disease which affects a lot of people. Part of the treatment of asthma is doing spirometry tests to keep track of the lung function. These tests can be done at the hospital or at home. However, since with home spirometry there is no medical supervision, errors could occur. One of these errors is leakage of air flow. This error can cause faulty data.

To find a solution for this problem, a sensor analysis and search for state of the art was performed. With the resulting knowledge from this research, a low fidelity prototype was made and tested. The results of this user testing was used to further develop the system.

A high fidelity prototype was designed and tested on its performance. Afterwards, a discussion was performed from which future work and a conclusion was derived.

Acknowledgement

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Chapter 1

Introduction [1]

Asthma is a chronic lung disease which affects 640,000 people in the Netherlands alone.[2] About 100,000 of these people are children.[2] People who have this disease often have to do a lung function test to see if their lung function is worsening or not. This can be done by a spirometry test which is a non-invasive test where the patient has to forcefully breathe into a hose. By doing this test, the condition of the lungs and how the patient is reacting on medicine can be monitored.[3] This test is how such a test will be done at the hospital. However, to keep better track of the lung function and detect signs of worsening earlier, a patient can also do an at home spirometry test with a handheld spirometry device. This device calculates, among others, the ratio between how much air is passing in the first second and the total lung capacity. When this test is done in the hospital, there will of course be supervision when a patient makes mistakes, these mistakes will be picked up and corrected by the supervisor. However, this is not the case when the test is performed at home. Therefore, errors when performing the test might occur.

One of these errors is airflow leakage. Miller [1], states that an acceptable data curve must meet the condition of not having leakage. In a personal interview, Matienne van der Kamp stated that his error can occur in two ways. Either the patient is not wearing the nose clip properly or at all, or the patient is not closing their mouth properly around the tube they have to breathe into. When either of these things go wrong, part of the air that the patient is supposed to blow into the tube will escape. This will result in data where the lung volume will appear smaller than it actually is. It is important to solve this issue because with the current knowledge, it can not be read from the data whether the patient is performing the test with an

[1] Parts of this chapter might built upon previously written reports for part one of my graduation project, the course Academic Writing or the course Design of Persuasive Health Technology.

[2] https://www.longfonds.nl/astma/alles-over-astma/wat-is-astma

[3] https://www.healthline.com/health/spirometry#procedure

airflow leakage error or if there is an issue with the patients lung function. Therefore, the goal of this project is to design a solution that will solve the problem of airflow leakage so that the measurements of a home spirometry test will be more usable and trustworthy.

To design a solution for this particular problem, a few aspects need to be kept in mind. First of all the way the design of how to detect the air leak flow. The next challenge is implementing this solution with the handheld home spirometry test. Another core element of the solution is a feedback system that is going to be designed to prevent airflow leakages from happening. This feedback system however has to be understandable for children since they will be the user of this product. An adult adopting a child perspective cannot interpret the child's perspective accurately, not even when engaging with the same situations [2]. Therefore, it is important to involve children in the design process. Combining all these aspects has formed the following research question. '*How to optimize the use of spirometry for asthma, by limiting the air leak flow, in a way that is understandable for children?*'

Answering this research question asks for some research on the topic. This is done by answering sub questions in the following chapter. This chapter will provide a background and a state of the art on the project. Based on this research, enough knowledge is available to design and make a prototype. During this design process, a design strategy developed for creative technology is used [3]. A visual overview of this design strategy can be seen in Appendix A. The design process has 4 stages. These stages are ideation, specification, realization and evaluation. The following paragraphs discuss these phases.

The project starts with the ideation phase. In this report, that phase is described through the chapter 'State of the art'. During this phase, ideas that solve the main research question are thought of. Inspiration for such ideas can come from the assignment itself, background information, related work, interviews etc.[3]. Therefore, Chapter 2 discusses findings from a literature review on the background of this topic, an interview, a comparison on hand held spirometers, a tinkering phase in which multiple possible sensors are discussed and state of the art systems under which the apllication of the overarching SpiroPlay project. At the end of Chapter 2, a direction for a possible solution to the problem is described.

When the ideation phase is done, and there is an idea for a possible solution, it is time for the specification phase. This phase is discussed in Chapter 3. During this phase, the idea that came out of the ideation phase is worked out further. This is done by creating low fidelity prototypes and evaluating those in order to get a better understanding of the user. This feedback is used in the next phase.

From the final outcome of the specification phase, a high fidelity prototype is developed. This is done in the realization phase. How this prototype is developed, how it works, and which components are used to develop the prototype is explained in chapter 4.

When the final high fidelity prototype is finished, it will be evaluated during the evaluation phase. This evaluation will be done by the target group, but also by professionals. The feedback that is gained from this evaluation, and the method with which the prototype is evaluated is described in Chapter 5. In Chapter 6, a conclusion is formulated in which there is a discussion about the entire project and a recommendation for future work.

Chapter 2

State of the art [1]

In this section, research was done to answer the research question *"How to optimize the use of spirometry for asthma, by limiting the air leak flow, in a way that is understandable for children?"*. This research consists of a literature review, an overview of some of the spirometers and how well they are accepted, a semi-structured interview with Matienne van der Kamp, and a search of different sensors of which the most important ones for this project are discussed. The questions of the interview with Matienne van der Kamp can be found in Appendix B.1. However, since the interview was done in Dutch, the questions are translated from Dutch to English.

To make solving the main research question easier, sub questions are made. These sub questions can be seen, ordered by subject, in Table 1.

Table 1: Research questions per category

Subject	**Sub question**
Asthma	What is Asthma? How is Asthma caused?
Spirometry	Why is doing spirometry important? Why is doing home spirometry important? How does spirometry work? What spirometers are there? What are errors in spirometry
Air leak flow	How does an airflow leakage occur? Why is it important to solve the airflow leakage error? How can the airflow leakage error be detected?
Feedback system	What is a good way to explain the feedback to the child? How can a child be motivated to perform the test properly

[1] Parts of this chapter might built upon previously written reports for part one of my graduation project, the course Academic Writing or the course Design of Persuasive Health Technology.

The next sections explain asthma, spirometry and it's flaws, the found important sensors, a discussion about the feedback system that is designed for children, and a conclusion about how to move forward from here on. This research is supposed to help answer the sub questions. When these sub questions are answered, an answer on the main research question is found.

2.1 Asthma

Elias et al. [4] state that *"Asthma is the most common disease in children worldwide"* [4, p. 2]. The precise cause of asthma is not known yet, but it is known that it is often inheritary. Asthma can also be developed in later life. There are multiple factors that can increase the risk of developing asthma. Some of these risks are, for example, when a person has allergies or when a child was born to early.[2] In the following paragraph, it is, by using multiple sources, explained what having asthma means and what happensin the body of an asthma patient.

When breathing, the air flows from the nose or mouth through the trachea and bronchi to the alveoli which transport the oxygen into the blood. The bronchi have small muscles on the outside which constrict while breathing out and relax while breathing in. On the inside of the bronchi is a mucous membrane which protects the lungs. People with asthma have chronically infected bronchi. This irritates the mucous membrane and causes it to swell up letting less air through the lungs than for a healthy person.[3] The difference between the lungs of a normal person and those of a person with asthma can be seen in Figure 2.1. Because of the chronic infection of the bronchi, the lungs are very sensitive to certain stimuli such as smoke. When such a stimulus appears, the muscles around the bronchi constrict and more mucus is produced, narrowing the air passage and making it hard for the patient to breathe. This is also known as an asthma attack. Asthma attacks are temporary and can disappear by themselves or through the use of medicine.[3] Elias et al. [4] state that besides medicine, self-management can increase the quality of life. This self-management can be done by performing home spirometry.[3] How spirometry works is explained in the following section.

2.2 Spirometry

To keep track of the severity of a patient's asthma, a lung function test is performed. This is called a spirometry test. Such a test can be done at the hospital or at home. In a personal interview, Matienne van der Kamp

[2]https://www.longfonds.nl/astma/alles-over-astma/oorzaken-astma
[3]$https://www.YouTube.com/watch?v = BPGKzUQOm6Q\&feature = emb_logo$
[5]https://hpathy.com/clinical-cases/case-bronchial-asthma/

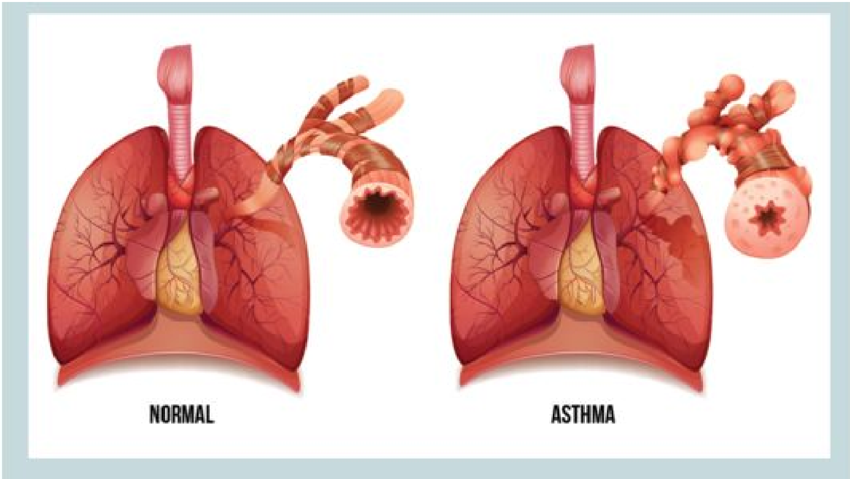

Figure 2.1: The lungs of a healthy person compared to those of a person with asthma.[5]

states that home spirometry tests usually have to be performed once a week. Miller et al. [1], describe spirometry as "*a physiological test that measures how an individual inhales or exhales volumes of air as a function of time*" [1, p. 320]. During a personal interview with Matienne van der Kamp, it was explained further, that a spirometry test measures the amount of air you are respirating. He explained that this air moves some sort of a small ventilator and the amount of rotations of this ventilator are counted using an infrared sensor. By doing this, it can be measured how much air is being respirated. According to van der Kamp, this value is expressed in, among others, forced respiratory volume in the first second (FEV_1) and forced vital capacity (FVC). Van der Kamp explained these values as the amount of air exhaled in 1 second and the complete amount of exhaled air respectively. Both of these values are expressed in Liters. Van der Kamp explained that the ratio of these two values (FEV_1/FVC) shows how much of the complete lung capacity can be respirated in 1 second. The amount of air respirated in one second is and indication of how severe the airway obstruction is and thus the asthma is.

Besides these two parameters, Miller et al. [1] also describe multiple other values that are measured during a spirometry test. First of al, the FEV_t, which Miller et al.[1, p. 326] describe as *"the maximal volume exhaled by time t seconds"* is measured. Furthermore, there is the $FEF_{25-75\%}$ value. Miller et al. [1, p. 326] describe this value as *"The mean respiratory flow between 25% and 75% of the FVC"*. Lastly, there is the PEF value. Miller et al.[1, p. 326] describe this value as *"the maximum respiratory flow achieved from a maximum forced expiration"*. However, FEV_1 and FVC are the main parameters used when monitoring the lung function with spirometry.

According to Miller et al. [1], the spirometry maneuver can be divided into three phases. These phases are *"1) maximal inspiration; 2) a "blast" of exhalation; and 3) continued complete exhalation to the end of test (EOT)"*[1, p. 323]. Miller et al.[1] describe the spirometry maneuver in more detail by stating that a patient should quickly inhale until full lung capacity, take the respiration tube in the mouth, exhale as powerful as possible through the tube and continue exhaling until the lungs are completely empty. Miller et al. [1] state that the results of the test will greatly depend on the effort of the patient and the coaching done by the examiner since. Therefore, it is important that the user of the spirometer gets motivated properly to perform the test.

2.2.1 Air-Next spirometer

For this project, the Air-Next spirometer from Nuvoair is used. The Air-next spirometer and its mobile application is shown in Figure 2.2. This spirometer has the ability to be linked with a mobile phone, giving patients the opportunity to get an overview of their illness [5]. This spirometer exists of the spirometer device itself and and interchangeable turbine which is used to breath through. The Air-Next is connectable to the phone with Bluetooth and the recorded data can be managed through the NuvoAir app.

The tube that is used in the NuvoAir spirometer is the resembles the FlowMIR disposable turbine rather closely. This turbine was invented to solve the need for a cheap and disposable way to measure the breathing flux. The reason that there is a need for a disposable turbine, is that regular turbines are usually used for a longer amount of time and maybe even with multiple patients. This way contagious illnesses could be spread to the next patient. To keep the hygiene standards high, it is important that such turbines are sterilized. Another downfall of other turbines is that things such as hair or fluff might get stuck into the turbine which will influence the mobility of part 2 in Figure 2.3 and 2.4.[7]

The FlowMir turbine solves both of these problems. By making the turbine disposable, there is no risk of spreading contagious illnesses and time is saved since sterilization is not necessary.[4] Besides the hygiene, the FlowMir has tilted the pieces inside of part 3 and 1 in Figure 2.3 and 2.4 45 degrees which makes it nearly impossible for dirt, fluff etc. to enter the turbine.[4] However, even if fluff or dirt gets stuck in the turbine, the disposable turbine is very cheap and can be replaced after every use.

Figure 2.3 and 2.4 show the turbine invented by FlowMir. Figure 2.3 shows the turbine in more detail than Figure 2.4 and Figure 2.4 shows the turbine when assembled. In Figure 2.3 and 2.4, number 1 and 3 show the

[6]https://www.prnewswire.com/news-releases/nuvoair-respiratory-platform-launches-in-mexico-300925815.html

[7]https://patents.google.com/patent/US7618235B2/en

Figure 2.2: The Air-Next spirometer and its mobile Application[6]

inlet and outlet deflector respectively.[4] These deflectors are placed in a 45 degree angle and made of plastic material. Number 2 shows a monoblock mobile equipment which will turn when air is blown into the turbine. Number 2 is made in a way that it will rotate around the rotation axis that can be seen at number 5 in Figure 2.3.[4] Lastly, number 4 shows the turbo-turbine in which all the other components are placed.[4]

To find out if and why the airnext spirometer is a good choice for this project, a comparison between multiple handheld spirometer was done. This comparison can bee seen in Table 2 (parts 1 to 3). Furthermore, this comparison gives an overview of what different types of measuring methods are out there. Table 2, provides an overview of which sensor is used, which data is measured, the flow range, volume and flow accuracy, life expectancy, the way data is shown and if the turbine is disposable or not.

Table 2 shows that the Nuvoair is doing quite well in most categories, however for the flow range and accuracy values, there are actually spirometers out there which have better specifications. However, together with the Spirobank smart, the Nuvoair spirometer is the only one which has a

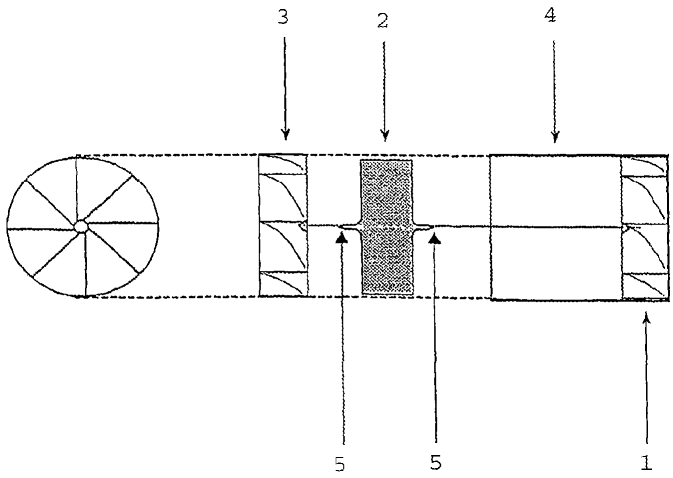

Figure 2.3: Technical drawing of the FlowMir turbine where pieces are not connected.[6]

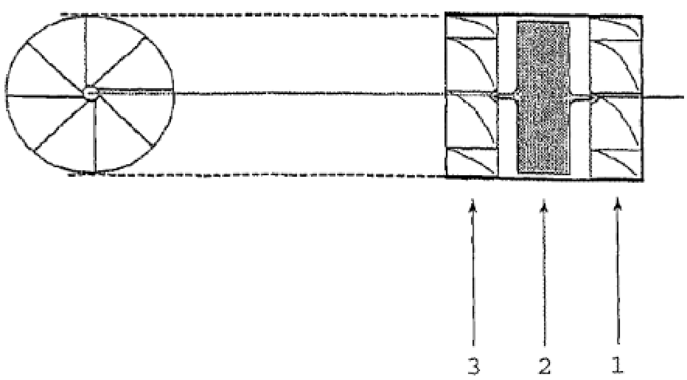

Figure 2.4: Technical drawing of the FlowMir turbine where pieces are connected.[6]

disposable turbine and where the data is not displayed on the spirometer itself. There is a slight difference in the flow range of the Spirobank Smart and the Nuvoair since that of the Spirobank is larger by 2 liters per second. However, in defence of the Nuvoair, the largeness of the flow range in this project is not such a big issue since the target group are children who do not have such a big lung capacity yet. Furthermore, for the Spirobank, the life expectancy was not stated while the life expectancy of the Nuvoair is 10 years. In conclusion, the Nuvoair and Spirobank seem to be rather similar.

Both spirometers even use a similar disposable turbine, which, as stated earlier helps in the hygiene of the spirometer.

Table 2: Comparison of handheld spirometers (Part 1)		
Spirometer	**Measurement method**	**Flow range**
Nuvoair (airnext spirometer) [8]	Infrared interruption	0-14 L/s
Vitalograph COPD6 Screener [9]	Rotor	0-9.99 L/s
Micro 1 handheld spirometer [10]	Transducer	Not stated
EasyOne air [11]	Ultrasounds	0-16 L/s
Spirobank smart [12]	Infrared interruption	0-16 L/s
Spiropalm [13]	Infrared interruption	0.8-20 L/s
Spirohome [14]	Ultrasonic flow measurement	0-14 L/s

Table 2: Comparison of handheld spirometers (Part 2)		
Spirometer	**Volume accuracy**	**Flow accuracy**
Nuvoair (airnext spirometer) [7]	± 3%	± 5%
Vitalograph COPD6 Screener [8]	± 3%	± 3%
Micro 1 handheld spirometer [9]	Not stated	Not stated
EasyOne air [10]	± 2%	± 2-5%
Spirobank smart [11]	± 3%	± 5%
Spiropalm [12]	± 2%	± 5%
Spirohome [13]	2%	Not stated

Table 2: Comparison of handheld spirometers (Part 3)		
Spirometer	**Displayed data**	**Turbine**
Nuvoair (airnext spirometer) [7]	External screen via Bluetooth	disposable
Vitalograph COPD6 Screener [8]	On spirometer	non-disposable
Micro 1 handheld spirometer [9]	On spirometer	non-disposable
EasyOne air [10]	On spirometer	non-disposable
Spirobank smart [11]	External screen via Bluetooth	disposable
Spiropalm [12]	On spirometer or computer	non-disposable
Spirohome [13]	External screen via Bluetooth	non-disposable

The reason why the Nuvoair, and actually also the Spirobank, are appropriate for this project, is mainly due to the fact that the data is displayed

[7] https://www.nuvoair.com/pages/support
[8] https://vitalograph.com/downloads/view/28
[9] https://www.medisave.co.uk/micro-1-handheld-spirometer.html
[10] https://www.nddmed.com/en-us/product/easyone-air.html
[11] https://www.spirometry.com/ENG/download/3brochures.asp?device=spirobanksmart
[12] http://www.futuremed.com/spiropalm.htm
[13] https://www.medicalexpo.com/prod/inofab-health-technologies/product-126225-921519.html

on an external display. This makes it easier to design a nice feedback system since an application for a phone or tablet can be designed because of this feature. This would have been harder when the display was on the spirometer itself.

