

BodyVis: A New Approach to Body Learning Through Wearable Sensing and Visualization

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ABSTRACT

Internal organs are hidden and untouchable, making it difficult for children to learn their size, position, and function. Traditionally, human anatomy (body form) and physiology (body function) are taught using techniques ranging from worksheets to three-dimensional models. We present a new approach called *BodyVis*, an e-textile shirt that combines biometric sensing and wearable visualizations to reveal otherwise invisible body parts and functions. We describe our 15-month iterative design process including lessons learned through the development of three prototypes using participatory design and two evaluations of the final prototype: a design probe interview with seven elementary school teachers and three single-session deployments in after-school programs. Our findings have implications for the growing area of wearables and tangibles for learning.

Author Keywords

Wearables; interactive body learning; physiological sensing

INTRODUCTION

Learning the position, structure, and function of internal body parts is challenging for children [29,30,35]. Unlike fingers, arms, toes, and other external parts, internal organs remain hidden beneath layers of skin, muscle, and tissue and operate without conscious thought, making it difficult for children—and even adults [3]—to understand the internal workings of their bodies. This body knowledge is important. For pre-school and primary school children, higher body literacy corresponds to greater compliance with health care regimens, better self-care practices, and increased self-understanding [30,33]. For example, young children with asthma are more likely to take inhaled medications if they understand how their lungs function [30]. Other researchers emphasize the critical role of anatomy and physiology in teaching and understanding basic science (e.g., biology) [11].

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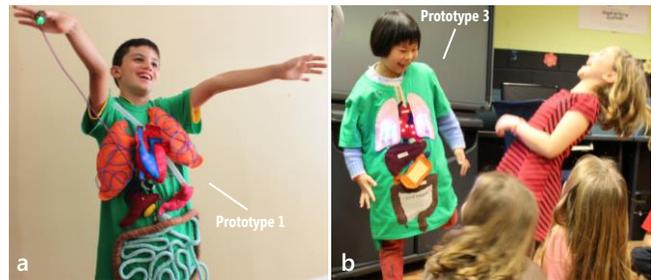


Figure 1: *BodyVis* is an interactive e-textile shirt for body learning that actively responds to the wearer's physiology and visualizes their body data on externalized anatomical models. Prototypes 1 and 3 shown above.

In pre-school and primary school education, human anatomy (body form) and physiology (body function) are traditionally taught using a mixture of techniques including 3D models and dolls, coloring and activity books, stories, audio-visuals, and video games [35]. With the advent of low-cost physiological sensing, ubiquitous computation, and electronic textiles (e-textiles), new approaches for body learning are now possible.

In this paper, we present *BodyVis*, a custom-designed wearable e-textile shirt that combines biometric sensing and interactive visualization to reveal otherwise invisible parts and functions of the human body (Figure 1). The wearer's physiological phenomena are visualized on externalized fabric anatomy, allowing the wearer and viewers to gain a unique view of the internal body. While past research has investigated wearables [22,23,24] and augmented reality [2,4,26] for body learning, *BodyVis* is the first exploration of a physical/digital manifestation that actively responds to the physiology of the wearer.

To investigate our approach, we iteratively designed and evaluated three *BodyVis* prototypes over a 15-month design cycle. While our long-term aim is to assess how a *BodyVis*-approach may impact learning, as an initial investigation, our research questions were exploratory: e.g., identifying key design considerations, exploring the understandability, aesthetics, and approachability of our prototypes, and examining how *BodyVis* engages children in body learning topics. Our design iterations were informed by two participatory design sessions with children, a MakerFaire exhibit, an early demonstration at a children and technology design conference (*IDC'13*) [27], and relevant prior work (e.g., importance of 3D models in learning [31], idea of bio-responsive e-textiles [21]).

