Design of a Health Monitoring Toy for Children

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ABSTRACT

Especially for young children measuring their physiological parameters to assess their health can be stressful, even when conducted at home by their parents. Therefore we present a concept that can relieve some of the anxiety correlated with an examination and implemented it in a test setup we call "MediCubes" to investigate how this approach is received. In this system cube shaped tangible objects are fitted with noninvasive sensors measuring pulse, temperature, blood oxygen saturation and lung capacity while interacting with them. Incorporation in a storytelling game allows guiding a child through a series of unperceived physiological measurements as an enjoyable experience. The acquired data is stored on a tablet computer and can be reviewed by parents or doctors. In this paper the design process and the developed hard- and software are presented. Furthermore we report on a usability study with 8 children and 12 adults indicating high acceptance and enjoyment of the system. These results as well as our "lessons learned" could have implications on the future development of home health monitoring toys.

Author Keywords

Health monitoring; home monitoring; pervasive healthcare; storytelling toy; children; Tangible User Interface; sensors.

ACM Classification Keywords

H.5.2. Information interfaces and presentation: User Interfaces - Input devices and strategies / Haptic I/O.

J.3. Computer Applications: Life and Medical Sciences.

INTRODUCTION

Measuring one's physiological parameters is not a particularly pleasant experience and usually people tend to perform it only rarely, for example when signs of an illness are already obvious [7]. Even more so for young children, taking routine measurements can pose a very unsettling situation and harmless devices like an infrared thermometer can appear threatening.

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Figure 1. Health monitoring can be fun with "MediCubes".

We propose to change this situation and even make it a joyful experience for children. For this purpose we investigate the idea to design a tangible storytelling game for health monitoring with our test assembly "MediCubes" (Figure 1).

As a basis for our system we employed the previously introduced "ACTO" system [24], a prototyping platform for tangible user interfaces, providing a basic infrastructure with programmable microcontroller, actuation mechanism and a smartphone as processing unit. From that substructure we designed three "MediCubes" as cube-shaped tangible objects with wooden housings. Each one is equipped with different noninvasive sensors, measuring physiological parameters i.e. pulse, temperature, blood oxygen saturation and lung capacity. The design of the affordances of the cubes and the incorporation in the gameplay stimulates intuitively correct handling. Holding the cubes in the correct way, at the right time and for a certain time period, unfolds a story to the player. This allows unperceived guidance of a child through a series of physiological measurements, simply by playing with the toy. The acquired data is recorded and stored in a profile on a smartphone, where it can be reviewed by parents or doctors in an informative form.

In this work we describe the conceptual design of this tangible storytelling game for health monitoring, discussing the affordances of the tangible objects and the game logic. Furthermore we present developed hard- and software for a test system we call "MediCubes". The general feasibility of the concept is evaluated in a usability study with 8 children and 12 adults using the system. We included adults since they are accessible more easily and their feedback is also valuable considering that a similar system could also be employed in rehabilitation or elderly care.

MOTIVATION & CONTRIBUTION

Monitoring one's health regularly would be important to recognize early symptoms of an illness or trends as soon as possible and could even save lives [23]. However especially for young children the entire situation of taking routine measurements can be correlated with uneasiness and stress, even though conducted by their parents in familiar surroundings. Moreover a lot of children (as well as adults) are suffering from chronic conditions that require regular health monitoring.

Grönvall et al. [8] point out that people tend to refuse surveillance technologies as in wearable or ubiquitous home health monitoring systems (see Related Work). Instead of passive monitoring, a variety of sensors for physiological parameters could be integrated into tangible objects to create health monitoring toys. We envision a system primarily for home use with children, which produces medically relevant data with comparable accuracy to conventional self-monitoring devices while being enjoyable to play with. This approach allows a conscious decision when to check one's health status and lowers the threshold of submitting to the procedure at the same time. The apparatus is not intended to replace a proper medical examination through a professional, but it could support preventive health care by showing parents early indications of an illness as well as alleviate the regular monitoring of chronic conditions.

In this paper we contribute to realizing this vision by investigating how this approach is received by children with our implemented test setup "MediCubes". We demonstrate the feasibility of guiding a player through a series of physiological measurements in the course of a storytelling game, determining the interaction with specific sensors for a certain time in a controlled sequence. Intuitively correct handling of each sensor is indicated through the design of the game and the tangibles, alleviating home use especially for children. In the course of the development non-invasive sensors for pulse, temperature, blood oxygen saturation and lung capacity and their suitability for integration in a home monitoring toy are investigated. Finally we show that our suggested approach can change monitoring one's health into a joyful experience, hopefully stimulating further research towards home monitoring toys.