2.2.2 Errors in spirometry

There are multiple aspects that can go wrong when performing a spirometry test. Miller et al. [1] wrote a paper on the standardization of spirometry which, among others, describes criteria that must be met in order to have an acceptable data curve. Some of these criteria can be seen in Table 3.

Table 3: Errors in spirometry [1]

To create an acceptable curve, the maneuver must be free of	
1	Coughing
2	Hesitation
3	A leak at the mouth
4	An incomplete expiration
5	An obstruction at the tube of the spirometer
6	Taking an extra breath

According to Miller et al.[1], the highest FEV_1 and FVC values have to be taken from three measurements that are all free from the problems stated in Table 3. The reason that is is so important for the data curves to be free from these 6 problems are because the result in false data. For example, having a cough during the measurement might result in a different FEV_1 value and being hesitant during the maneuver could stop the airflow which could change the values FEV_1 or FVC [1]. Thus, when one of these things happen, it could become very hard to give an accurate diagnosis or overview of the severeness of the illness.

When the spirometry test is done at the hospital, an examiner will oversee that the maneuver is performed properly and all of Millers criteria are met. However, this is not the case when a home spirometry test is performed. Since there is no professional helping the patient to perform the spirometry maneuver at home, errors might still occur. One of these errors, in fact the error that this project is supposed to solve, is the error of a leakage at the mouth. As explained in the introduction, Matienne van der Kamp explained that this particular error can happen either due to the patient not wearing the nose clip, or the patient does not close the lips properly around the mouthpiece. Matienne van der Kamp and Coates et al.[6] both state that children usually have little trouble with the nose clip since they will breathe through their mouth automatically when wearing the nose clip. Therefore, this project will focus on the airflow leakage at the mouth.

Coates et al. [6] do mention that children usually are able to create a good seal around the mouthpiece. However, this is on the condition that the children are reminded [6]. As stated before, there is no trained professional to oversee the maneuver when performing home spirometry. As opposed to their earlier statement, Coates et al. [6] state that leakage around the mouthpiece will cause a smaller measurement of FVC. This means that the data will thus be false and determining a proper diagnosis of the asthma severity will be hard to do. When the severity of asthma is wrongly diagnosed, under- or over-treatment might occur. According to Elias et al. [4], under-treatment of asthma can cause low quality of life quality or a higher risk of asthma attacks. On the other hand, Elias et al. [4] state that over-treating asthma causes an increase of medical costs and could make the body react badly at the medicine. Therefore, it is important to solve the error of airflow leakage.

2.2.3 Spirometry in children

Since this project will be mainly focussed on the spirometry usage through children. Therefore, it is important to know the difference between spirometry in adults and children. Multiple research papers, for example the standardization that Miller et al. [1], state that children are usually able to properly perform a spirometry test from 5 years old. However, in an interview, Matienne van der Kamp explained that with proper explanation and lessons, children are often able to perform a proper spirometry test at an even younger age.

However, according to Miller et al. [1], children should never be testing with adult circumstances. Miller et al. [1] and Coates et al. [6] both state that children should be tested in a place that makes children comfortable, for example with toys or paintings. According to the authors, this atmosphere combined with easy instructions and clear feedback helps the children perform the maneuver properly [1]. Doing the spirometry measurements at home will automatically put the children in a comfortable and known environment. Wensley et al. [7] tested the accuracy of spirometry measurements when children perform these at home. They used children from the age of 7 to 14. And gave them proper training beforehand. The research of Wensley et al. [7] surprisingly resulted in children still being able to do the spirometry test properly. However, the children showed a reduced compliance which led to invalid data. The children are thus perfectly capable of performing spirometry tests properly at home, given that they had a proper training beforehand.

2.3 Detecting air flow leakage

Detecting the error of airflow leakage can be done in multiple ways. To find these options, Wikipedia's list of sensors was used.[15]. This list of sensors was consulted to get an overview of which sensors exist. Sensors that seemed relevant for this particular project were split up in categories and for each category related work etc. was found by using external sources. This information is discussed in the following sections.

2.3.1 Air analyzing

Sensing the airflow that escapes during the expiration of the patient could be a solution which helps detecting the airflow error. During the interview with Matienne van der Kamp, he gave his opinion on this idea. Matienne thought that this idea might have some issues. These issues might occur due to the children using the device but not sitting still while using it. This way, random air might flow through the sensor and so the system will tell the user that he or she is not using the device properly while in fact this might be untrue.

To solve such issues, it should be known if the air flowing through the sensor is actually a part of the expiration of the user. There is a possibility to know if the air that is flowing is actually exhaled breath or just surrounding air. This is due to the fact that normal air has a different composition of gasses than exhaled air. This difference can be seen in Table 4 where the values of the main gasses in air and exhaled breath are displayed.

Table 4: Gasses in surrounding and exhaled air

	Surrounding air [16]	**Exhaled air** [17]
Nitrogen	78.048%	78%
Oxygen	20.9476%	16%
Argon	0.943%	0.09%
Carbon dioxide	0.0314%	4%

Table 4 shows that the most detectable differences between surrounding air and exhaled air are in the amounts of oxygen and carbon dioxide. These two gasses can be detected using sensors. Such sensors could thus, theoretically, determine if a certain air flow exists due to surrounding air or an airflow leakage. These sensors are discussed in the following two sections. Table 4 also shows a difference in the amount of argon between surrounding and exhaled air, however, this difference is rather small and would therefore

[15]https://en.wikipedia.org/wiki/List_of_sensors

[15]https://www.thoughtco.com/chemical-composition-of-air-604288targetText=Nearly%20all%20of%20the%20Earth's,ranging%20from%201%2D3%25.

[16]https://sciencing.com/chemical-composition-exhaled-air-human-lungs-11795.html

be difficult to detect. Because of that reason an argon detector was not considered using for this particular project.

Carbon dioxide sensor

As can be seen in Table 4, there is a significant difference between the amount of carbon dioxide in the normal air and the air that a person breathes out. Since the amount of CO_2 can be detected by a carbon dioxide sensor, it can be determined if an air flow exists of exhaled air or surrounding air. This technique could help detecting an airflow leakage in the spirometry maneuver.

Singh et al.[8, p. 2] describe how there are multiple ways of detecting CO_2. However, according to them, *"a low-cost yet sensitive technique is Non-Dispersive Infrared spectroscopy"*. NDIR measures the level of CO_2 by shining infrared light through an air sample. Some of the air will be absorbed by CO_2 particles. The leftover infrared light will be detected by an infrared detector. By comparing the amount of leftover infrared light with the amount of initial infrared light, the concentration of CO_2 can be calculated.[18] Singh et al. [8] used this technique to develop a handheld device to monitor asthma. This is a different technique than the earlier described spirometry test. Singh et al. [8] use a different test because they believe that the spirometry test asks too much cooperation from the patient and it therefore unreliable.

An example of a NDIR sensor compatible with Arduino can be seen in Figure 2.5. Since the sensor uses an air sample, this sensor might be rather hard to implement with the handheld spirometer. This is because, one has to explicitly blow into the NDIR sensor to detect the amount of CO_2. This would harm the spirometry maneuver since all of the respiratory air is supposed to go into the respiratory tube instead of into other sensors.

Oxygen sensor

Besides the difference of the amount of CO_2 in surrounding and exhaled air, there is also a significant difference in oxygen. Since it is possible to detect the amount of oxygen in the air with an oxygen sensor, this could be a solution to make a distinction between surrounding and exhaled air. This could again help to detect the airflow leakage during a spirometry test.

For example, Smallwood et al. [9], used a paramagnetic oxygen analyzer to monitor VO_2 values. Duncan and Pratt [10, p. 644], explain the workings of paramagnetic oxygen analyzer in the following way: *"Oxygen molecules,*

[18] https://www.co2meter.com/blogs/news/6010192-how-does-an-ndir-co2-sensor-work

[19] https://sandboxelectronics.com/?product=mh-z16-ndir-co2-sensor-with-i2cuart-5v3-3v-interface-for-Arduinoraspeberry-pi

Figure 2.5: Example of an NDIR CO_2 sensor compatible with Arduino[19]

unlike most other gases, contain unpaired electrons in their outer orbit (paramagnetic). Oxygen molecules are, therefore, attracted into a magnetic field. This attraction is utilised in paramagnetic oxygen analysers." In the same way as in the carbon dioxide sensor, a gas sample is taken and compared to normal air containing roughly 21% of oxygen. Next, the device will create an electromagnetic field which causes a differential pressure. The differential is converted to an electrical signal which then again can be converted into a percentage. This percentage is the amount of oxygen measured in the sample[10].

As stated before, this sensor again has to take a gas sample. The paramagnetic oxygen analyzer compatible to Arduino would thus look roughly the same as the NDIR sensor seen in Figure 2.5. Therefore, this sensor might again be rather hard to implement with the already existing handheld spirometry device.

2.3.2 Moisture sensor

A different way to detect if there exists an airflow leakage is by detecting if the lips are placed on the tube. Since lips are moist when you lick them, the presence of lips might be able to be detected by the moisture. Unfortunately, there is little related work on measuring lip moisture. However, moisture sensors are often used in different surroundings.

Soil sensor

For example, Sowmya et al. [11] used a moisture sensor in agriculture to see if the soil is moist enough or if there is a need for more water. To sense the amount of moisture in the soil, Sowmya et al. [11] use an Arduino combined with, among others, a soil sensor. The soil sensor can be seen in Figure 2.6. Sowmya et al. [11] designed their system by having the moisture sensor senses the amount of moisture in the ground and feeding this back to the Arduino. When the percentage of moisture is below a certain threshold, feedback will be sent to the user who can decide to water the plants.

Figure 2.6: Soil sensor compatible with Arduino [11]

Rain sensor

Another way to sense moisture is by using a rain sensor. For example, Yusoff et al. [12], designed a smart clothesline with among other a rain sensor, so that when it rains, a servo motor can collapse the clothesline. Yusoff et al. [12] use a rain sensor that, when rain falls on the sensor, senses the drops because they complete them circuit board on the sensor. A rain sensor compatible with Arduino can be seen in Figure 2.7.

[20]https://www.amazon.com/HaoYiShang-Humidity-Raindrop-Weather-Detection/dp/B01KJVH232

Figure 2.7: Rain sensor compatible with Arduino [20]

The soil moisture sensor and rain sensor could both be possible ways to detect the wetness of lips. However, as far as this research goes, no papers are found on using such moisture sensors for measuring bodily moisture. Therefore, it is hard to know if these sensors are implementable for this project. Furthermore, the rain sensor works by measuring moisture through raindrops. When lips are moist, they usually do not have drops on them. Therefore, the rain sensor might not be right to use for this project. Lastly, measuring the presence of the lips through moisture might be somewhat unintuitive since the user will have to have wet lips every time he or she uses the device which might not be something the user thinks of.

2.3.3 Light sensor

Besides sensing the presence of the lips, the airflow leakage could be sensed through light. This is because when the lips completely seal the mouth, the inside of the mouth is dark. Therefore, when no light is sensed, it could be concluded that there is no airflow leakage. Unfortunately, as far as this project goes, no related work was found on the usage of light sensors inside of the mouth.

A light dependent resistor can be used to sense the amount of light.

Such a sensor works as a resistor. When there is a lot of light, the sensor lets through a high amount of voltage and when there is no light, the sensor will let little voltage through. A light dependent resistor can be seen in Figure 2.8.

Figure 2.8: Light dependent resistor [21]

There are some aspects of the light resistor that might not be easy to implement into the system. This is because if using such a sensor it might have to be known where the lips are and how much of the tube is inside the mouth.

2.3.4 Presence sensor

As said before, the airflow leakage can be detected by sensing if the lip is present around the tube. This is however, by assuming that if the lip is present, it is closed tightly around the tube. There are multiple sensors to detect if something is present. These sensors will be discussed in the following subsections.

[21] https://www.everybitelectronics.co.uk/product/ldr-light-dependent-resistor/

Piezo resistive sensor

Piezoresistive sensors can measure a lot of different values. One of these values is force. The way piezoresistive sensors works is by a change in resistance in a certain material [13]. Regtien [13] states that this resistance can change when there is a deformation in the material. Multiple materials have this feature, however, Regtien [13] states that not all of these materials are sensitive enough to be used in a sensor. Hwang et al. [14] use, among others, a piezoresistive sensor to measure the amount of force applied on the stretchable transparent sensor they developed.

However, it can be questioned if the children apply force when they use the spirometer. If they apply very little force, it might be very hard to measure if the lips are sealing the tube or not. Because of this, a piezoresistive sensor might not be the way to go for this particular project.

Capacitive sensor [22]

According to Guaus et al. [15], for capacitive sensing, two conductors and a dielectric are needed. Using such sensors, Guaus et al. [15] states that the capacity is measured by the distance between the two conductors. In the system that is developed in this project, one of these conductors will be the lips, the other will be the capacitive sensor. Lastly, the air between these two is the dielectric. A capacitive sensor can be homemade with the use of aluminium foil. However, Guaus et al. [15] state that such sensor usually have some electrical problems and might thus not the way to go. An example of capacitive sensors compatible with Arduino can be seen in Figure 2.9.

An example of using capacitive sensing is made by Li et al. [16] who designed a retainer which tracks tongue movements by using capacitive sensing. Their system is called TongueBoard and can help a person who cannot speak to use certain speech apps. A picture of TongueBoard can be seen in Figure 2.10. Since The TongueBoard system works with a tongue and thus comes into contact with saliva, capacitive sensing seems to be a promising approach to use for sensing the presence of lips which are also moist.

Know that multiple sensors have been discussed, the next step is to think about how to get the data of the sensor system to the user. This has to be done by a feedback system.

[22]This section is built upon the course Sensors from Creative Technology given by Edwin Dertien

[23]https://github.com/PaulStoffregen/CapacitiveSensor

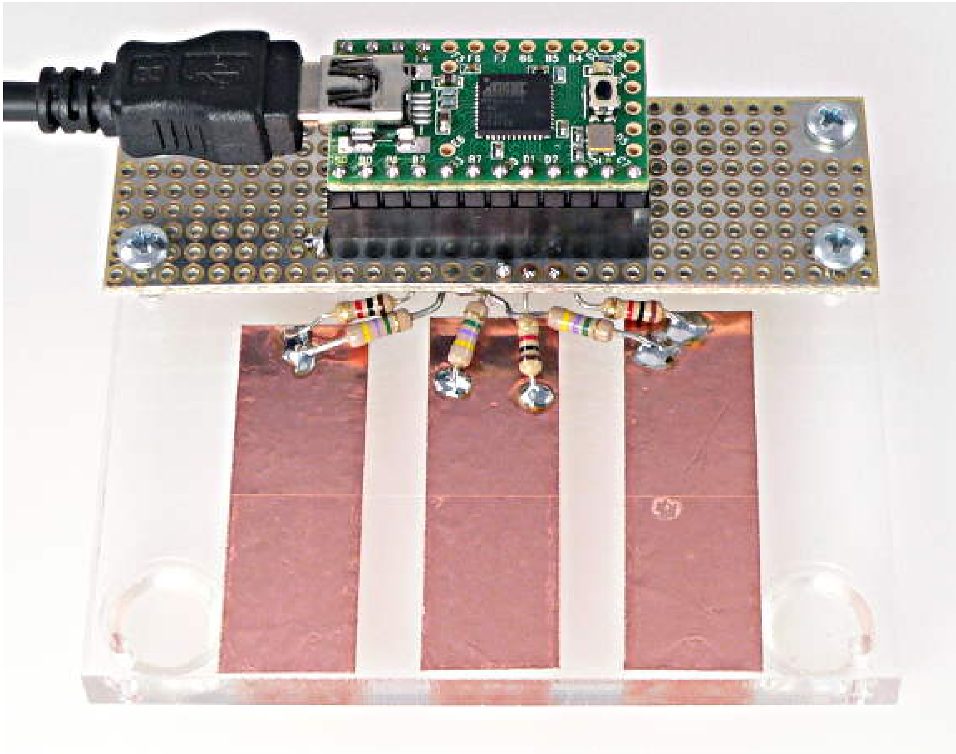

Figure 2.9: Capacitive sensors compatible with Arduino [23]

2.4 Feedback system

After the airflow leakage is detected, the user of the spirometer needs to get feedback. This feedback should show the user what is going wrong and how this should be solved. This feedback system should be easy to use for children, since they are the target group in this project.

To help children perform the spirometry test better, a serious game could be used. Coates et al. [6], state that children can be more motivated to perform a proper spirometry test when this test is combined with some kind of game with a motivating goal. One reasoning to this is that children use a lot of digital devices and play a lot of games [4]. They grew up with technology. Therefore, Elias et al. [4] state that using and involving this interest in technology and gaming, children might be more encouraged to do something that they usually find boring. Giunti et al. [17] define serious games are games that have *"the purpose of improving an individual's knowledge, skills, or attitudes in the "real" world"* [17, p. 386]. Giunti et al. [17] state that serious games should be fun to play, but at the same time, they should contribute to reaching a goal behaviour. Giunti et al. [17] add to this that to reach the behaviour goal, the game should give feedback on

Figure 2.10: The TongueBoard system [16]

how to do this and on what is going wrong in the behaviour of the player.

2.4.1 Feedback system of overarching project

In the overarching project, a serious game is already used to try and stimulate children to perform better at their spirometry test. For this game, the research group developed multiple metaphors and made a game out of these metaphors where the child breathing in and out controls the game. Screenshots of the game can be seen in Appendix C. However, since the application is made in Dutch as it is made for Dutch children, the text on the screenshots is also in Dutch. Figure C.1, shows the first screen of the application after the user has chosen their profile. When, in Figure C.1, the child chooses the option play, the next screen is Figure C.2. This screen shows all the metaphors the child can choose from, and as for now, metaphors that are still in development by the research group. Now, let's say one chooses the balloon metaphor. The next screen will then be Figure C.3. This screen describes shortly how the spirometry test should be performed. After a voiceover reads this text out loud, the text will go away and the user sees the screen in Figure C.4.

When at this screen, the spirometry test can begin. When the user breaths in, the crossbow tightens. When the user breaths out, the arrow will shoot away and hit the balloons. However, if the test is not performed properly, not all balloon will be popped. When this happens, the voiceover gives some advice on how to do the test properly. Afterwards, the test starts over.

2.4.2 Feedback systems in spirometry

To get an overview of what other feedback systems there are in handheld spirometers, one can look at the previous overview of spirometers. Many of these spirometers also use some kind of visualization to encourage the user to perform the test as good as possible.

For example, the Spirobank Smart [24], uses a metaphor with water. This metaphor can be seen in Figure 2.11. During the test, the water will rise as the patient is blowing air into the tube. Besides, the metaphor has a goal. This goal is to get as much water as the target goal which is displayed next to the value of the patient.

The Spiropalm spirometer[25], also comes with a metaphor on the display that is supposed to motivate the user. The metaphor of the Spiropalm spirometer can be seen in Figure 2.12. In this metaphor, blowing into the tube of the spirometer blows up the balloon of the girl in the picture where the clear goal is to get the balloon as big as the circle around it. This metaphor is quite easy to understand, since when blowing up a balloon you need to blow air out in the same way as you would do at a spirometry test.