The final prototype (Prototype 3) was evaluated in two ways: first, as a design probe in semi-structured interviews with seven elementary school teachers (Study 1); second, via three, single-session field deployments in local Boys and Girls clubs (Study 2). While the teacher interviews provide insight into how BodyVis may support classroom learning goals and new types of learning activities, the exploratory field deployments allowed us to assess children reactions to BodyVis (*e.g.*, engagement, playfulness, curiosity, social interactions, and general usability issues). Teachers were positive about BodyVis' ability to engage learners, to concretize otherwise abstract concepts, and to enable physical and collaborative learning although they expressed concerns about robustness, maintenance, and cost. Our Study 2 findings demonstrate BodyVis' potential to involve children in learning about their bodies, to engage them in self-inquiry and experimentation (*e.g.*, *What happens to my heart if I jump up and down?*), and to support social interactions and peer learning.

The contributions of this paper are: (i) the introduction of a new approach and system called BodyVis for body learning, which combines wearable biometric sensors and on-body visualization to provide new insights into anatomy and physiology; (ii) results from our iterative, participatory design process creating three BodyVis prototypes; (iii) findings from two evaluations: interviews with seven teachers and three field deployments at out-of-school programs; (iv) design reflections and directions for the emerging area of wearables and learning.

RELATED WORK

We discuss body literacy and current teaching strategies as well as previous research on sensor-based learning and tangible interactive computing.

Body Literacy and Teaching Strategies

As noted in the introduction, body learning is challenging. By age four most children have a well-defined understanding of their external body and the relationships between body parts; however, their conception of the inner-body is comparatively weaker [35]. Children between the ages of four and eight can recall approximately three to six internal body parts, most commonly the brain, heart, and bones [*ibid*]. However, children often misconceive their size, shape, position, and function. For example, the heart is typically drawn as a playing card "valentine" heart (*e.g.*, [8,12]) and the stomach is considered a respiratory mechanism because it moves in and out with breath (*e.g.*, [13]). In addition, few children have a clear idea of how food passes through their body and how waste is eliminated [28]. Although these conceptions improve with age [30], some misconceptions can persist into adulthood [3].

Most researchers emphasize that because internal organs are not accessible, they are difficult for children to understand, observe, and experiment with in daily life (*e.g.*, [29]). Although few experimental studies have compared teaching methods for children's body knowledge, a few

studies point to the benefits of using three-dimensional teaching aids [31,35,36]. Findings suggest that teaching artifacts should be engaging (*e.g.*, comprised of bright colors and different textures), realistic but approachable (not "scary"), and interactive. For example, Schmidt [31] discovered that children learn more from interactive lungs than their stationary counterparts. These results point to the benefits of an interactive tangible approach.

Sensor-Based Learning

Originally termed "microcomputer-based laboratories" and then later "probeware," sensor-based learning emerged in the 1980s to help children explore, experiment with, analyze, and visualize measured phenomena in the physical sciences (*e.g.*, sound [32], electricity [41], motion [5]). Researchers suggest that it is the tight coupling between an activity and the computer-mediated feedback that accounts for improvements in understanding [5].

Despite its long history, as Lee and Thomas note [24], there has been surprisingly little consideration of physiological and on-body sensors applied to learning contexts. The work that does exist (*e.g.*, [22,23,24]) explores off-the-shelf tracker tools rather than custom innovations (as we do here). Though on-body sensors have long been used in the health and medical sciences (*e.g.*, [9]) as well as human-computer interaction (*e.g.*, [7]), their potential to help children learn about their bodies remains largely unexplored. BodyVis represents a new generation of probeware where the "material" being measured is the human body and the visual representations are responsive, tangible, wearable models.

Tangible and Wearable Interfaces for Learning

Our work also relates to tangible interfaces [34]. Though conceptual and theoretical understandings of tangibles to support learning are still being developed [1,25], researchers suggest that tangibles: offer a natural and immediate form of interaction that is accessible to learners, promote active and hands-on engagement, allow for exploration, expression, discovery, play, and reflection, allow learning of abstract or complex concepts through concrete representations, and offer opportunities for collocated collaborative activity (as summarized by Antle and Wise [1]). In the domain of human anatomy, we could not find prior work in the tangible interactive space. However, augmented reality systems have been developed to allow users to "peer inside" a human body [2,4,26], for example, using a large-screen display [4,26]; however, these systems are aimed at medical students (not children), and the anatomical representations do not react to the sensed physiology of the user and are not tangible.