RELATED WORK

Employing tangible objects for interactive games in a therapeutic context has been proposed in previous works. For example Li et al. [11] present a tangible user interface providing occupational and physical therapy for children with movement disorders. Westeyn et al. [25] suggest to put sensors in "smart toys" to detect and record interactions for monitoring the developmental progress of children. Nevertheless there are only very few attempts to use sensors for measuring physiological signals in games. Shusong and Xia [26] report on a toy for post-stroke rehabilitation, where the muscle activity of a patient is measured to control the limbs of a toy robot. Nenonen et al. [16] present an interactive biathlon game with parameters like speed or steadiness depending on the current heart rate of the player. Both of these examples employ sensors to measure specific physiological parameters of the user, but only use the acquired data as input for the game in order to encourage the players to do physical exercise. Using the data for monitoring of the health status is not considered.

Using wearable sensors for health monitoring is currently a very active research area. Jalaliniya et al. [10] designed a system intended to be worn by children over the day, monitoring temperature and heart rate. "HealthGear" by Oliver et al. [17] describe wearable sensors which allow real-time sleep monitoring of blood oxygen level and pulse. But even though recent developments in biomedical sensing technology allow cheaper, smaller and easy-to-use sensors [18], typical shortcomings of wearable systems persist. One of them is the fact, that they are intended to be worn over an extended period of time, which can cause discomfort. Another very active field of research circumventing these drawbacks is ubiquitous health monitoring. The sensors are integrated in objects of the everyday life. For example Chigira et al. [5] were able to embed sensors into a drinking glass to allow heartrate monitoring during beverage consumption. Lim et al. [12] installed nonintrusive sensors accurately measuring heart and respiration rate as well as estimating blood pressure in all kinds of everyday equipment like beds, belts or toilet seats. However, according to Grönvall et al. [8] people might refuse over-protective or surveillance technologies logging one's physiological parameters unperceived all the time. According to the authors it is important that the control of when, where and how measurements are performed remains with the individual.

We want to provide a conscious way of measuring physiological signals without the uneasiness associated with medical devices. Storytelling offers rich opportunities for interaction while being a fun experience especially for children. Zhou et al. [27] explore the application of a cubical tangible object complemented with augmented reality technology called "3D story cube" for interactive storytelling. Fontijn et al. [6] show that a storytelling environment can be appealing for children of different ages from 2 to 6 years and even for "adults in the right mindset". Their "StoryToy" comprises of a farm made out of cloth and stuffed toy animals equipped with wireless sensors, which recognize manipulations and replay audio appropriately. The authors already envision serious applications while preserving the ease of use of toys but do not consider toys with a medical purpose.

CONCEPTUAL DESIGN

In order to engage children in a game while measuring health related parameters, it does not suffice to arrange a variety of sensors in a playful setup. Primarily we have to devise a way to control how a player interacts with integrated sensors to make sure that reliable measurements can be taken. For that purpose the affordance of the involved game objects as well as the game logic have to be designed accordingly. We pursue our idea to achieve this with a storytelling approach in our test system "MediCubes". Three tangibles equipped with different sensors are placed on a table and trigger specific parts of a story when held with correctly positioned fingers at the right time (see Figure 2).

Tangible Affordance

To permit an integrated sensor to measure physiological data reliably, we have to guide the player to intuitively grasp a tangible object in a specific way. We decided to use cube shapes for our tangibles, because the playfulness of this form has been proven over the last decades [21] and more importantly a cube's size and weight can influence how it is handled. We employed an equation developed by Cesari and Newell [3] that captures the geometric and biodynamic constraints on the act of grasping independently of the actor's sex or age. The resulting value describes the relationship between cube length and mass that effectively constrains the grip configuration used to pick up a single cube. According to this, to encourage children to pick up the cube with one hand, for an edge length of 6 cm the total cube weight should not exceed 120 g. One "MediCube" measures 6 x 6 cm with a height of 6 cm, except the spirometer cube (described below) which is 8 cm high due to the space requirements of the internals. To achieve the low weight we built housings from balsa wood which is also pleasing to touch. Including electronics one cube weighs just below 120 g. We placed the sensors on the front side, intended to be employed on the right thumb, and added a recess with sandpaper around the location. Furthermore we painted the cubes to provide an additional indication on how to grasp it.