Another example of a serious game in spirometry that was not found in the previously compared spirometers, is the InSpire system [4]. Elias et al. [4] developed a self-monitoring spirometry system combined with a serious game to motivate children to use the system. In Figure 2.13, you can see an example of the game that Elias et al. [4] created. This game motivates children to perform proper spirometry tests by making a dragon defeat enemies by breathing fire [4]. Elias et al. [4] based the Inspire system on two psychological models. Namely, the elaboration likelihood model and the social cognitive theory.

2.4.3 Elaboration likelihood model [26]

Van Gemert-Pijnen et al. [18] defines the elaboration likelihood model as *"a general theory of attitude change. It provides a framework for organizing, categorizing and understanding the basic processes underlying the effectiveness of persuasive communications."* [18, p. 33]. According to van Gemert-Pijnen et al. [18], the elaboration likelihood model thus shows how behaviour can be changed. Therefore, the system that is developed in this

[24] https://www.spirometry.com/ENG/download/3brochures.asp?device=spirobanksmart

[25] http://www.futuremed.com/spiropalm.htm

[26] This section is built upon the course Design of persuasive health Technology from Psychology at the University of Twente

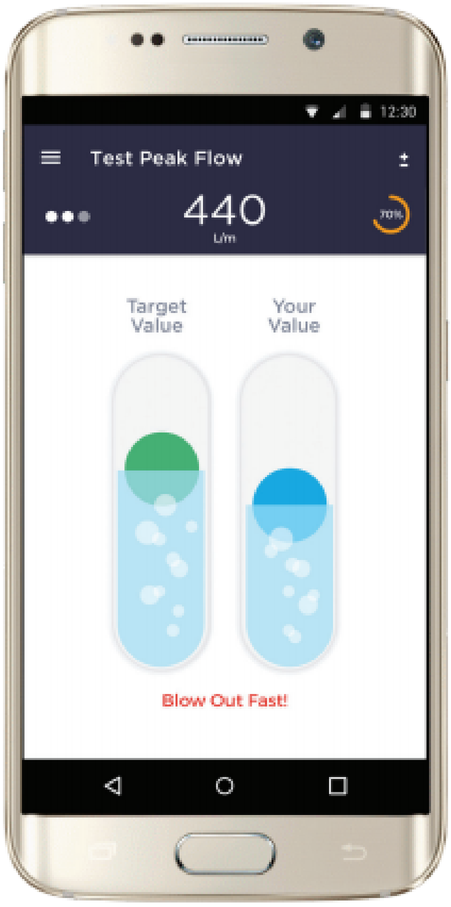

Figure 2.11: Feedback system of the Spirobank spirometer [11]

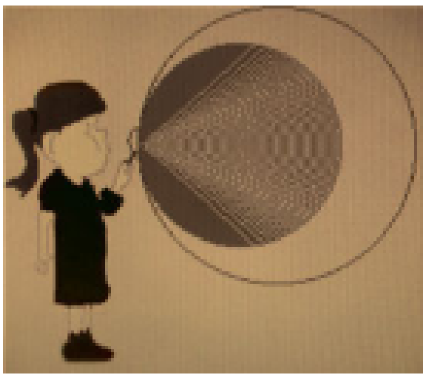

Figure 2.12: Feedback system of the Spiropalm spirometer[12]

Figure 2.13: game created by Elias et al. [4]

project can also be built upon the elaboration likelihood model since the behaviour of the children needs to be changed in a way that they will properly perform the spirometry test. According to van Gemert-Pijnen et al. [18], the way people perceive information depends greatly on how the information is brought on for example how motivated the receiver of the information is. Van Gemert-Pijnen et al. [18] state that the elaboration likelihood model focuses on this aspect by taking such factors into account and not just on giving the information to the user. The user has to be persuaded and motivated to do something with this information through the way the information is provided [18].

Social cognitive theory

Albert Bandura's social cognitive theory is another perspective on behaviour change. A scheme that explains the workings of the social cognitive theory can be seen in Figure 2.14.

Abert Bandura [19] states that the way people behave has often been explained just one factor. This means that the behaviour was either determined by the environment or by personality traits [19]. Social cognitive theory however, describes how there are 3 different factors that influences a person but also each other [19]. These three factors are behaviour, personal

[27] https://blog.originlearning.com/learning-by-watching-social-cognitive-theory-and-vicarious-learning/

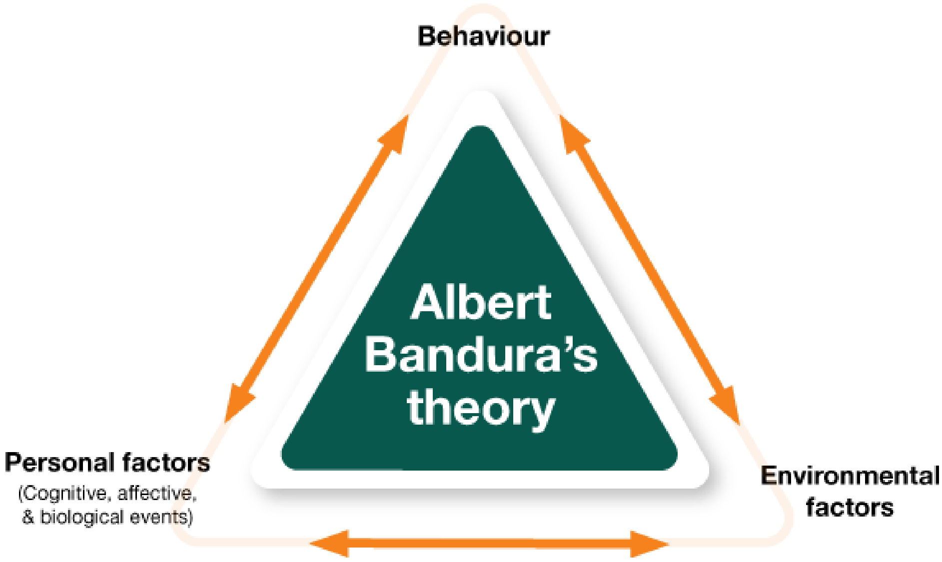

Figure 2.14: Schematic of social cognitive theory [27]

factors and the environment [19]. These three factors and how they influence each other can be seen in Figure 2.14. Although three different factors play a role in a person's behaviour, Bandura [19] states that these influences do not all have to be equally strong neither do they have to occur at the same time.

Bandura [19] states that the relationship between personal factors and behaviour, is that how people think and feel, but also how they work biologically, influences they way they behave. However, in the same way the way they behave influences people's thoughts. Furthermore, Bandura [19] explains the relationship between environmental factors and personality traits in a way that personality traits are developed by social influences for their environment. At the same time however, personality traits and physical characteristics of a person will alter their environment because people will look at a person in a certain way. Lastly, Bandura [19] explains the relationship between behaviour and environment as behaviour changing the environment around someone and again the environment that changes someone's behaviour.

2.4.4 Behaviour change techniques

The resulting system thus needs to have elements that will persuade the child to perform the correct behaviour. Michie et al. [20] designed an overview of behaviour change techniques that can help to motivate and persuade the child to perform the right behaviour. For the gamification of the feedback system,we selected the behaviour change techniques in the list below since these seemed relevant for the project. Incorporating these elements as well as possible into the feedback system, will hopefully get the child motivated to perform the spirometry test properly.

- Goal setting (outcome)
  - *"Set or agree on a goal defined in terms of a positive outcome of wanted behavior."* [20, p. 1]
- Discrepancy between current behaviour and goal
  - *"Draw attention to discrepancies between a person's current behavior (in terms of the form, frequency, duration, or intensity of that behavior) and the person's previously set outcome goals, behavioral goals or action plans"* [20, p. 2]
- Feedback on behaviour
  - *"Draw attention to discrepancies between a person's current behavior (in terms of the form, frequency, duration, or intensity of that behavior) and the person's previously set outcome goals, behavioral goals or action plans"* [20, p. 4]
- Instruction on how to perform a behaviour
  - *"Advise or agree on how to perform the behavior"* [20, p. 6]
- Prompts/cues
  - *"Introduce or define environmental or social stimulus with the purpose of prompting or cueing the behavior. The prompt or cue would normally occur at the time or place of performance"* [20, p. 9]

Looking at the list, the behaviour change techinques described can be incorporated into the system in the following way. The technique of goal setting, is incorporated in that the child will have the goal to perform the spirometry maneuver without the error of airflow leakage. However, for the child, the goal is to succeed the gamification of a certain metaphor. The discrepancy between current behaviour and goal is used by showing the child that the maneuver is not properly done. In the system the child gets feedback on its behaviour through the application. This application shows the child what is going wrong and how to improve it. The instruction on how to perform a behaviour is done by a visual instruction through the used metaphor. Lastly, the system might give the child prompts or cues on how to perform the test properly.

2.4.5 User-centered design

Besides having persuasive elements in the feedback system, the child obviously has to like the system and feel comfortable when using it. Therefore, user-centred design has to be involved in the design process. Stålberg et al. [2] describe this design method as *"the use of potential end-users of a product during the development process"* [2, p. 150]. According to Stålberg et al. [2] this will help find out what aspects the user will like or not. Because children are the target group of this project, they are included into the design process. Stålberg et al. [2] state that it is of great importance to involve children in the design process since they have different thinking strategies and skills than adults. Therefore, it is hard to design something for a child when the child is not included into the design process. Concluding, Stålberg et al. [2] state that the chance of acceptance of a product that is designed for children is increased when children are involved in the design process.

Chow [21] discusses that nowadays, there are a lot of apps and systems that track aspects of our daily life. These are things such as the amount of steps we set everyday our the amount of time we spend on a computer. People are getting more and more interested in observing this data and getting healthier. However, often this data is present in raw numbers and people using such systems do not always understand what to do with this data. Therefore, Chow [21] states that this data transformed into a representation to make the information more attractive and understandable.

Chow [21] states that it is important to make representations that the user of the product finds logical and sees the connection between the reality and the representation. If the user will understand a certain representation, Chow states that this is depended on the existing knowledge of the user. Chow discusses the conceptual blending method which makes a person understand a metaphor by blending the representation and the actual data. Doing this, what happens in the metaphor will help the user connect this to their own data and see what is going wrong in their behaviour.

Chow describes 4 steps that are needed for the design of a metaphor that is blended with the behaviour of the user.

- *"Identifying comparable scenarios from different domains."* [21, p. 55]
- *"Examining the mappings of scenarios with the behaviour."* [21, p. 55]
- *"Performing blends between the behaviour and the scenario."*[21, p. 55]
- *"Rendering the blended behavioral consequences as feedback that dynamically anchors the scenario for similar blends in users."* [21, p. 55]

For step one, Chow [21] describes multiple ways to find scenarios that are comparable to the behaviour of the user. The first option is to ask what users have to say about a system. The overarching project has already done this and came up with multiple scenarios that are greatly accepted by both kids using the spirometer and experts working with the spirometer. The second option is to build upon already existing metaphors. Since solving the airflow leakage problem is building upon the Spiroplay project, it would be logical to combine the metaphors of both the projects. Therefore, the metaphor that will be used during this project will be built upon one of the metaphors of the spiroplay project.

Chow [21] states that after it is known which metaphor is going to be used, it needs to be known how the scenario and the behaviour are exactly connected. Easily said, it needs to be clear what elements of both scenarios are the same and how this is blended into one metaphor. Doing this, has to be built upon the existing knowledge of the user so that the metaphor is easy to understand. When the scenario is chosen, Chow [21] states that the blends between the behaviour and the metaphor have to be made. Lastly, Chow [21] states that is important that the blend of the behaviour and the metaphor is important to be accepted by the user.

2.5 Resulting system

In conclusion, the airflow leakage is rather important to solve since such an error can result in wrong data. Therefore, a sensor system with a way of feedback to the child has to be developed.

When doing the sensor review, it became clear that the best option for the sensor is using a presence sensor. This is because the air analyzing way needs air samples which would interfere with the way the current system works. With the moisture sensors, the patient will have to have wet lips at all times which is not a guarantee. The light sensors will have to be inside of the mouth which could be considered somewhat unintuitive. Of the presence sensors, the capacitive sensor is prefered to use since this is a very cheap way to sense something's presence.

Such a sensor should be built upon the tube of the spirometer. However, in an interview with Matienne van der Kamp, it became clear that the tube that the Nuvoair spirometer uses is often replaced because of hygiene. Therefore, the sensor either has to be detachable, or a new kind of tube will have to be designed. In the next chapters, both of these options will be examined.

Furthermore, the literature review showed designing a gamified feedback system using metaphors will probably help in motivating the children to perform the spirometry maneuver correctly. However, the research also showed that to increase the chance of the children liking the feedback system, children have to be involved in the design process. Therefore, when designing the process, children are involved in this process as much as possible.

Chapter 3

Specification

In the previous chapter, a possible solution for the airflow leakage problem has been found. This solution was to use capacitive sensors to sense the presence of the lips around the tube. How well the child performs the spirometry test is going to be sent back to the child as feedback that will motivate the child to perform better.

As explained in the introduction, this part of the project is about understanding the user, improving the product, and to some extent indicating feasibility of the sensor solution. To reach this goal, a low fidelity prototype is made and tested with the target group to see what the user thinks about it and what they would change. Furthermore, the designed product has to meet the following requirements:

- The product has to detect or prevent airflow leakage.
- The product cannot harm the child.
- The product should not interfere with the normal spirometry test, meaning the data should not be influenced.
- The product has to be wireless.
- The tube must be detachable.

Some considerations that had to be kept in mind when designing this product are:

- The product has to be safe to use.
- The product has to be fun for the child.
- The product has to be understandable for the child.
- The product should be affordable.

Having these considerations in mind, a low fidelity prototype can be made. As stated before, when designing for children, it is very important to involve the children into the design process as much as possible. Therefore, low fidelity prototypes have been created and tested with children.

3.1 Sensor part

The lofi prototype consists of a sensor part and a feedback part. The sensor part of the prototype consists of a cardboard tube in which capacitive sensors are placed. These sensors are made of aluminum foil connected with a resistor and a wires to an Arduino. The capacitive sensors work in the following way. Capacitor consists of 2 conductors separated by a dielectric medium. Dielectric means that is does not conduct electricity. The conducting plates hold equal and opposite charges. The Dielectric forms an electric field. Usually, the conductors are both some kind of metal.[1] In this project, however, only one of the conductors will be made from a certain metal. The other conductor will be the lips of the user. Due to the dielectric material, this is safe and not even noticeable to the user.There are multiple formulas that can describe the capacitance of a capacitor.

Since one of the conductors is the lip of the user, this conductor can be brought closer or further away from the other conductor, the metal plate. When looking at formula 3.3, where the distance between the plates is described by d, it becomes clear that when changing the distance between the two conductive plates, the capacitance changes as well. This changes the speed with which the capacitor can load and release charge. So, if the distance between the conductors is the only parameter that changes in the sensor, the distance can be sensed using the speed with which the capacitor charges and discharges. Therefore, when the lips are touching the sensor, the distance between the plates is incredibly small which changes the charging speed of the capacitor drastically. This method can thus determine if the lips are touching the capacitor or not. This technique is used in the making of this project. To make the capacitor charge and discharge, a RC circuit is made. This system consists of a resistor, a capacitor, a sending and a receive pin. The sending pin will send voltage over the circuit with which the capacitor will charge and discharge. With the sensing pin, the speed of this charging and discharging can be measured. In Figure 3.1, a typical RC circuit can be seen. Together with this RC circuit comes Formula 3.1, that describes how the relation between the voltage over the capacitor which is sensed over time by the sensing pin and the voltage send by the sending pin.

$$V_C(t) = V_{in}(1 - e^{\frac{-t}{RC}}) \tag{3.1}$$

[1] $http \; : \; //wiki.edwindertien.nl/doku.php?id \; = \; education \; : \; sensors \; : \; 02_capacitive_sensing$

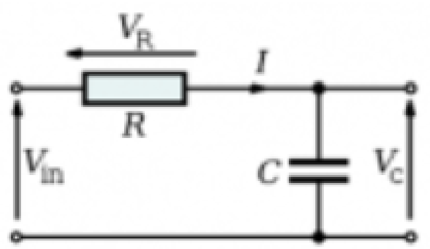

Figure 3.1: Schematic of an RC circuit. [1]

$$C = \epsilon \frac{A}{d} \tag{3.2}$$

Where C = capacitance, ϵ = permittivity of dielectric material, A = area and d = distance between the plates.[1]

$$C = \frac{\epsilon_0 \times \epsilon_r \times A}{T} \tag{3.3}$$

Where C= capacitance, ϵ_0= permittivity of air = $8.84 \times 10^{12} \frac{F}{M}$.[1]

Besides the distance between the plates, there are multiple other parameters that matter in the capacitance of the capacitor. Starting with the area of the plates, described as A in formulas 3.1 and 3.2. The larger the plates are, the larger the capacitance of the capacitor. Next there is the permittivity of the dielectric material, also described in formula 3.1 and 3.2 as ϵ. In formula 3 can be seen that both the permittivity of air is used as the one of the dielectric material itself. Multiplying these two values will result in the total permittivity.

There are many different materials that can be used for the conductive plates and the dielectric. However, since the low fidelity prototype should be affordable, simple and quick to make, the cheapest options are chosen for this. Therefor, aluminium foil is used as a conductor. As a dielectric, it is possible to use air alone. This is of course the cheapest option. However, when touching a capacitive sensor without any dielectric overlay, there might be electrostatic discharge which could cause a spark.[2] The voltage used for the capacitors is not very high since the Arduino will just give a signal of 5 volts. However this might still be uncomfortable to use for children and therefore, there should be another dielectric material between the conductive plates and the lips of the child. Another possible dielectric material is paper. Since the tubes are made of cardboard, placing the aluminium foil inside the

[2] $https://www.microchip.com/wwwAppNotes/AppNotes.aspx?appnote=en591898$

tube will allow the cardboard to act as the dielectric material together with air making sure that there will not be any electrostatic discharge.

A schematic image of the circuit can be seen in Figure 3.2. As can be seen in Figure 3.2, four different capacitive sensors are used. These sensors are all placed in the tube to sense the presence of the lips at four different locations. The other thing that can be seen in Figure 3.2, is that a 10 megaOhm resistor is used. This resistor is necessary for the RC circuit. A range of values could be used for this resistor. However the larger the resistance, the more sensitive the sensor is [3]. After some trial and error, it became clear that for this prototype, a 10 megaΩ resistor seems suitable.

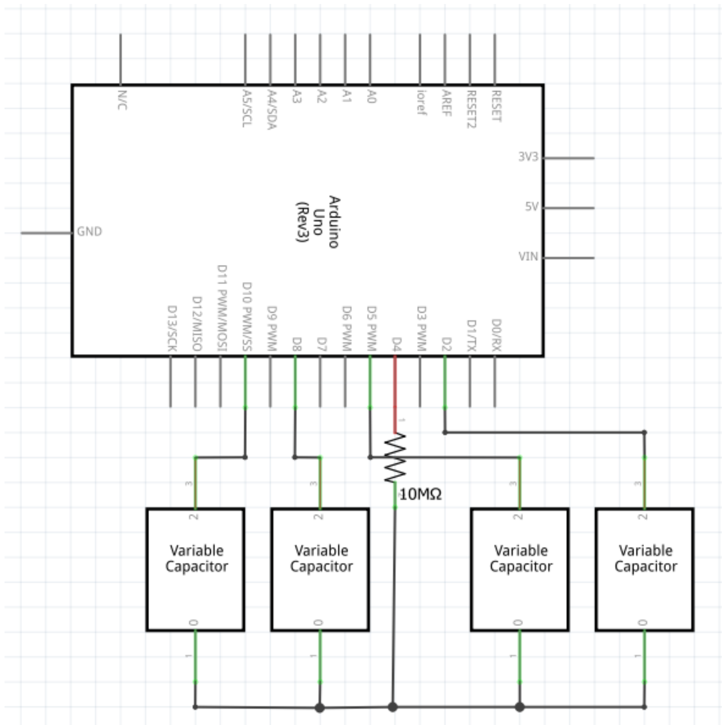

Figure 3.2: Schematic of the lofi circuit

3.2 Feedback part

For the feedback part of the lofi prototype, as stated before, one of the metaphors of the overarching project will be used. In the overarching project, the research group involved children as much as possible into the design process of the metaphors. The development of the metaphors in the overarching project was done in the following way.