Finally, the way information is *represented* is a critical aspect of tangible interface design. In the science domain, such as molecular biology or astronomy, designers often represent microscopic or macroscopic forms as semi-realistic models imbued with computational behaviors; the computation is used to provide dynamism and augmented

information (e.g., [10,14]). Our work is similar in that we attempt to concretize the invisible structures and functions of the internal body by coupling tangible physical models (structure) with embodied digital forms (function). The abstraction of the look, function, and feel of an organ in our tangible representations and its effect on learning is an open research question, though we begin exploring it here.

DESIGN PROCESS AND GOALS

We pursued an iterative, human-centered design approach over 15 months. To help engage with and better understand children’s perspective with our designs, we employed a participatory design method called *Cooperative Inquiry* (CI) [15]. Here, seven children (ages 7-11; four girls) and four adults (2 from research team) worked together at key points in the design process to co-design BodyVis features and to provide feedback on our prototypes. We conducted three CI sessions in total but report only on the first two due to space limitations (the third session focused on the future of BodyVis post-Prototype 3). All children had at least three months of general co-design experience. We also received feedback on Prototype 1 from the IDC community [27] and informal feedback from parents, teachers, and children at a MakerFaire exhibit midway through our design process. Our more formal qualitative studies with teachers and children were conducted after the development of Prototype 3 and are presented after the design section.

Design Goals. Before describing the three prototypes and lessons learned, we present seven high-level design goals in Table 1, which focus on user experience (e.g., playful, multi-sensory, responsive), hardware and materiality (e.g., lightweight and robust), and learning attributes (e.g., personal relevance, support for peer learning). These goals were informed by related work, outcomes from the initial CI session, and our experience building the first prototype.

Anatomical Overview. Though our prototypes differ in how they sense the wearer’s physiology and in anatomical representations, there are commonalities. Using a t-shirt as the visual medium, all three prototypes include the *thoracic region* above the diaphragm and the *abdominal region* below it (Figure 2). For the thoracic cavity, we include the



Figure 2: Design evolution of the three prototypes.

lungs, heart, and esophagus. The abdominal cavity includes most of the digestive organs including the esophagus, stomach, liver, gallbladder, pancreas, small intestine, and large intestine. Currently, none of our prototypes depict reproductive organs, the thymus gland, trachea, human waste orifices, or the interactions between organ systems. We return to the tension between abstractions and scientifically accurate representations in the Discussion.

ITERATIVE DESIGN OF THREE BODYVIS PROTOTYPES

We present our three BodyVis prototypes (Figure 2) along with lessons learned throughout the design process.

CI Session 1: Initial Ideation

In the initial ideation phase, we conducted a CI session to explore potential design options and gain insight into how children understand their bodies. The CI group used a low-tech prototyping technique, called *Bags of Stuff* [15], to create interactive t-shirts that represented their anatomy. Our bags consisted of art and textile supplies including markers, yarn, felt, and pom-poms. Children and adult design partners were split into groups and given 40 minutes to design interactive anatomical shirts. Afterward, all groups gathered to share and present their designs to the team. Following the *Big Ideas* CI approach [15], an adult design partner recorded group ideas on a whiteboard, and discussed surprising and related ideas with the team. Thus, ideas were analyzed and categorized *in situ*.

CI Outcomes. Though each group created unique designs, a set of overarching themes emerged around the use of color, sound, lights, and movement (Figure 3). Color was used to distinguish organs (e.g., red for veins and heart). For sound, children used audio to increase the playfulness and reactivity of their shirts: e.g., breakable ribs and spines with “cracking” sound effects, “talking” organs, and using the spine as a musical instrument. Lights mainly indicated an action such as a pumping heart, hunger, or blood moving through veins. Finally, the most popular design theme was illustrating movement within the human body: food traveling through the digestive system and dissolving in the stomach, physically pumping hearts, and “breathing” lungs. In summary, while the design ideas ranged in feasibility, there was a clear emphasis on dynamics, interactivity, and reactivity to the human form and function.