Game Logic

For ensuring a controlled series of measurements, we have to guide a player on which sensor to interact with for how long and provide inherent feedback on the correct handling. For our "MediCubes" we employed a storytelling approach to accomplish that. We chose a story that allows us to incorporate the act of breathing in the game play for breath or lung related measurements. For that reason we selected the popular fairy tale "Three Little Pigs" [9], which includes several breathing elements. In this tale a wolf tries to blow down the three houses of three little pigs but finally fails. Symbolic pictures on top of the tangibles indicate the part of the story they represent. To hear the whole story the user has to pick up one tangible after another and hold it in a way to allow the sensors to acquire valid data. For example the first 10 seconds of the story are replayed through audio speakers and stop mid-sentence with the words "The three little pigs…" as an indication to pick up the next cube with the corresponding picture on top. Additionally the appropriate tangible starts to slightly shake from left to right after a short time to emphasize the desired action, then rotates back to a predefined angle that suggests right hand use. After the correct cube is picked up and held correctly, it confirms it with a short beep played from a speaker inside and starts measuring. The story continues and stops for example with the word "house", emphasized with shaking of the correlated cube. For the blowing part the playback pauses for example with "I'll huff and I'll puff and I'll blow your house in" to imply that the participant should blow into the appropriate cube. As confirmative feedback a blowing sound is played while blowing into the cube. This pattern is repeated for all parts of the story, incorporating all desired "MediCubes" for an appropriate time. In order to keep the game interesting after repeated use, the pictures on top are easily exchangeable which allows all kinds of stories to be told with the same set of "MediCubes".

Basic Setup

As already stated before our setup builds upon the core functionality of the prototyping platform "ACTO" [24], which provides the basic components of an actuated tangible user interface. An ACTO tangible offers a programmable microcontroller similar to the Arduino electronics platform, which supports the integration of additional electronic components. Furthermore a motor for positioning on the table as well as protocol and hardware for wireless communication with an Android smartphone are supplied. The Android smartphone is placed below a transparent table with the front-camera directed upwards to track fiducial markers on the bottom of multiple tangibles and to manage their position on the table's surface (please refer to [24] for further details). For our system we use a well-lit 53 x 48 cm foldable acrylic glass table with 48 cm height, which keeps the assembly mobile and easy to set up. We employ an ASUS TF201 Android tablet under the table with additional audio speakers to ensure a good sound quality and easy volume adjustment of the replayed story. Figure 2 shows the entire setup with three "MediCubes" arranged on the table.

Figure 2. Test system with three "MediCubes".

HARDWARE INTEGRATION

For measuring physiological parameters we require sensors that are suitable for integration in a tabletop game. They have to provide meaningful health parameters but record data in a noninvasive and mostly unperceived way. At the same time they have to be realizable in a small enough form factor and applicable for microcontroller-based systems. Although they are not intended for exact measurements as for example conducted in a hospital, the attainable accuracy should be close to conventional home measurement devices.

Under these requirements we selected sensors for pulse, temperature, blood oxygen saturation and lung capacity and constructed the three "MediCube" tangibles presented in the following sections.

Pulse & Oxygen Saturation Tangible

For the measurement of the heart beats per minute (bpm) we decided to use the Pulse/Oxygen Saturation Sensor by Modern Device, which uses the Silicon Labs SI1143 chip in combination with red and infrared LEDs. It employs a noninvasive technique called pulse oximetry. A common method is to use an infrared LED and a phototransistor to sense the rhythmic change of blood vessels in a patch of skin like a finger, as small but detectable variations in contrast, a Photoplethysmogram (PPG). Furthermore this approach also allows an estimation of the blood oxygen saturation with an additional red LED since the ratio between the concentrations of deoxygenated blood and oxygenated blood is proportional to the ratio of red light absorption to infrared light absorption [1]. For the integration in a tangible we wired the sensor according to the Serial Peripheral Interface (SPI) standard. A library provided by the manufacturer is used to manage the communication between the chip and an Arduino. The changes in skin contrast caused by the heart beat are sensed automatically when putting a finger on the phototransistor of the chip, which facilitates integration in a game play. However, a minimum sustained measuring time of one minute is suggested for reliable data. We also added a piezo speaker for audio feedback in the tangible. Figure 3 shows the resulting MediCube with the Modern Device Sensor on the front side of the cube to be employed on the thumb.