[3]https://playground.Arduino.cc/Main/CapacitiveSensor/

First, multiple brainstorms in groups were performed, in which ideas were drawn on post-its. During the brainstorms, two examples were given to spark inspiration. For this same purpose, inspiration cards were used. The brainstorms were done with partners, children from the age of 6 to 8 and children from the age of 10 to 12. Next, some preselection took place. This was done by the researchers themselves and experts who based the selection on proper blowing potential and by participants of the brainstorm who were allowed to pick their favorite idea. This preselection resulted in a selection of 24 ideas. After the preselection, the different groups (6 to 8 years old, 10 to 12 years old and experts), had to rank the different ideas on fun, proper blowing and repeatability. From this, the highest rated ideas were elaborated on. These ideas and how they work can be seen in Table 5.

Table 5: Metaphors overarching project

Ideas	**Start**	**Breath in**	**Goal**
Dandelion	You see a dandelion	Dandelion changes to fluff ball	Blow the fluff away
Growing dog	You start with a bald dog	The dog gets very short hair	Grow the hair by blowing
Bowling alley	You start with a bowling alley with pins	Not clear yet	Make the ball roll by blowing
Shooting balloons	Not clear yet	Row with multiple balloons	Shoot a dart through the balloons by blowing
Car	Not clear yet	Starting the car	Make the car drive by blowing
Competitive diving	Not clear yet	Get ready to dive	Blowing makes the diver jump, the better the breathing the better the jump
Ebb and flow	Not clear yet	The sea is calm	Sea gets bigger and people are running away from it
Fire Breathing dragon	Not clear yet	Not clear yet	Not clear yet

During this project, the existing metaphors in Table 5 had to be elaborated more. To give feedback on the sensor data, one of the metaphors has to get a part before the actual start of the spirometer test which has to encourage the child to put the lips around the tube. After considering the different metaphors, the following elaborations on the metaphors came to mind

Table 6: Possible metaphores for the airflow leakage	
Metaphors	**Elaboration**
Dandelion	Leaves of the flower only occur when sensor is touched Touching the capacitive sensors makes the dandelion grow
Growing dog	Dog is lying down and stands up when sensors are touched Touching the sensors will feed the dog
Bowling alley	Pins occur when sensors are touched
Shooting balloons	Balloons occur when sensors are touched Touching the sensors makes the balloons grow
Car	Touching the sensors fills the tank of the car The wheels of the car occur when sensors are touched
Competitive diving	Touching the sensors makes jumper climb the stairs Touching the sensors fills the pool
Tides	Touching sensors makes people enter the beach
Dragon	Touching the sensors makes the dragon grow Touching sensors feeds the dragon.

As explained earlier, using Chow's [22] paper, for a metaphor to make sense, it is important that the reality should be blended with the metaphor. The exercise of putting the lips around the tube should thus have a connection to the metaphors in order for the metaphor to work properly. Therefore, a lot of ideas do not seem right for this project. However, the ideas that do have some kind of correlation with reality are the metaphor of the dandelion where putting the lips on the capacitive sensors makes the leafs appear, and the idea of the balloons where putting the lips on the capacitive sensors makes the balloons appear. Both of these metaphors are or can be made round which is in correlation with the shape of the tube. Besides the shape, both metaphors also correlate with the spirometry test in that blowing on or in the object gives you a certain result. Therefore, the metaphor might be a logical step.

These two metaphors were therefore made into a paper prototype which can be seen in Figure 3.3 an 3.4. The idea of the paper prototypes is that the leafs and balloons are different pieces of paper which makes them easy to remove or place on the paper when the lips are or are not touching the capacitive sensors. The feedback system itself was made on a mock up tablet so that it might be easier for the children to imagine that they are using an app on a real tablet instead of just playing with a piece of paper.

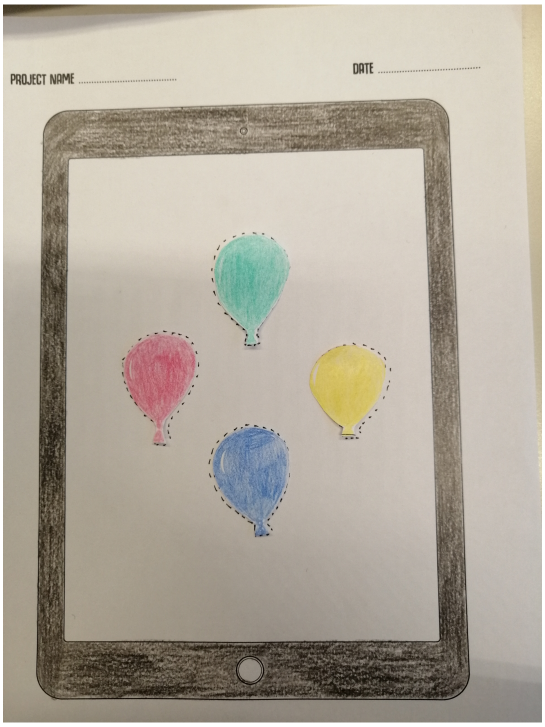

Figure 3.3: Paper prototype of the balloon metaphor

Figure 3.4: Paper prototype of the flower metaphor

Chapter 4

Testing of the lofi prototype

With the resulting lofi prototype (which can be seen in Figure 4.1), testing is done on the BSO de vlinder. The overarching project also does their tests on this BSO and so the consent was already taken care of by the research group. At the BSO, the lofi prototype was tested with four kids of which two boys, ages 7 and 8, and two girls both aged 7. The kids were tested in groups of two in order to make them less nervous. All of the kids were asked to use to prototype correctly and wrongly with both metaphors. After they did this they were asked what they thought of the test with questions such as do you think the metaphor is fitting and if you could change anything what would you change. All these specific questions can be found in a protocol in Appendix D.1. However, since the testing was done in Dutch, the protocol is translated from Dutch to English.

All the answers to the questions can be found in Appendix E.1. However, since the test was performed in Dutch the questions and answers in Appendix E.1 are translated form Dutch to English. Overall, the kids thought the tests were a lot of fun to do. However, one of the kids did not particularly like that see had to do the test together with someone else since she already knew what was going on. The fact that the test was done with two children at a time may have also altered the results slightly since in each group one of the kids was clearly more dominant than the other and this might have influenced the answers of the children who were a little shy.

While the full answers of the interviews can be found in Appendix E.1, a summary is given here. In Table 6 , it can be seen that 75% of the children have already participated in one of the asthma tests of the research group. This probably caused the fact that all children successfully did they exercise on the first try. There was one child who did not perform in one of the Asthma tests before. However, this child was second in his group to do the test and therefore might have seen how it should be done from their partner. Table 6 also shows that all the children successfully completed both tests on the first try. Furthermore, Table 6 shows that children were often quicker to

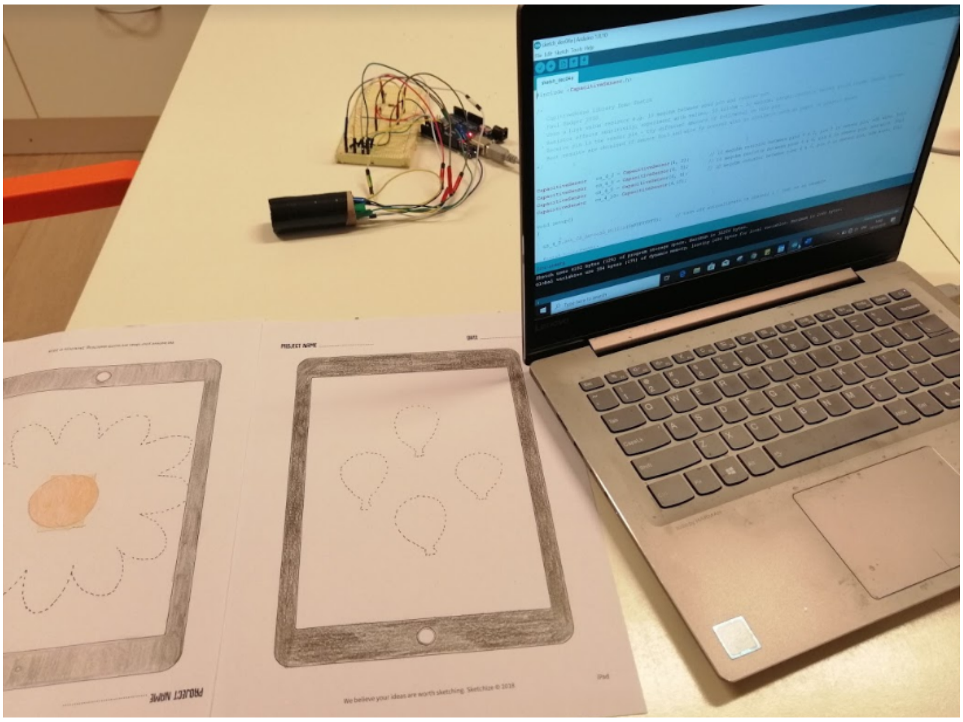

Figure 4.1: Test setup used for the lofi user test at BSO de Vlinder

understand the balloon metaphor, for using it both correctly and incorrectly. However, during the tests, the balloon metaphor was always completed after the flower analogy which might mean there was a learning curve. Lastly, Table 6 shows that most children liked the flower image the most but felt that the balloon image was more suitable for the exercise. At the end of the test, the children were allowed to make suggestions about how they would like to change the images. This feedback is visible in Table 7.

Table 6: Data from the lofi testing			
Question	**Yes**	**No**	*Partly*
The child participated in one of the previous spirometry tests.	75%	25%	0%
The flower went correctly right away.	100%	0%	0%
The balloons went correctly right away.	100%	0%	0%
The child understood how the image of the flower would change.	50%	0%	50%
The child understood how the image of the balloons would change.	75%	0%	25%
The child understood what would happen with the flower if used incorrectly	50%	50%	0%
The child understood what would happen with the balloons if used incorrectly	100%	0%	0%
	Flower	**Balloon**	
Which image did the child like the most.	75%	25%	
Which image did the child find the most fitting for the exercise	25%	75%	

Table 7: Feedback of the children on the paper prototypes	
Flower metaphor	Something else than a flower Other color Add stem Add animals
Balloon metaphor	Something else than a lower Add more balloons Balloons in different shapes Add a rope

In conclusion, all of the children seemed to like and understand doing the exercises. None of the children stated that there was anything unpleasant about any part of the test. However, it is hard to draw a conclusion from the test results since there is a strong chance that the children were influenced by each other. Besides that the results about which of the metaphors is better lie pretty close together. Nevertheless, if the possible influencing and learning effects are neglected, the balloon metaphor seems to be the best choice for the high fidelity prototype since this metaphor was best understood and according to the children it fitted the best with the exercise.

4.1 Testing with children

During the lofi user testing, it became clear that testing with children can be hard and a lot of factors can influence the behaviour and answers of the child. Therefore, during the following hifi user testing, the methods in the paper of Read et al. [22] are used to make the user test as reliable as possible.

According to Read et al. [22]. There are four factors that could influence they answers of the children. These are, 'Satisficing and Optimizing', 'Suggestibility', 'language effects' and 'question formats' [22].

The first factor, makes a distinction between optimization and satisfaction. Optimising means that the participant of the test fully understands the question and gives a reliably answer that was retrieved from their memory [22]. Satisficing on the other hand, happens when the participant might not fully understand the question or does not know the answer. When this happens, the participant will give a rather superficial answer [22]. According to Read et al. [22], The degree or level of satisficing is known to be related to the motivation of the respondent, the difficulties of the task, and the cognitive abilities of the respondent. Suggestibility has to do with how children are influenced by surrounding factors [22]. This for example concerns the influences of a researcher performing the user testing. Furthermore, the questions that the children have to answer could also influence the reliability of the answers. Read et al. [22] state, that questions where children are free to recall and tell about a memory, work very well with children. Lastly, the language abilities of children can have a great influence on the children since this ability determines how well the child understands the question asked [22].

Read et al. [22], state multiple ways that can help get more reliable answers on the user test. The methods relevant for the test that is performed in this project are the following.

- *"Keep it short: ..... This will reduce the effect of satisficing by keeping their motivation high."* [22, p. 86]
- *"Pilot the language: In a survey using written language, children will take short cuts if they cannot read the questions. Teachers can be useful in checking to see if the words used in the survey make sense, they may point out where words may mean something different to children."* [22, p. 86]
- *"Provide assistance for non/poor readers: Even with the language checked, there will be some children who may understand the words but not the questions. Try to read out written questions if possible."* [22, p. 86]
- *"Use appropriate tools and methods: Reduce the effects of suggestibility and satisficing by using special methods. ....In interviews, use visual props to help articulate ideas."* [22, p. 86]

- *"Expect the unexpected: Have a back up plan. If an entire project depends on the results of a survey with children it may well fail! Triangulate where possible ideas include observations and post hoc reports from researchers and children."* [22, p. 86]

- *"Don't take it too seriously: One of the great pitfalls in research and development work is to read too much into data. The information gained from a single group of children in a single place is not likely to be especially generalisable. Avoid the temptation to apply statistical tests to children's responses, rather look for trends and outliers!"* [22, p. 86]

Chapter 5

Realization

With the test results of the lofi prototype, a further realization of the final product is done. This results in a high fidelity prototype. This high fidelity prototype should be as much integrated with the application of the overarching research group as possible. To do this, there are a few upgrades that need to be made from the low fidelity prototype. These upgrades can be divided into upgrades to the sensor system, the feedback system and the tube of the spirometer. The upgrades will be discussed in the next section

5.1 Sensor system

There are multiple points about the sensor system of the low fidelity prototype that should be changed. In principle, the prototype was working accordingly. However, the aluminum foil capacitive sensors broke quickly and were rather unstable to work with. If anything shifted, the values were not right anymore. This should not happen when the sensor is used in real life. Furthermore, with the low fidelity prototype, the used Arduino was still connected to a computer to read the data. The spirometer used in this project, however, is wireless. It would therefore be rather unintuitive to attach a wire between the sensor and an external device. Also, the application of the overarching project works on a phone and thus the data should not have to be read from a computer.

First of all, there should be a replacement for the aluminium foil capacitive sensors. As stated before, the sensor should stay as cheap as possible. Thus, a cheap yet stable material had to be found to replace the aluminum foil. Common materials for the electrodes of capacitive sensors are: copper, carbon, silver ink, PEDOT and ITO. For this project copper was chosen in the form of copper tape. Copper tape is an affordable and flexible material which makes it ideal for this project.

However, when working with the copper tape, it became clear that just a single 10 MegaΩ resistor did not make the capacitive sensor sensitive enough and the data that came through did not make any sense while using just one of these resistors. This is due to the fact that with changing the material, the resistance of the material changes. This change in resistance means that the total resistance in the circuit becomes larger or smaller, slowing down or speeding up the charging and discharging of the capacitor. This can be seen by looking at Formula 3.1 The resistance of the aluminimum foil is $2.65 * 10^{-8}$ and that of the copper tape is $1.68 * 10^{-8}$.[1] Changing the material form aluminimum foil to copper tape thus lowered the overall resistance. To get proper values again, the resistance per capacitive sensor is changed to 20 MegaΩ.

Adding a small capacitance between the sending pin and the resistors, should make the capacitive sensor more stable.[2] However, when trying this, the sensors returned rather strange data. Therefore, the extra capacitor has not been implemented with the hifi prototype. Another element that supposedly improved the circuit is a small resistor of about 100 Ohms between the electrode and the sensing pin.[3] This resistor was implemented to protect the sensing pin in case the voltage returned to the sensing pin would be to high for the pin. Figure 5.1 shows a schematic of the updated circuit.

Next, the sensor should be wireless. This can be done by both Bluetooth as Wifi. Bluetooth is often used for short distance transmittance of data since it has a shorter range. Wifi has a larger range, but is often a more expensive option. Besides the costs, Wifi is also a lot of work to set up where Bluetooth is a lot easier to work with. Besides, the spirometer already uses Bluetooth to connect with the application of the overarching project. Therefore, Bluetooth will be used as well during this project. The project as it is has to use two different Bluetooth modules since one of the two is built into the spirometer. However, if this project would be used in real life, the project could be implemented in a way that only the Bluetooth of the spirometer itself is necessary.

When using Arduino, there are two different options when working with Bluetooth. These options are using a Bluetooth shield, or a Bluetooth module. A Bluetooth shield that is often used is the V1.1 which can be seen in Figure 5.2. For the Bluetooth module, a much used option is the HC-05 which can be seen in Figure 5.3. One obvious difference between these two options is the prize. A Bluetooth module such as the HC-05, can often be bought for around ten euros. The Bluetooth shield, however, can quickly cost around thirty euros. Nevertheless, if this project would be completely implemented into the spirometer, the Bluetooth inside of the spirometer could be used. Therefore, money is not that important for choosing which

[1] $https://en.wikipedia.org/wiki/Electrical\_resistivity\_and_conductivity\#In\_metals$

[2] https://playground.Arduino.cc/Main/CapacitiveSensor/

[3] $https://www.youtube.com/watch?v=BHQPqQ_5ulc$

[3] https://www.quora.com/Should-I-use-WiFi-or-Bluetooth-to-control-Arduino-with-my-smartphone-Is-so-then-why

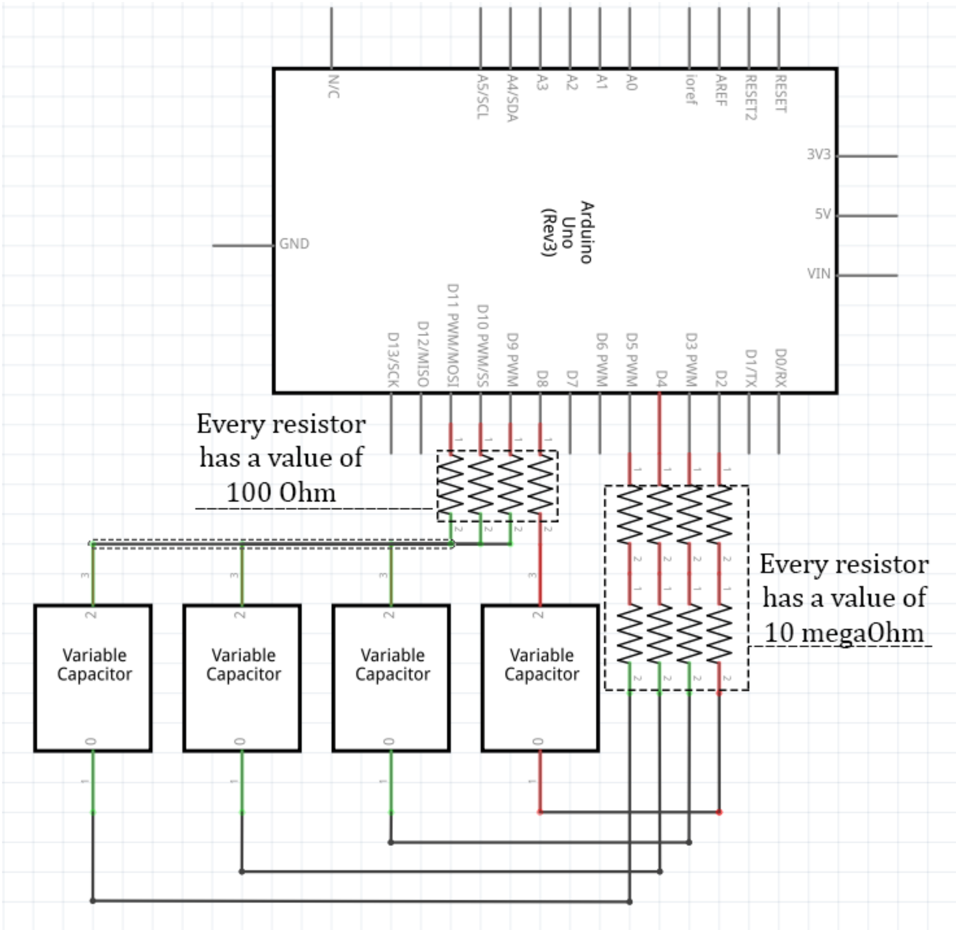

Figure 5.1: Schematic of the hifi circuit

Bluetooth option to use.