Figure 3. Pulse and oxygen saturation cube.

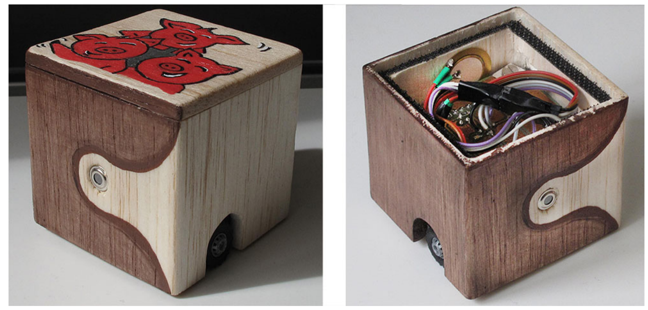

Figure 4. Tangible for temperature measurements.

Temperature Tangible

For the estimation of the core body temperature during game play we employed the infrared sensor Melexis MLX90614 ESF DAA. This sensor has an accuracy of 0.1ºC in a limited range around the human body temperature. It requires unobstructed view to the user's skin but does not allow direct contact. We connected the sensor to the tangible over a bus closely related to the Inter-Integrated Circuit (I2C) standard.

Since the skin temperature is in general lower than the core temperature, the radiated heat loss has to be taken into account. Therefore we use a technique known as arterial heat balance [19], which includes a weighted difference of surface temperature T_s and ambient temperature T_a to estimate the core body temperature T_c:

$$T_c = k \cdot (T_s - T_a) + T_s$$

The constant coefficient k depends on the measuring area, so it can be adapted to the perfusion rate (the rate of blood flow through the tissue) of hands or fingers.

In general the estimation of the core body temperature is more inaccurate the further away from the core the temperature is measured. Although the quality of the data could be increased if put on more appropriate places of the body, it could also decrease the acceptability of the system [10]. For that reason we decided to employ the sensor on the thumb. Assuming a constant hand perfusion rate we were able to estimate the core body temperature from the thumb in laboratory conditions to a reasonable accuracy comparable to results from a conventional infrared thermometer measured on the forehead. We mounted it into a recess on the front side wall of the tangible (Figure 4). A piezo speaker for audio feedback is also integrated.

Spirometer Tangible

Spirometry measures the lung function for example through the pressure drop in a tube during exhalation. These so called differential pressure flowmeters are cheap and small, since they require only a tube that creates a controlled pressure difference at a restriction.

Figure 5. Spirometer tangible with skin conductance contacts.

According to Bernoulli the velocity of the fluid through the restriction is increased and the pressure at this section is decreased. With the Bernoulli equation we can calculate the flow rate q as:

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

Whereas d_1 and d_2 are the two different diameters in the tube, p_1 and p_2 are the measured pressure values at these diameters and ρ is the mean air fluid density.

For our spirometer tangible we 3D printed a tube with an annular restriction inside according to the specifications of a so-called Venturi tube. These tubes have specific angles around the restriction and a certain placing of the pressure tapping points, avoiding undue drag and facilitating a constant flow rate. We extended the design to allow standard paper mouth pieces to be attached and also printed several washable plastic mouth pieces (Figure 5). To measure the pressure difference between the two tapping points we used the MPX5010 Differential Pressure Sensor by Freescale Semiconductor, which is connected by two silicone tubes with our Venturi tube and directly wired to analog inputs of the microcontroller.

We also integrated a piezo speaker and included aluminum contacts on front and back of the spirometer cube to measure the conductance between thumb and middle finger. Skin conductance can e.g. be viewed as indication of the emotional and mental state identified with stress [15]. In this setup we use it to detect user contact with the cube.

SOFTWARE

The course of events for the storytelling game as already described in the section Game Logic is implemented in a "MediCubes" application running on the Android device. In addition to the game mechanics we supplied functionality to create multiple user profiles by choosing from the existing contacts saved on the device. After starting a game over the user interface, the recorded measurements for the current player are transmitted wirelessly from each "MediCube" to the Android device where they are stored permanently in an SQLite database.

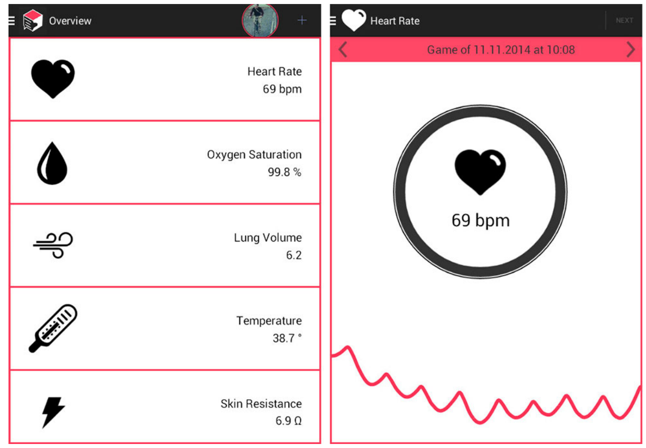

Figure 6. Overview and detailed view in our Android app.

For review by parents or doctors we also provided informative visualization of the measurements (Figure 6). After selecting a user profile, an overview page containing the averaged values of the data recorded during all played games of the corresponding user is shown. By selecting one of the physiological parameters, a detailed view can be opened, illustrating the development of this specific value over the course of the last played game. In this view it is also possible to browse through the recordings of previous games, which could be especially useful to recognize trends or review the progression of symptoms over time.

EVALUATION & RESULTS

In the following sections we will present the conducted user study to gain insights into the usability of our test system and the feasibility of our idea to use a storytelling toy for home health monitoring.

Study Design

In order to evaluate if our concept is suitable for children and can produce medically relevant measurements, we observed children and adults playing with the "MediCubes". We conducted an unstructured passive observation, as suggested by Markopoulos et al. [13], in a familiar environment like the participants' homes. Interaction between the evaluator and the participants is minimal in order to show if the game is easy to use and understand for children and can guide their actions as intended. Furthermore it should leave room for unexpected behavior. The test sessions were recorded on video for later analysis.

A total of 8 children (age 5 to 12) and 12 adults (age 27 to 67) participated in our study. Additionally two adults took part in a pre-test to identify possible problems of the test setup in advance. In order to avoid any confusion, in this work the term "adult" always refers to adults participating in the study while "parent" is only used for the parents of the participating children. As already mentioned we included adult participants because they are accessible more easily and also provided us with valuable feedback as well as a larger user group. However the study was primarily designed for children and the gathered feedback is always evaluated separately.

The sequence of events for a test session started with an evaluator introducing the test procedure. The participant, or a parent in case of the children, was asked to sign a consent form, which contained an introductory part explaining the use of data and guaranteeing anonymity. Children and adults answered some general questions about their age and current emotional state, and the parents some additional inquiries about their children. Afterwards the evaluator introduced the setup to the participant. The three "MediCubes" were arranged on the table in a predefined order and orientation, as already presented in Figure 2, while the player sits in front of it. Since both pre-testers assumed that just touching was enough, for the actual study we explained that the three cubes on the table can tell a story as long as they are held correctly. After that the participant played preferably without interruptions until the story was finished. Additional hints were only given if the player had obvious difficulties with part of the game over a specific time span. The acquired physiological data was stored in a database on the tablet. After finishing the game, measurements of temperature, heart rate and oxygen saturation were taken with conventional home measurement devices to estimate if the sensors in the tangibles were able to acquire data.

Afterwards the participant was asked to fill out a concluding questionnaire to provide further feedback on the system (see section Subjective Feedback). Some more difficult questions were included in a separate questionnaire to be answered by the parents, whereas the adults answered this part themselves. The test session was concluded by thanking the participant and explaining any open questions. On average one game including questionnaire lasted about 15 minutes.

Video Analysis

We analyzed the recorded video of each session on the basis of previously defined guiding questions, which are presented in this section. The adults required almost no hints after the introduction and since children are our major target group, we focus our observations on the usability of the system for our eight younger participants:

Did they intuitively understand which tangible to pick up?

For all eight children the slight shaking of the cube after two seconds was sufficient cue to pick up the correct first tangible. Two were seeking additional confirmation by looking to the evaluator. Two put down the first cube too early but picked it up again when it started shaking, holding following ones correctly. For subsequent cubes for half of the participants the auditive cue in the story was sufficient, the other children waited for the shaking.

Was the cube design and pose sufficient cue to use the right hand?