An aspect that is in fact important for choosing which sensor to use is the way the options connect to the Arduino. The Bluetooth module takes multiple pins from the Arduino in order to work. The Bluetooth shield, however, can be placed on the Arduino in such a way that almost all pins of the Arduino can still be used the same way as before. Since during this project eight digital pins are already in use, the preferred option is the Bluetooth shield. Therefore, in the beginning of the realization phase, the Bluetooth shield was used to make the Bluetooth connection. However, after some trial and error it became clear that the Bluetooth shield often comes with a lot of trouble when trying to make a connection between the shield

[4] https://www.elecrow.com/Bluetooth-shield-masterslave-p-332.html

[5] $https : //nl.banggood.com/HC - 05 - Wireless - Bluetooth - Serial - Module - With - Baseplate - For - Arduino - p - 959393.html?akmClientCountry = NL\&\&cur_warehouse = CN$

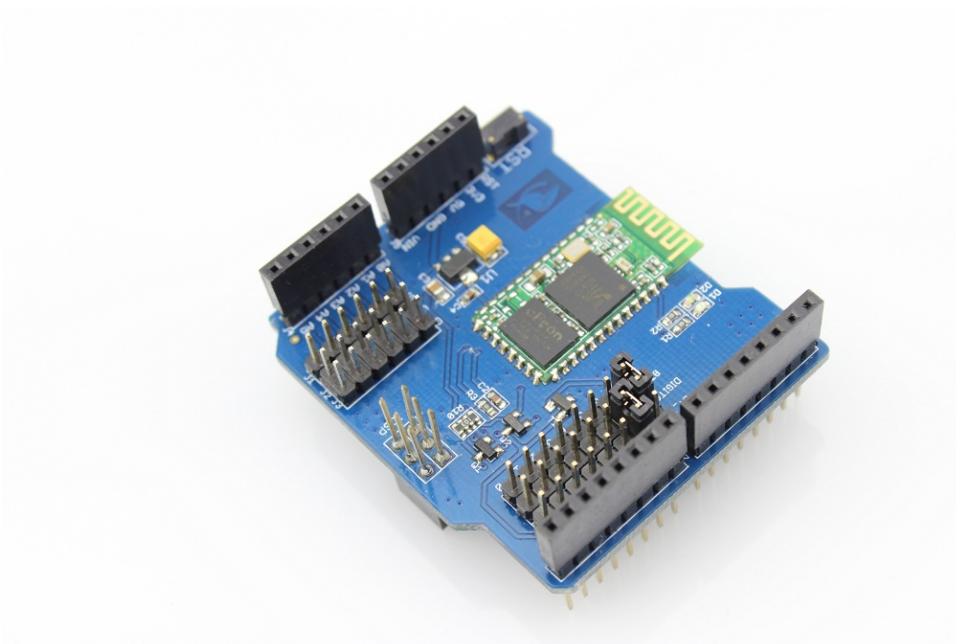

Figure 5.2: Image of the V1.1. Bluetooth shield [4]

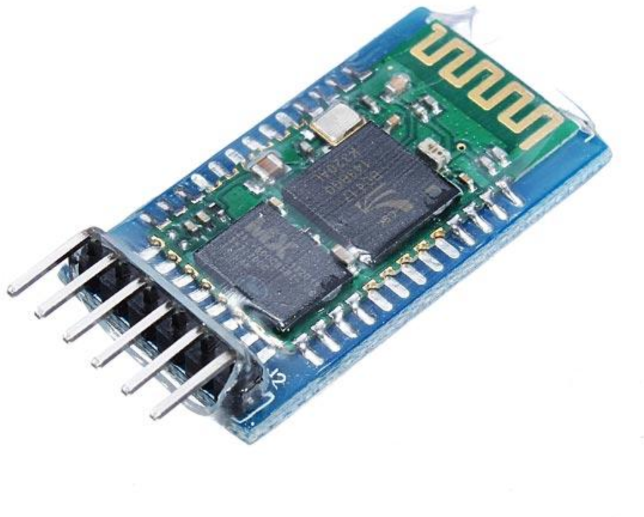

Figure 5.3: Image of the HC-05 Bluetooth module [5]

and the tablet since the Bluetooth shield simply does not connect.

In conclusion, the updated sensor system thus consists of two more resistors, of which some for sensitivity purposes and others for stability purposes. Furthermore, the system now sends its data via Bluetooth to an application instead of via USB serial to the computer. This Bluetooth connection might give some problems when trying to connect with the application. However, this will not be too big of an issue because when the project is integrated with the Nuvoair, the Bluetooth of the Nuvoair will be used. The updated sensor system can be seen in Figure 5.4.

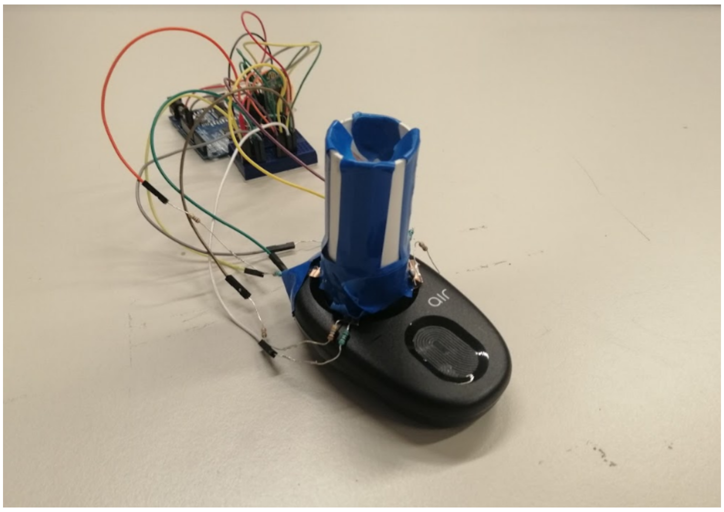

Figure 5.4: Image hifi sensor system

5.2 Tube

For the lofi prototype, a round piece of cardboard was used to act as the tube of the spirometer. In the hifi prototype, the actual tube of the spirometer is used. In the hifi prototype, the capacitive sensors are placed on the outside of the tube. During the specialization phase, these sensors were placed on the inside of the tube. The reason for this change is that the wires of the circuit would have to go through the turbine if the sensors are placed on they inside. However, this is not possible since there is very little space inside the turbine and this might disrupt the flow of the air and thus give false data. Therefore, the sensors are placed on the outside of the tube for this updated version. How the sensors are placed outside of the tube can be seen in Figure 5.4

In the hifi prototype, the wires of the sensors are connected to an Arduino outside of the spirometer itself. If the product would eventually be realized, this would have to change since the Arduino system is rather bulky and takes away the handheld quality that the spirometer usually has. In the final product, the Arduino and Bluetooth module can be replaced by components that are inside the spirometer itself. This does however raise the question as to how the sensors are connected to the spirometer. Furthermore, the spirometer has a replaceable tube. The way the hifi prototype is designed right now, the tube is not easy to replace, and since the sensors are on the tube itself, the sensors would get lost every time the tube is replaced.

To solve both the problem of the inside circuit and the replaceable tubes, two possible solutions are suggested. These solutions can be seen in Figure 5.5. Solution number one, looks the most like the prototype as it is right now. The sensors are still mounted on the tube of the spirometer (the sensors are displayed in blue) and two wires are attached to each sensor. However, the difference is that the rest of the circuit can be found inside of the spirometer. To connect the tube to the spirometer, the wires can simply be inserted into the small holes that can be seen on the spirometer. These holes would be very similar to the pins on an Arduino With this first solution, the tube would still be thrown away every use. This unfortunately means that the sensors also would have to be thrown away. However, since the sensors are made of copper material, and the rest of the circuit is already in the spirometer, this is a fairly cheap option and it would not add too much to the cost of the tube.

Up till now, the the idea was to work with the fully disposable tube of Nuvoair. However, Nuvoair also provides a tube which is more reusable. To prevent a lot of waste of the sensors, this solution might be more suitable for the reusable tube. It is important to note that only the turbine of the reusable tube is actually reusable. Therefore, if the sensors really should have to be reusable, the carton of the tube should be replaced with a more reusable material.

The second solution takes on a different approach. In the second option some sort of overlay is used that can be attached around the tube. On the inside of the overlay, the capacitive sensors are placed. This way, the inner tube can be replaced after every use for hygiene, while the outer layer can be reused multiple times until the child understands how to perform the spirometry test properly. To make this system successful however, another type of dielectric material has to be used. This material should be flexible and appropriate to use multiple times.

5.3 Feedback system

The main upgrade about the feedback system is obvious, the paper prototype has to become an application. The best way to do this is by implementing the metaphor of this project with the application of the overarching project. The application of the overarching project actually consists of two applications.

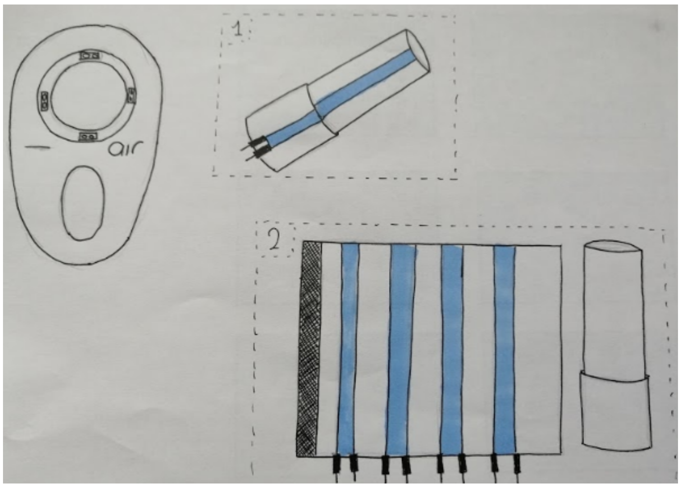

Figure 5.5: Sketches of possible solutions for the replaceable tube

One part connects to the Bluetooth inside the spirometer, the other part uses the data from the spirometer to control the serious games that were explained before. These apps are made in Android Studio and Unity by hired developpers of the overarching project.

Unfortunately, implementing the metaphor of this project with the overarching project, seemed to be rather difficult. Especially the second Bluetooth module caused some troubles. Therefore, it was decided to make a separate application for detecting the airflow leakage. This application can then be in a later stage combined with the application of the overarching project. The application for this project is made with Processing in Android mode which is a way to make applications for Android phones and tablets. The code of this application and the accompanying Arduino code can be seen at Appendix 2.1 and 2.2 respectively. Screenshots of the processing application can be seen in Figure 5.6 and 5.7. In Figure 5.6, the app is shown when none of the capacitive sensors are touched, while Figure 5.7 shows the app when all capacitive sensors would be touched.

As stated in Chapter 2, multiple behaviour change techniques could be used to encourage the child to perform the correct behaviour [20]. The techniques that were named as appropriate for this project were:

- Goal setting
- Discrepancy between current and goal behaviour
- Feedback on behaviour
- Instruction on how to perfrom the behaviour
- Promts/cues

The goal setting technique is incorporated in the feedback system by giving the user the goal to get all the balloons colored in. Both the technique's 'discrepancy between current and goal behaviour' and 'feedback on behaviour' are incorporated through the balloons showing the users how well they are doing. If a user has more balloons colored in, the user will know that he or she is going in the right direction. As the prototype is right now, the feedback system does not have clear instruction on how to perform the behaviour. However, this can be added when incorporating this project into the larger project where there is actually a moment in the game where the user gets explained how to do certain things. Lastly, the behaviour change technique of promts and cues is somewhat used since balloon will appear and disappear when the user is performing a certain behaviour. This can thus be seen as a cue on how to perform the behaviour.

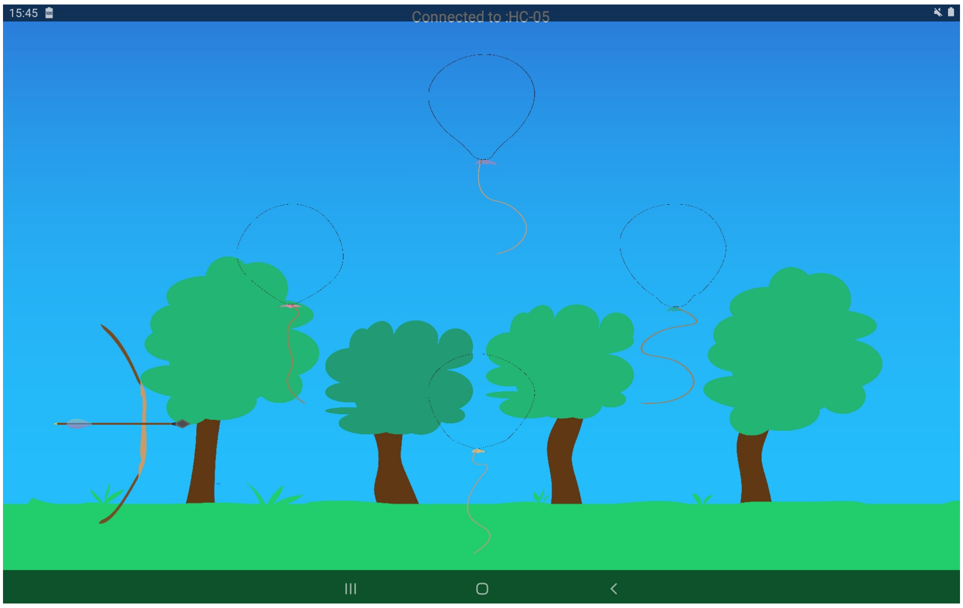

Figure 5.6: Screenshot of the application when none of the sensors are touched

An aspect that had to be kept in mind, is that immediately after ensuring that the lips are properly around the tube, the spirometry test should start. This is due to the fact that while at the start of the test, the child should blow all the air out of their lungs, then put the tube into their mouth, and then breath in. This means, that when the child has just put the tube into their mouth, they are almost gasping for air. Therefore, after the lips are properly in place, the child should be able to immediately continue the test. To make this possible, the bow and arrow are already added to the airflow leakage screen. Besides, the app is programmed in such a way that when all of the sensors are touched, the balloons go from floating in a circle to

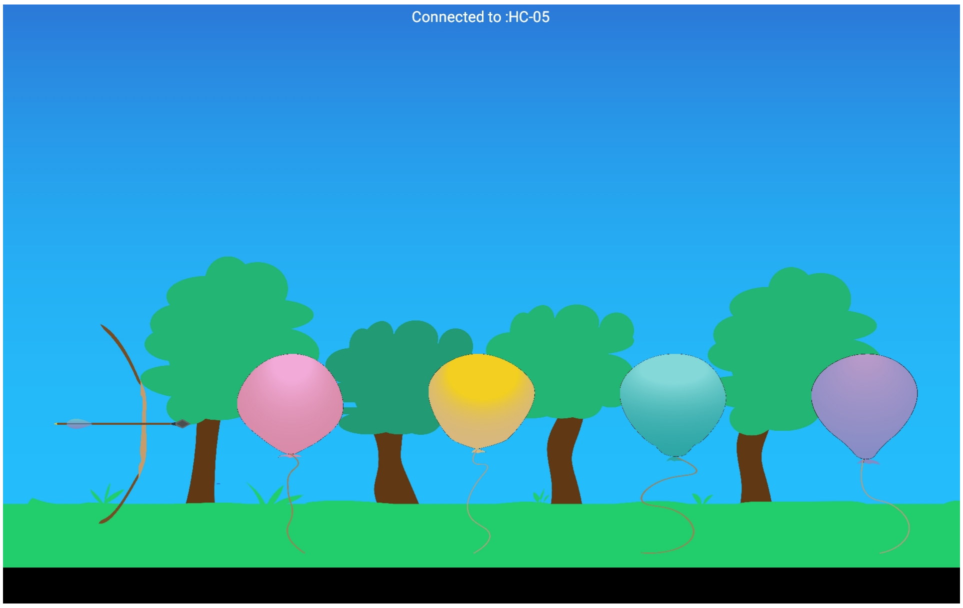

Figure 5.7: Screenshot of the application when all of the sensors are touched

floating in the line to get shot by the arrow as they are in the overarching application.

Another aspect about the feedback system that should be changed for the high fidelity prototype, is the metaphor itself. With the user tests in the specialization part and the existing metaphors of the overarching application, it became clear that the metaphor with the balloons was most favorable. However, during the user test, the children did have some comments on how they wanted to change the metaphor. All the children stated that they would like for the balloons to be in different shapes. For the high fidelity prototype, the visualisations of the overarching project are used to keep some consistency between the two applications. In Figure 5.8 however, a visualization of the prototype where the feedback of the children is taken into account can be seen.

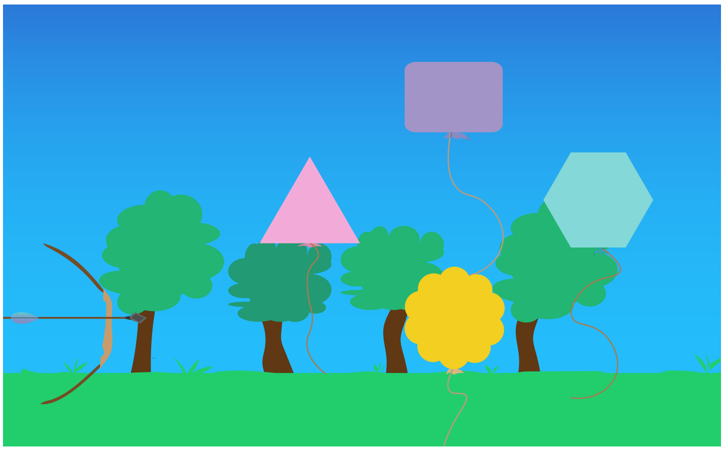

Figure 5.8: Application with the adaptations form the children

Chapter 6

Evaluation

Now that the high fidelity prototype is finished, evaluation can be done to see what users and experts think of the product. This evaluation might lead to small last minute changes to the project and are intended to help answer the research question in a more conclusive way. The user evaluation is again done at the BSO de Vlinder and the expert evaluation of the hifi prototype comes from Matienne van der Kamp.