The first cube initially standing on the right side of the table was picked up by all children with the right hand. However the second cube positioned on the left was picked up by three of eight children with their left hand, one of them was the only left-handed participant. The third cube was standing in the middle and only one child grasped it with the left hand, changing the hand consequentially. For the most part only one hand was used, with the exception of the two youngest children, who used the left hand as support in one case and both hands equivalently in the other.

Was the cube handled to permit acquisition of sensor data?

The first cube (temperature) was grasped by six of eight children intuitively as intended with the thumb positioned correctly. The remaining two required a hint at the location of the sensor to reposition their fingers. For the second cube (pulse oximeter) all participants placed their hand correctly or were actively searching for an equivalent spot to place their thumb. However, two picked up this cube with their left hand, which caused initial confusion finding the right finger position. For the third cube (spirometer) only one child had to reposition the fingers a couple of times after switching the hand. While listening to the story or breathing into the cube some temporarily lost their grip, but immediately repositioned the fingers for the playback to continue.

Was the respiratory tube used correctly?

With the additional hint by the evaluator that they might try to blow the house away, all participants except one blew instantly into the correct side of the tube. However at first five children either tried blowing from a few centimeters distance into the tube or blowing only very gently into the tube. For subsequent parts of the story involving the tube, only the youngest participant required further advice once.

Subjective Feedback

The answers from the concluding questionnaire provided us with additional subjective feedback on the system. Questions determining the enjoyment of the game and the cube design were answered over pictorial representations, which makes it easier for children to state their feelings or opinions. For that purpose we employed a 5-point scale called "Smileyometer" representing a range of feelings from awful to brilliant, proposed by Read and MacFarlane [20] to measure enjoyment and fun.

Figure 7. Smileyometer rating for the enjoyment of the game.

Figure 8. Smileyometer rating for the cube design.

Figure 7 shows the overall enjoyment of the game, for which over 60% of the children chose the most positive smiley (avg. 4.6), and even the adults gave very high ratings (avg. 3.9). The design of the cubes was also rated very high (Figure 8) by children (avg. 4.5) as well as adults (avg. 4.8).

In order to collect feedback about the perceived desirability we asked the participants to choose from a set of adjectives the five that describe their attitude towards the game most fittingly, a method proposed by Benedek and Miner [2] called "Product Reaction Cards". For children this task would probably have been overwhelming, which is why the parents answered this part in their place. Although the combination of positive and negative adjectives should make it more comfortable to also express negative opinions, the majority of the choices were positive. In Figure 9 the size of each word represents the number of times it has been selected. Of the 20 responders the adjectives most frequently chosen were "Entertaining" and "Creative" (7x), followed by "Fun" and "Sophisticated" (6x) as well as "Friendly", "Novel" and "Exceptional" (5x). The most frequent negative adjectives "Time-consuming" and "Difficult" each were selected two times. Noteworthy in this context are also "Useful" (4x), "Effortless" (3x) and "Understandable" (2x).

In accordance to [13,20] we avoided "Yes" or "No" questions and preferably included free-recall questions. In order to verify that the children listened to the story and not only tried to "pass" the test by reaching the end, we asked them for a short summary of the story. Although only half of them knew the fairy tale before, all of them except the youngest participant could reproduce every part of the story. Noticeably one child who had not heard the story before could reproduce it almost word for word. We also asked the children to elaborate on their most positive and most negative events to reveal any specific problems with the system. A lot of positive and only few negative incidents were reported, but the answers were all related to the content of the story thus they did not reveal any problems with the presented concept.

Figure 9. Word cloud of the Product Reaction Card choices.

All 12 adult participants were satisfied with the game and 11 stated that they find the story perfect and very entertaining for children. One adult expressed doubts if the game concept is understandable for children and that the story could be too boring. Furthermore they were asked if they would recognize the cubes as medical devices and 9 of 12 stated that they would not. The remaining ones stated they were reminded of a medical device only while blowing in the spirometry tube. Thinking of further improvements for the system the majority suggested to construct more cubes and different stories.

Additionally the parents were asked if their child would prefer such a system over conventional measurements conducted at home. All of the 8 questioned parents could imagine to use the developed game instead of conventional measurement techniques. Two parents found that the cubes and the corresponding story are a good distraction, so children are not bothered about the physiological measurements. Two parents were concerned about the time that is needed for the setup and the game compared to conventional measurements.