During the lofi, user testing, it seemed that the children were very influenced by each other which raised the question if the received data was actually useful. However, it is important that the children feel comfortable. Therefore, for this project, it is considered that testing with one child at a time is not an option. To still make the data as reliable as possible, other factors that may influence the opinions of the children should be minimized. This is done by using the paper of Read et al. [22]

6.1 Expert evaluation

For the expert evaluation, Matienne van de Kamp was contacted. A meeting was set up where the hifi prototype was explained. After the sensor system, the code and the feedback system was explained, and Matienne van der Kamp confirmed that he fully understood the system, a semi structured interview was held. The precise questions and answers of this interview can be seen in Appendix B.2. However, since the interview was held in Dutch, the questions and answers have been translated from Dutch to English.

Overall, Matienne thought that it was a nice idea to detect the presence of the lips around the tube. However, he did wonder if the system would actually be able to detect all the different and strange ways a child could put the tube in their mouth. Besides that, he also wondered if the lips are indeed present around the tube, is it then absolutely certain that no airflow is escaping. Matienne did think that after explaining the metaphor, the child would be perfectly capable of understanding the feedback.

Furthermore, the duration that such a product should be used was discussed. On this topic, Matienne said that it would actually be best to always use this system. This is because you can never know if the child would always do the test right. The child might be very capable of doing the test, however, when he or she is distracted, a lot of thing could still go wrong.

Lastly, the different ideas for the tubes were discussed. Matienne thought that both ideas could be feasible, but seemed most enthusiastic about the idea of a new kind of tube.

After the semi-structured interview, Matienne wanted to show the prototype to his colleague who was also quite enthusiastic about the idea. Together they discussed if the tube had enough sensors to fully detect if the lips are properly placed around the tube. During this discussion the idea began that even more capacitive senors could be placed around the tube to measure more precisely. Furthermore, they talked about the issue of breathing fully out before putting the tube in the child's mouth. As stated before, in the prototype the balloons immediately stand in a line when all the sensors are touched so that little time would be wasted and the child would not run out of air. However, during the meeting, it became clear that it would actually be better if the child would start breathing in and out before the actual test with the tube already in the mouth. This was something the overarching project might want to integrate into the application. If this is happening, this would actually be very good for the detection of the lips since the child will have more time to put the lips properly around the tube.

6.2 User testing

After the interview with Matienne van der Kamp, another user testing was done at BSO de Vlinder. During this user test, the hifi prototype from figure 6.1 was tested. However, to ensure safety a wooden box was built around the Arduino, breadboard and other components. Besides that, all the electrical components that could not be fitted into the wooden box are lined with isolation tape in order to prevent the children from getting electrical shocks.

The goal of this user test was supposed to be ensuring that the children were motivated to perform the spirometry test without any air flow leakage. However, this is rather hard to test. Therefore, it was instead tested if the hifi prototype behaved the way it should. This is done by giving the children different ways to put their lips around the tube of the spirometer and see what kind of feedback the processing application gives.

During the test, the children are given multiple cards with exercises on them. The cards designed can be seen in Figure 6.2. However, since the paper of Janet Read [22] suggested that letting a teacher proofread the text to see if a child would understand it, this was done with a student from the Fontys PABO - Eindhoven. This student stated that the children would

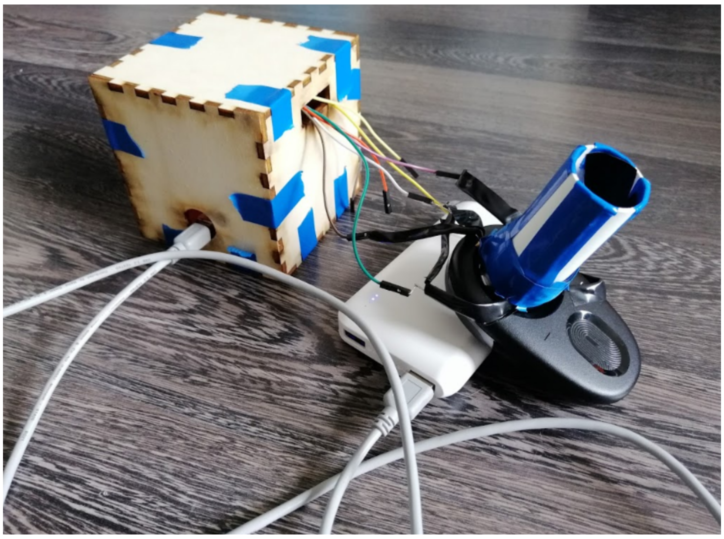

Figure 6.1: Hifi prototype where electrical components are covered up

probably be able to read the text but not fully understand the exercise. Therefore, before starting the exercise, I will read every card out loud, show the child how to perform the exercise and ask the child if they understand it for completion. The child is allowed to pick the order in which he or she will perform the exercises. After doing the first exercise, the child should put the card face down on the table and continue to the next exercise. When finished with this exercise, the child should again put the card face down next to the first card and so on until are exercises are done and the cards are lying in order on the table. Meanwhile, I, the examiner do not get to see in which order the child is performing the exercises. However, I do look at the application which is giving feedback on the exercises and note this feedback down. When the child is done with all the exercises and it is confirmed that the order in which the cards are lying on the table is in fact the order in which the child performed the exercises, the noted data gets compared with the order of the cards. This shows how well the feedback system detects an air flow leakage.

The cards, shown in Figure 6.2, show different ways in which the child has to put the tube in their mouth. Since the user test is performed with Dutch children, these cards are also in Dutch. On the tube, an image is made which should visualise the tube and how the to take the tube into the mouth. The cards have different letters which stand for different ways to put the tube in the mouth. The 'T' stands for putting just the teeth on the tube, the 'L' stands for putting just the lips on the tube and the 'X' stands for putting both the lips and teeth on the tube. The different, most logical ways to put the tube in one's mouth are:

Figure 6.2: Cards made for hifi user testing

- Closing the lips and teeth completely around the tube.
- Closing the lips an teeth completely around the tube except on the left side.
- Closing the lips an teeth completely around the tube except on the right side.
- Putting the lips and teeth only on the upper and lower sensor.
- Closing just the lips completely around the tube.
- Putting just the lips on the upper and lower sensor.
- Putting just the lips on the left and right sensor.
- Putting just the teeth on the upper and lower sensor.

These different ways are the most obvious mistakes the child can make when putting the tube in their mouth, together with two cards that tell the child to perform the test properly. To be sure these exercises are indeed the most obvious mistakes a child can make, this list has been verified with Matienne van der Kamp. The card where the child only puts the lips on the left and right side is a rather unnatural way to hold the lips. However, Matienne van der Kamp suggested to test it nevertheless since there are children who pout their lips in such a way that this could happen. Furthermore, Matienne did say that children can have very strange ways of putting the tube in their mouth and therefore, this test cannot test all the possible ways that the airflow leakage may occur. However, it is a nice starting position to see if the system works. In order to actually get the child to perform the test properly, this is explained at the beginning of the test how to do this.

Besides testing if the device works by letting the children perform the exercises on the cards, Matienne van der Kamp suggested testing if the difference between putting just the teeth and putting the teeth and lips on the tube could be sensed. To test this, the children are asked to, after doing the exercises, first put just their teeth on the tube and then their teeth and lips on the tube. The data of will be recorded and looked at after the user testing.

The reason that this test differs a lot from the lofi test is because during the lofi test, it became clear that the children at BSO de Vlinder very often participated in the user tests of the overarching project which made them rather good at performing a spirometry test properly. Therefore, simply letting the child use the tube and looking at if the performance became better through the application would have probably led to very little results since the children would already perform the test properly. Therefore, this different type of test was designed.

Every user test is designed in a certain way. For example, a test can be between-subject or within-subject. Because every child that participates in the user testing, this test has a within-subject design. This kind of design usually comes with a learning effect because the user will get used to how the tests work. However, during this particular experiment, there is most likely no learning effect since the children already know how to perform the user test. Furthermore, every test has dependent and independent variables. Independent variables are changed by my, the examiner. Dependent variables are the variables that are measured during the test. The independent variables, are to be fair, not changed by the examiner in this case, but by the participant. This is because the independent variable of this test is the order in which the exercises are performed. The dependent variables are the way the application is giving feedback on the performed exercises. This namely, tells how well the application works.

The protocol of the hifi user testing can be seen in Appendix D.2.

6.3 Results

The hifi user test was done with six children. The first four children ranged form the age eight to then. The last two children were six and seven. During the test, it became clear that the method of the test was to difficult to understand for the two younger children. This resulted in them repeatedly asking what they had to do and what the certain exercises meant. Due to this, it was not possible to keep the order in which the exercises were performed hidden from me, the examiner. Besides, it was very clear that even when the two younger children were told what to do at the exercise, they were simply not doing it properly. This lead some false data. Therefore, the results of the exercises of the last two children were not taking into account. However, their answers on the further questions are discussed in this section.

Table 8 shows the data of the four children of which the data was in fact usable. The first column describes the exercise they were asked to do, the second column describes in what way the exercises were performed and the last column states the remarks if any were made. As can be derived from Table 8 already, the system does not seem to work 100 percent all the time. There could be multiple reasons for this. The first and most important explanation is that the sensors themselves are not working properly. This might mean that they are not sensitive enough, or maybe the data is not being sent fast enough. Another reason for false data might be that the exercises were to hard for the children or they did not understand properly how to do it. The children were beforehand explained how to perform every exercise, however, they may have forgotten how to do something.

To get an idea of how the children felt about the exercises, they were asked what they thought about each exercise. This resulted in that some exercises were perceived hard to do. How many children found an exercise hard, can be seen in Table 8. Furthermore, when looking at the exercise where the left sensor should not be touched, the application displayed that actually the left sensor was touched but the right sensor was not. It could be argued here that the children mixed up their lefts and rights. In Figure 6.3, a chat of how many times the application displayed an exercise correctly can be seen. In comparison, Figure 6.4, shows the same data but with the data of children who found the exercise hard to do and had it wrong and the possible mix up of left and right removed.

Table 8: Results of hifi user testing		
exercise	**performed**	**remarks**
Closing lips and teeth completely around the tube	5 times correctly 2 times missing left 1 time missing right	none
Closing lips and teeth completely around the tube except on the left side	2 times correctly 1 times missing right 1 time left is added	2 children found it hard
Closing lips and teeth completely around the tube except on the right side	1 time correctly 2 times left is missing 1 time left is missing	1 child found it hard child might have mixed up left and right
Lips and teeth are put on the upper and lower sensor	2 times correctly 1 time everything is touched 1 time down is missing	none
Closing just the lips completely around the tube	1 time correctly 1 time left is missing 1 time right is missing 1 time up and down are missing	2 children found it hard
Putting just the lips on the upper and lower sensor	4 times correctly	none
Putting just the lips on the left and right sensor	1 time correctly 1 time all sensors were touched 1 time only the upper sensor was touched 1 time all sensors were touched except the right sensor	3 children found it hard
Putting just the teeth on the upper and lower sensor	3 times correctly 1 time just the lower sensor was touched	none

Figure 6.3: Chart with full data set

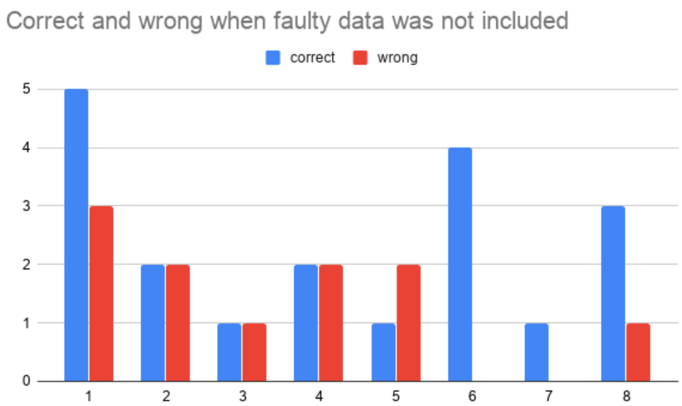

Figure 6.4: Chart with part of data set

In Figures 6.3 and 6.4, the different exercises are displayed by numbers one to 8. The exercises with their corresponding numbers can be seen in the list below.

- 1 = Closing the lips and teeth completely around the tube.
- 2 = Closing the lips and theeth completely around the tube except on the left side.
- 3 = Closing the lips and teeth completely around the tube except on the right side.
- 4 = Lips and teeth are put on the upper and lower sensor.
- 5 = Closing just the lips completely around the tube.

- 6 = Putting just the lips on the upper and lower sensor.
- 7 = Putting just the lips on the left and right sensor.
- 8 = Putting just the teeth on the upper and lower sensor

As can be seen when comparing Figures 6.3 and 6.4, the second chart is more positive about how well the device works. However, while all the comments of the children were taken into account, the device still does not register all the mistakes properly. As said before, it is quite hard to say if the device is just not working properly, or if the children made some mistakes when doing the exercises. Therefore, to really get a good view of how well the device works, there might be need for another user test where the data is more in depth discussed with the participants to really get a good overview of what is going on when the device is not registering something properly.

Furthermore, Matienne van der Kamp asked if the difference between putting just the teeth or the lips and the teeth could be sensed. As stated before, this was supposed to be tested with every child after doing the exercises. However, with almost all children there were technical difficulties. For the first 2 children there was no proper connection between the device and the computer and so no data was coming through on the laptop while it was actually working on the application. In between the first and second group, the code was uploaded again on the tablet, which improved the data stream from the device to the computer. However, for the third child, the data was still lagging a lot and was therefore not reliable. However, when it was the turn of the fourth child, the data stream was not lagging anymore and some proper data was received. Unfortunately, the connection between the device and the computer was not working at the last two children anymore so there was no data received there. The one data set that was correct can be seen in Table 9.

Table 9: Difference between using just the teeth and using the lips and teeth

Teeth only upper sensor	**Teeth only lower sensor**	**Lips and teeth upper sensor**	**Lips and teeth lower sensor**
2631	3773	4666	5827
2165	3647	4713	5817

The data of Table 9 is unfortunately quite incomplete. However, this data does show, that the difference in putting just the teeth on a sensors and putting the lips and teeth on the sensor can be detected. If this data is indeed valid, this would be a nice addition to the application since the app could then give even more detailed feedback on which mistakes are made.

In Table 10, the data from the questions during the hifi user test can be seen. This data shows that, in comparison to the other user test, less children did a spirometry test before and also less children have a proper understanding of how the system works. This could thus mean that understanding spirometry, might play a role into how well the child understands the metaphor.

Table 10: Data from the questions during hifi testing

Question	**Yes**	**No**	**Partly**
The child previously performed in one of the spirometry tests	33.3%	67.7%	0%
The child understand how and why the image is changing	49.9%	33.3%	16.7%

As the last part of the test, the children got to mention what they wanted to change about the application this can be seen in the list below.

- Make more of a game out of it where you can earn coins.
- Add a sun.
- Add flowers.

Chapter 7

Discussion

As in most projects, there are a quite some points of discussion in this project. These points are discussed in this section. For these projects, the points of discussing are the following.

- The idea behind the sensor
- The logic behind the metaphor
- The fact that the tube is fixed to the device
- The setup of the tests
- The data

7.1 The sensor

The first point of discussion is the sensor. During the state of the art, a sensor analysis was done. During this analysis, multiple possible sensors were found. The capacitive sensors is chosen as a solution. However, some of the other sensors might have been better.

The reason that there might be a sensor that is more appropriate for this problem, is due to the reason that with capacitive sensing, it is not measured if there is any airflow leakage. Matienne van der Kamp also stated this during his expert evaluation. With the current system, you can measure if the lips are around the tube. However, with the knowledge available right now, it is not know if that gives any certainty on if there is airflow leakage or not. This is something that should be measured.

7.2 The metaphor

Furthermore, the used metaphor is up for discussion. During the lofi user testing, two metaphors were tested. These were the flower and the balloon metaphor. These metaphors were chosen because they seemed to have the most logical connection between the metaphor and the maneuver of putting the lips around the tube.

During the first user tests, the results did show that the children had a rather good understanding of the system and seemed to find the connection with the metaphors quite logical since almost all of the children understood how the images would change if the position of the lips would change. However, during the hifi user testing, the children seemed to have less of an understanding on how the image would change and what the connection between the image and the putting the lips around the tube was. This difference between the results might have been due to the fact that during the first test, more children had done spirometry tests before than in the second test. The children in the first test could have had better understanding on how spirometry tests work and therefore, it might have been easier for them to make a connection between the metaphor and the maneuver.

The connection between the metaphor and the act of putting the lips around the tube can thus be questioned and there might be a metaphor that is more appropriate for this exercise. Another reason for this is that the two metaphors that were tested in the lofi prototype were chosen because of the connection that I, the designer, saw in these metaphors. Did does not mean that the children see the same connection as well. In chapter 2, Stålberg et al. [2] was quoted with how it is important to involve children in the design process as much as possible and that was not done in the process of choosing the metaphors for the lofi prototype.

7.3 The tube

The next point of discussion is the tube. As stated before, the ability of the Nuvoair to remove and replace the tube, is important because of hygienic reasons. However, as the hifi prototype is right now, the tube cannot be removed from the device anymore. This is due to the fact that the sensors on the tube are fully connected to the rest of the system and the tube can thus not be easily replaced. This should be changed in a way that the tube can be easily replaced with a new tube.

7.4 The user tests

The last point of discussion is the user testing. This section is divided in a discussion of the lofi test and the hifi test.

7.4.1 Lofi user testing

During the lofi user testing there were some points that might not have been optimal. Therefore, it can be questioned if the data of the lofi user test is reliable.

First of all, the tests were done in groups of two children at a time. On the one hand, it was good that this was done so that children would not feel to uncomfortable. However, in the way that the test was performed, the children were clearly influencing each others opinions. Furthermore, because the children had to perform the tests after each other, the second child could already listen to the answers of the first child and might therefore have had a better understanding of the tests and the metaphors than it would have had if they did not have this information beforehand.

Furthermore, during the test, there was probably a learning effect. This was because the test actually consisted of two tests which were performed within subject. This means that all children had to test both metaphors. Doing this, the children could have taken their knowledge from testing the first metaphor into the testing of the second metaphor. This was also visible in the results as the balloon metaphor was better understood than the flower metaphor and the balloon metaphor was tested in secondly during all the tests.

7.4.2 Hifi user testing

The hifi user testing was designed in a different way than the lofi user testing. However, the hifi user testing also had points that could have been done differently.

First of all, this test again was done in groups of two to make the children feel at ease. However, due to the design of this test, the children could not influence each others opinions too much since the children did not have to give a lot of opinions. However, during the questions about if they understood how the image was changing, and what they wanted to change about the image, the children could still have influenced each other.

Furthermore, there is the way the test is set up. During the test, the children were given exercises which were designed to see if the application worked. This design was made because most of the children at BSO de Vlinder already performed in previous spirometry tests. Therefore, testing if the device motivated the children to perform the test better was not an option. That is why it was chosen to test the device itself instead. However, after the hifi user test, it became clear that the device registered the exercises differently multiple times. After the test, it was very hard to determine if this wrong registered exercise was due to the device not working properly or if the child was not doing the exercise correctly. Therefore, the test was actually not designed well enough to determine if the device is working properly.

Lastly, the length of the wires of the hifi prototype might have influenced the test results. As can be seen in Figure 6.1, the wires are quite short. Due to this, it might have been hard for the children to do the exercises properly and this may have influenced the results of the hifi user test. However, none of the children mentioned this during the hifi test.

7.5 The data

Lastly, it can be questioned if the sensor system influences the test in any way. Especially for the lofi prototype, the flow of the exhaled air might have been altered due to the sensors that were inside the tube. For the hifi prototype, the sensors and wires were placed on the outside of the tube which might interfere less with the flow. However, it is not know for certain if the system does not influence the data.

Chapter 8

Future work

From the discussion, points can be taken into account when doing future work on this project. In the coming sections, recommendations are made that can be used in the future to improve the device.

8.1 The sensor

As stated in the discussion, the capacitive sensors might not be the best way to prevent air flow leakage as, right now, it is not known if touching all the sensors really does prevent air flow leakage. In the future, is should be first be tested if touching all the capacitive sensors really does prevent airflow leakage. If this is not the case, two things can be done.

The first option is to see if adding more capacitive sensors could better aid in the prevention of airflow leakage. This was a suggestion made by Matienne van der Kamp during the expert evaluation. He stated that he was not sure if four sensors would be enough since children can put the sensors in their mouth in all kind of weird ways. Adding more capacitive sensors, might help detecting these strange and unexpected ways as well.

The second option is to again go through the options that came out of the sensor analysis. These sensors all seemed somewhat possible to solve this problem. Continuing research on these sensors might result in another solution to the airflow leakage problem.

8.2 The metaphor

To get a good conclusion about the logic behind the metaphor, multiple metaphor should be tested. Since during the lofi prototype only two metaphors were tested which were chosen because of the logic seen by me, the designer, this does not give a good conclusion. Therefore, it is recommended to test with more metaphors and involve the children even more into the design process.

To do this a brainstorm session could be organized where together with the children, a logic connection between the metaphors of the overarching project and maneuver of putting the lips on the tube can be found. This will hopefully give a metaphor that is more logical to the children.

8.3 The tube

As stated in the discussion, the tube sensors on the tube of the spirometer have to be designed in such a way that the tube can still be replaced. In Chapter 5, two possible ways to do this were already discussed. These options can be seen in Figure 5.5. The recommendations for future work are thus to try and develop both of these options to see which of the two options works for this problem.

8.4 The user tests

To get a proper conclusion on both the lofi and the hifi user testing, multiple adaptions should be made. First of all, further testing should be done with more participants in the future to get a more complete test group. Besides, both tests would also improve if in the future, they are done with children who have never done spirometry tests before since this would rule out making connections between the metaphor and the maneuver by using previous knowledge.

8.4.1 Lofi user testing

If the specific user testing would repeated in the future, for example to get a better conclusion, certain aspects need to be changed. First of all, the learning effect should be removed from the test. This can be done by letting all children just test one of the metaphors. However, to ask the children which metaphor they find most suitable, the children have to test multiple metaphors. To solve this problem, participants could test the metaphors in different orders, which might help rule out the learning effect.

Furthermore, when repeating this test in the future, the children should not be able to influence each other anymore. However, the children should still participate in the test in groups of two to make sure they feel comfortable.

8.4.2 Hifi user testing

If the hifi user testing would be repeated in the future, a different type of test should be designed. A future test should rule out any possibility of the children doing the test wrong. A good way to do this, is by only having participants who have never done spirometry tests before, so they do not know how to put the tube in their mouth and there is a big chance that they will do it wrong. During this test, a medical professional should oversee the spirometry test and write down what the child is doing wrong. This can then be compared to the feedback of the application. If this is correct, it could be concluded that the application is indeed working properly. This way, the way the child performs is not an important factor in testing the application.

8.5 The data

To make sure that the system does not influence or alter the data in any way, tests should be performed. A way to test this could be to let the user use both the tube with the system and without the system. The user should then do multiple spirometery tests with both devices and this data can be compared. If there is a large difference in the data, another design should be considered where the system does not influence the flow of exhaled air since it is very important to keep receiving proper data.

Chapter 9

Conclusion

In this chapter, it is discussed if the research question, *"How to optimize the use of spirometry for asthma, by limiting the air leak flow, in a way that is understandable for children?"*, is answered with this project. This done by dividing the research question in a part about limiting the air leak flow, and a part about if the system is understandable for children.

9.1 Limiting the air leak flow

As stated before, it is quite hard to determine if the system is really preventing airflow leakage. The system will probably limit the air leak flow since it does encourage the user to put the lips properly around the tube. However, to know if putting the lips around the tube prevents all air leak flow, tests should be performed on this. Furthermore, the hifi user test did not point out if the system itself worked properly since it was not clear if the received data was wrong due to the system that might not have been working or due to the participants not performing the exercises properly.

In the end, I feel that the capacitive sensing can be a good first step into preventing airflow leakage. However, more testing has to be done to know for sure if this method is really working.

9.2 Understandability for children

For making the system understandable for children. Metaphors were used to aid in the understandability. The user tests did point out that the children understood the metaphors used. However, as stated in Chapters 7 and 8, different metaphors could be tested to optimize the understandability for the children. Nevertheless, I do feel that using a metaphor and elaborating on the metaphor of the overarching project is a very good way to go since this keeps a nice consistency in between the system and the overarching project which will be understandable for children.

To conclude this project, the answer on the research is the following. A possible way to prevent air flow leakage is capacitive sening. However, to make sure that this way works properly, more testing is needed. Furthermore, a nice way to make this system understandable is by elaboration a metaphor of the overarching project.

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Appendices

Appendix A

Design process

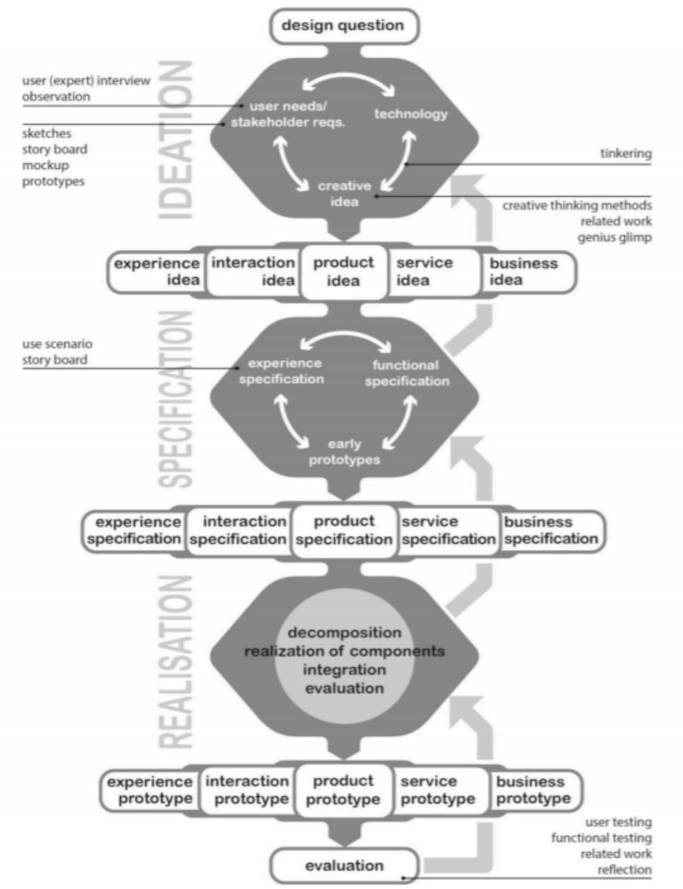

Figure A.1: Design process of Creative Technology [3]

Appendix B

Interviews with Matienne van der Kamp

B.1 Questions and answers of the first interview

- What happens when someone suffers from asthma?
  - *People who have asthma have narrowed airways which makes it harder for the air to flow through the airways.*
- What is measured at a spirometry test and why is this important to know?
  - *During a spirometry test, the amount of air that is exhaled will turn some kind of wheel. An infrared sensor measures how often this wheel is going round. With this measurement, the amount of air exhaled can be calculated. This is than expressed in the* FEV_1 *(the Forced respiratory volume in the first second) and the* FVC *(Forced vital capacity). The first value is the amount of air that is exhaled within 1 second. The second value is the complete amount of air that is exhaled during the test which should be the same as the total lung capacity. Both values are expressed in litres. The ratio of these two values (*FEV_1/FVC*) shows how much of the complete lung capacity is exhaled in 1 second. This value can help determine how badly the airways are narrowed.*
- How often do children have to do a home spirometry test?
  - *Usually once per week*
- How does the error of airflow leakage happen?
  - *This error can happen in two ways. Either the user is not wearing the nose clip, or the user does not seal the lips properly around the*

tube. The tube should be put in the mouth by putting the teeth on it and closing the lips entrilery around the tube. Young children often have little harm of the nose clip since they don't have the reflex to breath through the nose and lips at the same time.

- Are there already some solutions to solve the error of airflow leakage?
  - *Not to my knowledge*
- What do you think about detecting the error with an airflow sensor?
  - *Measuring airflow might be a problem since children often don't sit still. Therefore, it could happen that surrounding air is measured instead of breath and so there might not be an airflow leakage.*
- What do you think about detecting the error with pressure sensors?
  - *Putting sensors on the tube itself might be a problem since the tube often has to be replaced due to hygiene.*
- Are there any problems with explaining a child why there is an error?
  - *Most children have little problem with the explanation of the error and doing it right after being told how to do the test. According to research, children should be able to do a spirometry test successful from 6 years old. However, we noticed that with proper instruction, thus is usually possible from an earlier age. This often causes the children to still perform the test properly when they are older.*

B.2 Questions of the second interview

- What are your first thoughts about the prototype?
  - *This is a very nice way to detect if the lips are around the tube. However, I am wondering if you can actually detect all the strange ways a child can put the tube into their mouth. Besides, you still do not know if any flow is escaping, but we could measure that. Why did you chose for four resistors? I am doubting if that would be enough since everywhere around the tube could be a leak.*
- Do you think the children are able to work with the feedback?
  - *I think they will understand the feedback. However, I do think you will have to properly explain to the children once how the*

metaphor works. Besides, it is very important that if the upper sensor is touched, the upper balloon appears. Otherwise, the metaphor would make little sense.

- For what period of time do you think the children will need the air flow leakage detection system?
  - *This is very different per child. I do think that in most cases they will do the test properly right away when they are explained how to do it. However, I would aim for always using this smart tube because you can never be certain that they are doing the test right. Having a flowleak is registered by the device as a lungfuction that is less good and if that is not the case, you do not want to act on that. Therefore, I would always use the device just to be sure. Besides, you cannot say that once someone has done the test properly three times, it will do it correctly all the time. A child's focus can always be bad and so an error can always exist.*
- How would you feel about a third type of tube especially for children who have trouble with putting the lips properly around the tube?
  - *Yes, I think it is a nice Idea and it should be feasible.*

Appendix C

Screenshots of application overarching project

Figure C.1: Start screen of the overarching application

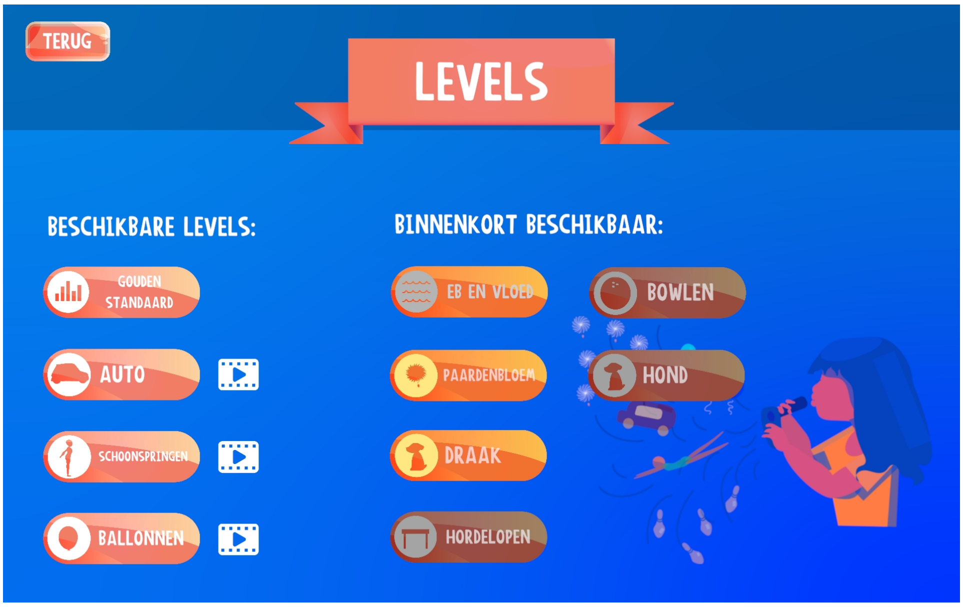

Figure C.2: Screen where the user can pick the metaphor in the overarching application

Figure C.3: Explanation screen of the overarching project

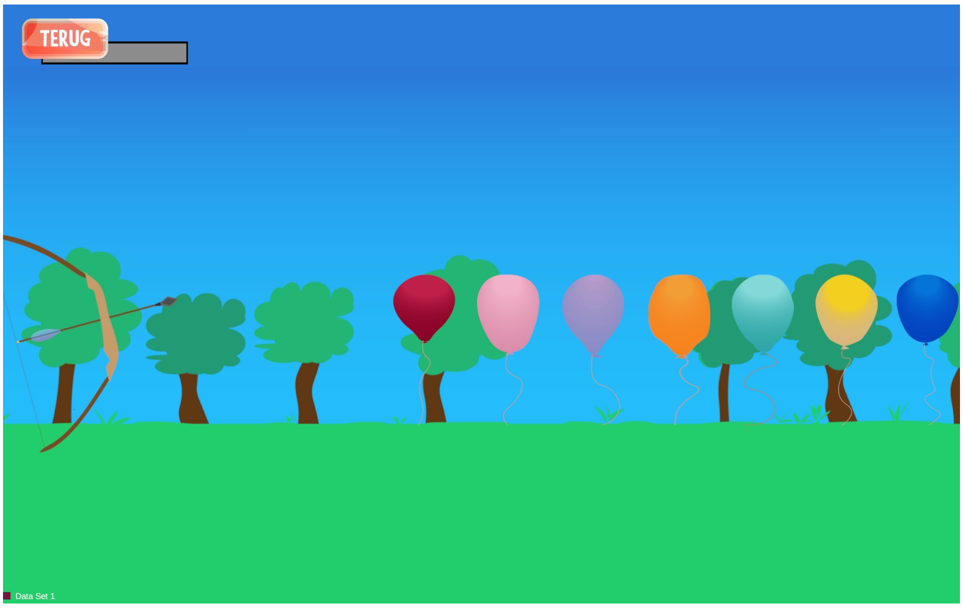

Figure C.4: Screen of the balloon metaphor of the overarching application

Appendix D

User testing protocol's

D.1 lofi testing

- Beginning of the test
  - I introduce myself to the children who are participating in groups of two and let them introduce themselves to make them feel at ease.
    - Would you like to help me with this test? It is important that you know you cannot do anything wrong. I am just here to test this tube en to see what you think about it. So I am not testing you.
  - I explain what is going to happen during the test and ask if they ever performed in any of the previous spirometry tests.
    - I would like to test this device with you.
    - Did you ever perform in test before?
    - Okay, what we are going to do is the following:
      - You have to put this tube in your mouth, and via the laptop I can see how your lips are around the tube.
      - While you do that, I will show you images of a flower and balloons on this fake tablet.
      - The way the image looks, depends on how you are putting your lips around the tube.
      - In what way do you think the image of the flower will change?
      - In what way do you think the image of the balloons will change?
      - Do you understand what you have to do?
- During the test (one time with the flower and one time with the balloons)

- The child takes the tube into their mouth.
- The amount of capacitive sensors that are touched determines which image I show the child.

- When the child performs the test correctly immediately.
  - Show the complete image
    * Ask the child what they see and what they think of the image. In other words does the child feel that they did the test correctly.
  - Ask the child to perform the test incorrectly.
    * Ask what changed about the image.
    * Aks what they think of the image . they feel that something is wrong? Do they feel that the image is complete?

- When the child puts the tube incorrectly in their mouth.
  - Show one of the incomplete images.
    * Aks wat they think about this image. Is the image complete?
    * If the child does not think the image is compleet ask what is missing.
    * Ask how they think they can get the image complete.
  - Try to motivate the child to put the tube correctly in their mouth.
    * Ask what changed about the image and what they think about it now.

- End of the test
  - Ask the child if they understand how to get from one image to the other.
  - Ask what image they enjoyed the most to do the test with.
  - Ask which of the two images they thought was most appropriate for the exercise.
  - Ask if there is anything they would change about the images.
  - Thank the children for helping

D.2 hifi

- Beginning of the test
  - I introduce myself to the children who are participating in groups of two and let them introduce themselves to make them feel at ease.

    * Would you like to help me with this test? It is important that you know you cannot do anything wrong. I am just here to test this tube en to see what you think about it. So I am not testing you.
  - I explain what we are going to do during the test and ask if the children have previously performed in one of the spirometery tests.
    * I would like to test this device with you.
    * Did you ever perform in test before?
    * Okay, what we are going to do is the following:
      · I will give you 9 cards with exercises on them. These excersices have to be performed with with this device. If you have completed one of the exercises, you have to put the card face to before you. You have to do this with all of the cards. This means that you put the cards in order that you perform the exercises in.
      · In the meantime, I explain every card to the children.
      · While you do the exercises, I will look at the app and try to guess which exercise you are doing. voeren bent.
      · How the image on the app looks depends on what exercise you are doing.
      · When you are done with the exercises, you can turn the cards around and show me in what order you have done the exercises.
      · Do you understand what you have to do?

- During the test
  - Every child gets a piece of plastic foil around the tube because of hygiene reasons.
  - The child gets the cards and is performs these in a certain order with the tube.
  - I look at the tablet to see de feedback of the app and write this down.
  - At the end of all the exercises, the child turns around the cards.
  - I ask the child if they indeed performed the exercises in this order.
  - I make a picture of the order of the cards and compare this after the test with my notes.

- End of the test

- Ask the children to put the tube two more times in their mouth. One time with only the teeth around the tube and one time with the teeth and the lips around. In the meantime, I will copy this data and look at it later.
- Ask the child if there were any exercises they found hard to do.
- Ask the child if they understand how to get from one image to the other.
- Ask if there is anything they would change about the images.
- Thank the children for helping

Appendix E

Results of the user testing

E.1 Results of the lofi user testing

4 kinderen in totaal deden de test in tweetallen

- Boy 8, clearly knew what had to happen and had a clear opinion about everything.
  - Have you ever performed in one of the tests before?
    - Yes, very often with the tests of the university and also quite often with spirometer tests.
  - How do you think the image of the flower is going to change?
    - The lines will be colored in.
  - How do you think the image of the balloon is going to change?
    - The lines will also be colored in.
  - Flower was done correctly right away, what do you think of the image, is it correct like this?
    - After putting down the leaves neatly, the child said the image was correct.
  - Now, the flower is used incorrectly on purpose.
    - What do you think will change?
      - The flower will get smaller
    - What changed?
      - A part of the leaves disappeared.
    - How can you get to the correct image?
      - By putting the tube properly in the mouth, the child shows how.
  - The image of the balloons was done correctly right away.

        - What do you think of the image is it complete like this?
            - Yes the image is correct.
    - Now, the balloons are used incorrectly on purpose.
        - What do you think of the image?
            - Something is missing.
        - Try to get the image right again.
            - Puts the tube correctly in the mouth.
    - End of the test.
        - Do you understand how to get from one image to another?
            - Yes, if a piece of your mouth is not on the tube, a piece of the image is missing.
        - What image did you like the most?
            - The flower
        - Which of the two images do you think suited the exercise the best?
            - Both
        - Is there anything you would want to change about the images?
            - The flower could be in the shape of a diamond.
            - The image of the balloons should have more balloons.