Sensor Data Acquisition

After the participants finished the game, we took measurements of temperature, heart rate and oxygen saturation with conventional home measurement devices. These comparative measurements allowed us an initial estimate if the tangibles were handled correctly and our approach allows the sensors to acquire data as intended. However, we want to reemphasize that the objective of this work is to collect information about the usability and acceptance of our concept and the designed tangibles, but not the development of new sensor technology. Drawing conclusions about the accuracy of the measured physiological data would require a completely different study design, measuring simultaneously with the game, which would have biased the gameplay and the gathered feedback.

Pulse and Oxygen Saturation

The agreement between our method and a conventional Contex CMS 65DL fingertip pulse oximeter produced reasonable results. For 75% of the participants the mean difference of the heart beats per minute was -3.87 bpm (SD: 5.21), whereas the mean difference of the calculated oxygen saturation was 0.21 % (SD: 1.29). Considering that the measurements were taken a few minutes apart and the measuring accuracy of the conventional pulse oximeter is specified +/- 2 bpm for heart rate and +/- 2 % for oxygen saturation, this indicates that it is possible to acquire pulse oximetry readings as intended with our approach. The remaining users produced similar results, but their sustained measuring timespan was below the specified one minute of the sensor manufacturer due to repeated switching of finger or hand position.

Temperature

In a laboratory setting as well as during the pre-tests our temperature cube produced satisfyingly reliable data. The mean difference of 0.13°C (SD: 1.19) temperature between the user tests compared to results from a Sanitas SFT 65 infrared thermometer on the forehead afterwards would seem reasonable especially considering that it was measured on the thumb. However, almost half of the participants did not produce valid readings because of various reasons: On the one hand, due to different thumb form and size of the children, for some of them the finger was directly touching the sensor, which caused it to overheat immediately, reporting absurdly high temperatures. On the other hand, four participants showed a temperature of the thumb below 30°C, which was below our lower threshold for detecting user contact. Finally other two test persons emitted a high enough temperature just by sitting in front of the table, that this was mistaken for user contact and recorded as finger temperature. Regarding these observations, although the temperature tangible was handled as intended, the current constellation does not reliably allow the sensor to acquire readings.

Spirometer

In Figure 10 the top row shows standardized flow-volume examples as presented in “Standardisation of Spirometry” [14]. On the left the pattern of a healthy subject, in the middle one of a person with airflow limitation and on the right a typical curve for an elderly person. In the bottom row we show related recordings acquired with “MediCubes” during the user tests. The curve on the left resembles most of the recordings, while the one in the middle belongs to a child suffering from a mild form of asthma and the right-most curve shows the recordings of an elderly participant. The results show marked similarities in the curve form as well as in the recorded liters per second as described in [14], which indicates that our approach can produce plausible flow-volume recordings.

DISCUSSION OF RESULTS

During the user study our test system “MediCubes” proved to be appealing to children and even adults. The reported enjoyment ratings were very high and the most frequently used adjectives to describe our system were “Fun”, “Entertaining” and “Friendly”. These properties would be highly desirable for a home health monitoring concept.

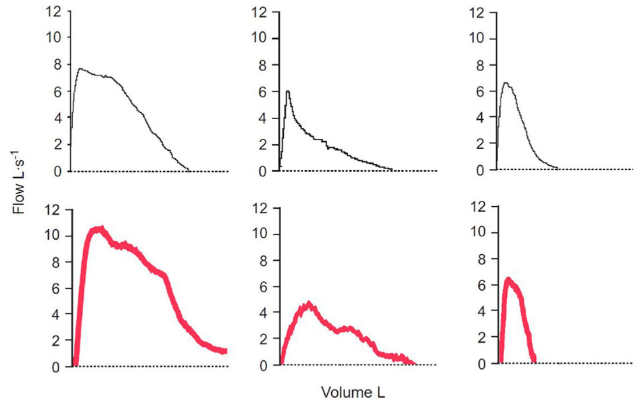

Figure 10. Top row: Flow-volume graphs as presented in [14]. **Bottom row: Measurements recorded with “MediCubes”.**

The children showed no signs of uneasiness during our observations, but enjoyed the session. Furthermore the majority of adult participants stated that the cubes did not obviously resemble medical equipment. All of this supports our proposition that this approach can significantly alleviate home health monitoring for children.

The affordances of our tangible objects in combination with the auditive cues from the story, the pictures on top and the shaking of the cubes proved to be effective incentives to guide children through a series of physiological measurements almost unsupervised. If the handling of a cube was not immediately clear to individual children, a simple hint was enough and it was handled correctly afterwards. This indicates that such difficulties are subsiding after first time use. Furthermore we observed that children tend to use the hand that is closer to the object to pick it up. Currently our design favors right-handed use, but in order to improve suitability for children it could be designed symmetrical, for example with the same sensors on both sides.

Our observations on the acquired data suggest that for future home monitoring toys the game design has to be stricter on when to record data and incorporate better quality control of the data. For some tangibles like the spirometry tube a basic introduction is advisable to guarantee correct usage. At the same time, it is essential to keep the game attractive, so the children do not lose interest, but also not too exciting to avoid influencing the measurements.

The experiences with our temperature cube provided valuable insights for improvements. One possibility would be to relocate the sensor to the side of the cube, so it measures the temperature of the hand’s palm. This would eliminate the problem of direct contact with the thumb and also more closely resembles the body’s core temperature which would make an estimation more reliable without compromising the acceptability. A separate contact sensor would also be advisable for detection of user contact.

In the user study reported in this work we focused on collecting information about the usability and general feasibility of our approach. However although the pulse oximetry unit as well as the spirometry unit were able to record data that could bear medical relevance, this provides us only with a preliminary assessment. Before developing a health monitoring toy that would be ready for home use, an extensive user study with the suggested hardware and gameplay improvements has to be conducted in order to confirm the medical relevance of the recorded data and to allow a substantiated conclusion about the attainable accuracy of such an approach.

CONCLUSION & FUTURE WORK

We presented a novel approach of home health monitoring for children and evaluated the general viability of the concept with our test assembly "MediCubes". The positive feedback from the reported user study shows very high acceptability. The design of affordances and the incorporation into a storytelling game permitted a guided series of physiological measurements that was enjoyable for the examined person. Our work demonstrates that conducting home health monitoring with a storytelling toy is feasible and should be pursued further.

Consolidated by the encouraging results from this work, we plan to continue to investigate the potential of our approach. We want to perform further signal processing, for example removing outliers and applying filtering methods, to improve the reliability of the recordings. Furthermore, we also plan to extend the functionality of "MediCubes" with additional sensors. Current advances in non-invasive sensing technology are promising, for example reducing the size while improving the accuracy and reliability. There are attempts to use a PPG signal similar to the recordings from the pulse oximetry cube to estimate the differential blood pressure [4]. There are even reports on the possibility of detecting diabetes and cancer from the breath [22].

Our present test assembly builds upon the core functionality of the ACTO prototyping platform [24], but we currently exploit only a fraction of the possibilities. For example using the positioning on the table to a larger extent would allow more complex stories and more exciting interactions, like moving tangibles that have to be caught. Furthermore our system could be easily adapted to other stories and it would be interesting to integrate sensors into the gameplay which have to be used on specific places on the body, for example a measurement on the forehead could be a "crown" in a fairy tale.

We also want to conduct an extensive user study with a larger group in order to confirm the medical reliability of "MediCubes". Therefore we also aim for a closer involvement of medical doctors to be able to assess and improve the accuracy of measurements that is possible with the system. In addition to that, we plan to investigate applicability for remote therapy for rehabilitation and home health monitoring for elderly people. Furthermore we asked a pediatrics specialist working in a children's hospital about the relevance of our concept for hospitals. In the professional's opinion the cubes could be a valuable supplement in doctor's offices and would save time especially with children who are afraid of examinations.

We believe health monitoring toys have the potential to be employed at home, in doctor's offices and elderly homes everywhere and relieve people from some of the anxiety related with physiological measurements. We hope that our work encourages further research into medical toys and soon systems like ours can be found in everyday households.

SELECTION & PARTICIPATION OF CHILDREN

8 children, aged 5 to 12, participated in the study reported in this paper. All of them were from semi-rural areas, except one from a city. They were recruited from parents who showed interest during the course of the project.

Initially the children were asked if they want to participate in a study by trying the developed storytelling game. Their parents were informed about the purpose of the game and consented officially for them. After the test session all open questions by the children concerning the system, aim of research, etc. were explained in detail. In addition the children were rewarded with a personalized printed certificate stating how helpful they have been.

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