- Boy 7, very shy and was probably influenced by the opinions of the other child.
    - Have you ever performed in one of the tests before?
        - A few times with some tests but never with spirometry tests.
    - How do you think the image of the flower is going to change?
        - The leaves are missing and those will appear.
    - How do you think the image of the balloon is going to change?
        - The balloons are missing and those will appear.
    - Flower was done correctly right away, what do you think of the image, is it correct like this?
        - Yes.
    - Now, the flower is used incorrectly on purpose.
        - What do you think will change?
            - I don't know
        - What changed?
            - A part of the leaves disappeared.

    * How can you get to the correct image?
        - By putting the tube properly in the mouth, the child shows how.
- The image of the balloons was done correctly right away.
    * What do you think of the image is it complete like this?
        - Yes, the image is complete.
- Now, the balloons are used incorrectly on purpose.
    * What do you think of the image?
        - Some of the balloons are missing.
    * Try to get to the right image again.
        - Puts the tube correctly in the mouth.
- End of the test.
    * Do you understand how to get from one image to another?
        - Yes.
    * What image did you like the most?
        - The flower.
    * Which of the two images do you think suited the exercise the best?
        - Both.
    * Is there anything you would want to change about the images?
        - The flower could have another color.
        - The image of the balloons should have more balloons.

- Girl 7
    - Have you ever performed in one of the tests before?
        * Yes with multiple tests and also with spirometer tests.
    - How do you think the image of the flower is going to change?
        * The flower does not have nice flowers and that is going to change.
    - How do you think the image of the balloon is going to change?
        * The same way the flower will change.
    - Flower was done correctly right away, what do you think of the image, is it correct like this?
        * The flower looks nicer now because it has leaves.
    - Now, the flower is used incorrectly on purpose.
        * What do you think will change?

        - The flower will get less pretty.
      - What changed?
        - A part of the leaves disappeared.
      - How can you get to the correct image?
        - By putting the tube properly in the mouth, the child shows how.
  - The image of the balloons was done correctly right away.
      - What do you think of teh image is it complete like this?
        - Yes, the image is correct.
  - Now, the balloons are used incorrectly on purpose.
      - What do you think of the image?
        - Some of the balloons are missing
      - Try to get the image right again.
        - Puts the tube correctly in the mouth.
  - End of the test.
      - Do you understand how to get from one image to another?
        - Yes.
      - What image did you like the most?
        - The flower.
      - Which of the two images do you think suited the exercise the best?
        - The balloons, because you also have to put your lips around a balloon when you inflate it.
      - Is there anything you would want to change about the images?
        - The flower needs a stem and a bee.
        - The balloons should be in different shapes.

- Girl 7, did not like it that see had to do the test after the first girl because she already knew what was going to happen.
  - Have you ever performed in one of the tests before?
      - Yes with multiple tests and also spiromtery tests.
  - How do you think the image of the flower is going to change?
      - The lines will be filled in.
  - How do you think the image of the balloon is going to change?
      - The balloons are missing and those will appear.
  - Flower was done correctly right away, what do you think of the image, is it correct like this?

    * Yes the image is correct.
  - Now, the flower is used incorrectly on purpose.
    * What do you think will change?
      · A part of the leaves will disappear.
    * What changed?
      · A part of the leaves disappeared.
    * How can you get to the correct image?
      · By putting the tube properly in the mouth, the child shows how.
  - The image of the balloons was done correctly right away.
    * What do you think of the image is it complete like this?
      · Yes, the image is compleet.
  - Now, the balloons are used incorrectly on purpose.
    * What do you think of the image?
      · Some of the balloons are missing.
    * Try to get the image right again.
      · Puts the tube correctly in the mouth.
  - End of the test.
    * Do you understand how to get from one image to another?
      · Yes.
    * What image did you like the most?
      · The balloons.
    * Which of the two images do you think suited the exercise the best?
      · The balloons.
    * Is there anything you would want to change about the images?
      · The flower needs more animals and colors in the background.
      · The balloons need ropes and should be in different shapes.

E.2 Results of the hifi user testing

- Child 1, 8 years old
  - Have you ever performed in a spirometry test before?
    * No

Table 11: Data of the child doing the exercises			
	Feedback of app	**Exercise**	**Notes**
1	Upper and Under	Lips upper and under	
2	All sensors touched	All sensors touched	
3	Upper and under	Upper and under	
4	Upper and under	Upper, under and left	
5	Upper, under and left	All touched just lips	
6	All sensors touched	All sensors touched	
7	Left and right	Left and right just lips	Hard to do
8	Under	Teeth upper and under	
9	Upper, right and Under	Upper right and under	

- Can you explain how the image changed if you changed the exercise?
    * There was a difference in changing the lips and the teeth
- Is there anything about the image you would like to change?
    * No

• Child 2, 10 years old

- Have you ever performed in a spirometry test before?
    * Yes

Table 11: Data of the child doing the exercises			
	Feedback of app	**Exercise**	**Notes**
1	Upper	Upper and under	
2	All sensors touched	Upper, right and under	
3	Upper, right and under	Upper, left and under	
4	All sensors touched	All sensors touched	
5	All sensors touched	All sensors touched	
6	Upper and under	Teeth upper and under	
7	Upper, under and left	Left and right just lips	Hard to do
8	Upper and under	Lips upper and under	
9	All sensors touched	All touched just lips	Hard to do

- Can you explain how the image changed if you changed the exercise?
    * The balloons are colored when the tube is touched.
- Is there anything about the image you would like to change?
    * The balloons should be in hart shapes and you could earn coins.

- Child 3, 8 years old
  - Have you ever performed in a spirometry test before?
    - Yes

Table 11: Data of the child doing the exercises			
	Feedback of app	**Exercise**	**Notes**
1	Upper, right and Under	Upper, under and left	Hard to do
2	Upper and under	Upper, right and under	Hard to do
3	Upper, right and under	All touched just lips	
4	Upper, under and left	All sensors touched	
5	Upper	Left and right just lips	
6	Upper and under	Teeth upper and under	
7	Upper and under	Lips upper and under	
8	All sensors touched	All sensors touched	
9	All sensors touched	Upper and under	Hard to do

  - Can you explain how the image changed if you changed the exercise?
    - The image changing through touching the tube.
  - Is there anything about the image you would like to change?
    - You could earn coins with which you could buy nice things for the game.
- Child 4, 9 years old
  - Have you ever performed in a spirometry test before?
    - Yes

Table 11: Data of the child doing the exercises			
	Feedback of app	**Exercise**	**Notes**
1	Upper, under and left	Upper, under and left	Hard to do
2	Upper and under	Lips upper and under	
3	Upper, right and under	All sensors touched	
4	Upper and right	All touched just lips	
5	Upper, right and under	Upper, right and under	Hard to do
6	All sensors touched	Left and right just lips	Hard to do
7	Upper and under	Teeth upper and under	
8	Upper, right and under	All sensors touched	
9	Upper and under	Upper and under	

  - Can you explain how the image changed if you changed the exercise?

    * The device sees where you put pressure.

  - Is there anything about the image you would like to change?
    * It would be nice to shoot the arrow

- Child 5, 7 years old
  - Have you ever performed in a spirometry test before?
    * No

Table 11: Data of the child doing the exercises

	Feedback of app	Exercise	Notes
1	Upper and under	All touched just lips	
2	All sensors touched	Teeth upper and under	
3	Under	Upper, right and under	
4	Nothing touched	Upper and under	
5	Nothing touched	Upper, right and under	
6	Upper, right and under	Upper right and under	
7	Upper and under	Upper and under	
8	Upper, right and under	Left and right just lips	Hard to do
9	Upper and under	Teeth upper and under	

  - Can you explain how the image changed if you changed the exercise?
    * No.
  - Is there anything about the image you would like to change?
    * There should be a sun.

- Child 6, 6 years old
  - Have you ever performed in a spirometry test before?
    * No

Table 11: Data of the child doing the exercises

	Feedback of app	Exercise	Notes
1	All sensors touched	All sensors touched	
2	Upper, right and under	All sensors touched	
3	Nothing touched	Teeth upper and under	
4	Upper and under	Upper and under	
5	Upper	Left and right just lips	
6	Nothing toucehd	Upper,under and left	
7	Upper and under	Lips upper and under	
8	Under	All touched just lips	
9	Upper	Upper, right and under	

- Can you explain how the image changed if you changed the exercise?
  * No.
- Is there anything about the image you would like to change?
  * There should be a sun and flowers

Appendix F

Code

F.1 Lofi

F.1.1 Android code

/* Upload this sketch into Crowduino and press reset*/
include ¡CapacitiveSensor.h¿
include ¡SoftwareSerial.h¿ //Software Serial Port
CapacitiveSensor $cs_{28} = CapacitiveSensor(2, 8)$;
CapacitiveSensor $cs_{29} = CapacitiveSensor(2, 9)$;
CapacitiveSensor $cs_{31}0 = CapacitiveSensor(3, 10)$;
CapacitiveSensor $cs_{41}1 = CapacitiveSensor(4, 11)$;
void setup()
Serial.begin(9600);
void loop()
// long start = millis();
long total1 = $cs_{28}.capacitiveSensor(30)$;
// int total2 = $cs_{29}.capacitiveSensor(30)$;
// int total3 = $cs_{31}0.capacitiveSensor(30)$;
// int total4 = $cs_{41}1.capacitiveSensor(30)$;
String tot1 = ”U” + String(total1);
String tot2 = ”R” + String(total2);
String tot3 = ”D” + String(total3);
String tot2 = ”L” + String(total4);
Serial.println(total1);
Serial.print(tot2);
Serial.print(tot3);
Serial.print(tot4);

F.2 Hifi

F.2.1 Processing code

```
/*
    Code by Tamara Droogsma
    Small code snippets are form:
    Application for DIY- Speedometer
    can be used with Arduino hardware
    code by www.circuitdigest.com
    coded on 08-04-2017
    */
    //**Import the necessary header files**//
    import android.content.Intent;
    import android.os.Bundle;
    import ketai.net.bluetooth.*;
    import ketai.ui.*;
    import ketai.net.*;
    import android.bluetooth.BluetoothAdapter;
    import android.view.KeyEvent;
    //_Endofimports_//
    BluetoothAdapter bluetooth = BluetoothAdapter.getDefaultAdapter();
    PImage achtergrond, BalloonDown, BalloonLeft, BalloonRight, BalloonUp,
boog, pijl, RopeDown, RopeLeft, RopeRight, RopeUp;
    KetaiBluetooth bt;
    int DataUp, DataRight, DataDown, DataLeft;
    int receivedData;
    int data, i;
    String cninfo = "";
    float angle;
    boolean sw;
    String stringUp = "";
    String stringRight= "";
    String stringDown = "";
    String stringLeft = "";
    int val;
    byte [] data1;
    //**To start BT when app is launched**//
    void onCreate(Bundle savedInstanceState)
    super.onCreate(savedInstanceState);
    bt = new KetaiBluetooth(this);
    void onActivityResult(int requestCode, int resultCode, Intent data)
    bt.onActivityResult(requestCode, resultCode, data);
    //_BTlaunched_//
```

```
//**To select bluetooth device if needed**// (not required for our program
void onKetaiListSelection(KetaiList klist)
String selection = klist.getSelection();
bt.connectToDeviceByName(selection);
//dispose of list for now
klist = null;
//Endofselection//
//** To get data from blue tooth**/
void onBluetoothDataEvent(String who, byte[] data1)
if (data1 != null)
String str = new String(data1);
for (int i = 0; i ¡ str.length(); i++)
if ( str.charAt(i) == 'R')
if ( str.charAt(0) == 'U')
stringUp = str.substring(1, i);
DataUp = Integer.valueOf(stringUp);
else
stringUp = str.substring(0, i);
DataUp = Integer.valueOf(stringUp);
//stringRight = str.substring(i+1);
// DataRight = Integer.valueOf(stringRight);
print(str);
print('+');
for (int j = 0; j¡ str.length(); j++)
if (str.charAt(j) == 'D')
stringRight = str.substring(i+1, j);
DataRight = Integer.valueOf(stringRight);
println(stringRight);
for (int k = 0; k ¡ str.length(); k++)
if (str.charAt(k) =='L')
stringDown = str.substring(j+1, k);
DataDown = Integer.valueOf(stringDown);
stringLeft = str.substring(k+1);
DataLeft = Integer.valueOf(stringLeft);
//if (data1 != null)
// String str = new String(data1);
// println( str);
// if (str.charAt(0) == 'U')
// stringUp = str.substring(1, str.length());
// DataUp = Integer.valueOf(stringUp);
//
// if(str.charAt(0) == 'R')
```

```
// stringRight = str.substring(1, str.length());
// DataRight = Integer.valueOf(stringRight);
//
//if(str.charAt(0) == 'D')
// stringDown = str.substring(1, str.length());
// DataDown = Integer.valueOf(stringDown);
//
//if(str.charAt(0) == 'L')
// stringLeft = str.substring(1, str.length());
// DataLeft = Integer.valueOf(stringLeft);
//
//datareceived//
//**To get connection status**//
String getBluetoothInformation()
String btInfo = "Connected to :";
ArrayList¡String¿ devices = bt.getConnectedDeviceNames();
for (String device : devices)
btInfo+= device+"";
return btInfo;
//–connection status received//
//**Settings for the Android Application**//
void settings()
fullScreen(); //make the app for in full screen
//settingscompleted//
//**Executes only once**// (similar to arduino)
void setup()
orientation(LANDSCAPE);
textSize(31);
bt.start(); //start listening for BT connections
bt.getPairedDeviceNames();
bt.connectToDeviceByName("HC-05"); //Connect to our HC-05 bluetooth module
//size(216,384);
//load images//
achtergrond = loadImage("achtergrond.png");
BalloonUp = loadImage("BalloonUp.png");
BalloonLeft = loadImage("BalloonRight.png");
BalloonDown = loadImage("BalloonDown.png");
BalloonRight = loadImage("BalloonRight.png");
RopeDown = loadImage("RopeDown.png");
RopeLeft = loadImage("RopeLeft.png");
RopeRight = loadImage("RopeRight.png");
RopeUp = loadImage("RopeUp.png");
```

boog = loadImage(”boog.png”);
pijl = loadImage(”pijl.png”);
//**Draw function**//
void draw() //The infinite loop
// deze images blijven het hele spel staan
imageMode(CENTER);
image(achtergrond, width, height/2, width*2, height);
image(boog, width/8, height*0.7, width/20, height/3);
image(pijl, width/8, height*0.7, width/7, height/60);
if ((DataUp ¿2000) (DataRight ¿2000) (DataDown ¿ 2000) (DataLeft ¿ 2000))
Complete();
else
notComplete();
textfun(); // voor bluetooth connectie
showData(); // kan straks weg
// notComplete(); //laat de ballonnen invullen op de nog niet juiste plek
$///_{Endofdraw}{}_{//}$
void showData()
textSize(30);
textAlign(CENTER);
fill(255);
cninfo = getBluetoothInformation();
text(cninfo, width/2, height-height/1.03);
text(DataUp, width/2, height/2.8);
text(DataRight, width/2, height/2.7);
text(DataDown, width/2, height/ 2.5);
text(DataLeft, width/2, height/2.3);
noFill();
//Function Display the text on top of the application**//
void textfun()
textSize(30);
textAlign(CENTER);
fill(255);
cninfo = getBluetoothInformation(); //get connection information status
text(cninfo, width/2, height-height/1.03);
noFill();
$//_{Endoffunction}{}_{//}$
void notComplete()
imageMode(CENTER);
image(RopeUp, width/2, height*0.25, width/9, height/3);
image(RopeDown, width/2, height*0.75, width/9, height/3);

image(RopeRight, width*0.7, height/2, width/9, height/3);
image(RopeLeft, width*0.3, height/2, width/9, height/3);
if (DataUp ¿ 2000)
image(BalloonUp, width/2, height*0.25, width/9, height/3);
if (DataRight ¿ 2000)
image(BalloonRight, width*0.7, height/2, width/9, height/3);
if (DataDown ¿ 2000)
image(BalloonDown, width/2, height*0.75, width/9, height/3);
if (DataLeft ¿ 2000)
image(BalloonLeft, width*0.3, height/2, width/9, height/3);
void Complete()
imageMode(CENTER);
image(RopeUp, width*0.9, height*0.75, width/9, height/3); //misschien de ballonnnen nog opschuiven hier
image(RopeDown, width/2, height*0.75, width/9, height/3);
image(RopeRight, width*0.7, height*0.75, width/9, height/3);
image(RopeLeft, width*0.3, height*0.75, width/9, height/3);
image(BalloonUp, width*0.9, height*0.75, width/9, height/3);
image(BalloonRight, width*0.7, height*0.75, width/9, height/3);
image(BalloonDown, width/2, height*0.75, width/9, height/3);
image(BalloonLeft, width*0.3, height*0.75, width/9, height/3);

F.2.2 Arduino code

/* Upload this sketch into Crowduino and press reset*/
include ¡CapacitiveSensor.h¿
include ¡SoftwareSerial.h¿ //Software Serial Port
define RxD 6
define TxD 7
define DEBUG$_{E}NABLED1$
SoftwareSerial blueToothSerial(RxD, TxD);
CapacitiveSensor cs$_{28} = CapacitiveSensor(2, 8)$;
CapacitiveSensor cs$_{39} = CapacitiveSensor(3, 9)$;
CapacitiveSensor cs$_{41}0 = CapacitiveSensor(4, 10)$;
CapacitiveSensor cs$_{51}1 = CapacitiveSensor(5, 11)$;
int BluetoothData;
void setup()
blueToothSerial.begin(9600);
pinMode(RxD, INPUT);
pinMode(TxD, OUTPUT);
setupBlueToothConnection();
void loop()
// long start = millis();
int total1 = cs$_{28}.capacitiveSensor(30)$;

int total2 = cs$_{39}.capacitiveSensor$(30);

int total3 = cs$_{41}0.capacitiveSensor$(30);

int total4 = cs$_{51}1.capacitiveSensor$(30);

String tot1 = "U" + String(total1);

String tot2 = "R" + String(total2);

String tot3 = "D" + String(total3);

String tot4 = "L" + String(total4);

String tot = tot1 + tot2 + tot3 + tot4;

//char recvChar;

blueToothSerial.print(tot);

//blueToothSerial.println(tot2);

// blueToothSerial.print(tot3);

// blueToothSerial.print(tot4);

delay(20);

void setupBlueToothConnection()

blueToothSerial.begin(9600); //Set BluetoothBee BaudRate to default baud rate 38400

blueToothSerial.print("$^\circ$+STWMOD=0°"); //set the bluetooth work in slave mode

blueToothSerial.print("$^\circ$+STNA=CrowBTSlave$^\circ$"); //set the bluetooth name as "CrowBTSlave"

blueToothSerial.print("$^\circ$+STPIN=0000°");//Set SLAVE pincode"0000"

blueToothSerial.print("$^\circ$+STOAUT=1°"); // Permit Paired device to connect me

blueToothSerial.print("$^\circ$+STAUTO=0°"); // Auto-connection should be forbidden here

delay(2000); // This delay is required.

blueToothSerial.print("$^\circ$+INQ=1°"); //make the slave bluetooth inquirable

Serial.println("The slave bluetooth is inquirable!");

delay(2000); // This delay is required.

blueToothSerial.flush();