BodyVis Design Goals	
Incorporate multiple senses: use touch, sound, vibration, visuals	Promote active, playful, and hands-on movement-based engagement that is situated in the physical world
Link action to representation: provide immediate feedback to bodily actions in the physical world	Personal relevance: to help provoke curiosity and engagement, data should be personalized either to the individual learner and their body or their peers/classmates
Multiple timescales: representations should convey that organ systems work at different timescales (e.g., the circulatory system vs. digestive)	Collaborative learning: allow learners to compare their physiology to others & collectively engage in self-inquiry (e.g., to provoke questions such as “ <i>how are our bodies the same or different?</i> ”
Robust & lightweight: the shirt should allow for and be robust to movement, encouraging the wearer to self-experiment and move about the world	

Table 1: Our seven BodyVis design goals.



Figure 3: To help design BodyVis, we conducted two participatory design sessions with children ages 7-11. Above: the results of our first session where children co-designed interactive anatomy t-shirts.

Prototype 1: Plush, Colorful, interactive

Informed by our first CI session as well as prior work (*e.g.*, [21,33,35]), we designed and implemented our first prototype (Figures 1a, 3, and 4). Organs were created using two pieces of fabric, cut into anatomically correct shapes, sewn together, and filled with pillow stuffing. This approach resulted in a plush, tangible aesthetic designed to attract a child’s attention and touch. We attempted to correctly shape and position each organ on the shirt; however, to avoid occlusion, some organs were slightly modified (*e.g.*, the stomach, liver, gallbladder, and pancreas were spread out, some organs were disproportional).

We selected a green t-shirt as the base, and bright and colorful fabrics to make each organ salient. Although our palette is not anatomically correct, the intention was to use distinctive colors that may help children remember the functionality and purpose of each individual organ. For example, one team in the CI session had a brown-colored large intestine in their design, as it represented the final stage of the digestive system, “where the poop comes out.”

Heart and Lungs

The heart is made of red and blue fabric embedded with flashing red/blue LEDs, which represent blood entering and leaving the heart (Figure 3). The LEDs are connected to a pulse sensor (pulsesensor.com) controlled by an Arduino Uno, which uses infrared to detect the wearer’s heart rate. Through experimentation, we found that the pulse sensor functioned best when attached to the finger (visible in Figure 1a). For the lungs, we used orange fabric with red and blue electroluminescent (EL) wire to represent veins. As veins, the EL wire animated blood moving through the lungs. Prototype 1 did not contain a respiratory sensor, so the wearer’s breathing rate was not visualized.

Digestive System

The digestive system consists of the esophagus, stomach, liver, gallbladder, pancreas, small intestine, and large intestine. Though we had originally planned to infer eating automatically using a microphone-based machine-learning approach (*e.g.*, [39]), our early attempts were unsuccessful. Thus, the digestive system was made solely of low-tech materials and was not dynamically responsive to the wearer. The esophagus was created from the grooved portion of a suction pump, chosen because of its visual similarity to the human esophagus, which uses surrounding muscles to pinch inward and send food to the stomach. Connected organs are sewn together (*e.g.*, the esophagus is visibly attached to the beginning of the stomach). In our CI



Figure 4: The design of Prototype 1 including (a-b) the heart and lung blood flow animations, and (c-d) playing with the shirt; the latter image highlights how children can explore their intestinal length via Velcro.

session, one team used strings of yarn to represent the extent of their small intestines. We designed our small intestine to detach and unravel from the shirt allowing children to fully investigate its surprising length (*e.g.*, 450cm or 14.7 feet in five year olds [37]). See Figure 3d.

Evaluating Prototype 1

Prototype 1 was informally evaluated via design critiques with lab colleagues, a MakerFaire exhibit (Figure 5), feedback from our IDC demo [27], and informal demos with our CI group. Though parents, teachers, and children were excited by many aspects of our design—*e.g.*, at MakerFaire, a number of teachers and after-school coordinators gave us their contact information to volunteer for future tests—our evaluations uncovered a number of issues related to comfort, robustness, and understandability.

Lessons Learned. While attractive, the animated EL wire over the lungs was hard to see in normal room lighting and was often misinterpreted as representing *breathing* rather than blood flow. Second, though the plush, stuffed organs seemed to attract touch (*e.g.*, Figure 5a), they were heavy and encumbered movement. Third, our pulse sensor did not work reliably across wearers, occasionally failing to detect pulse altogether. Fourth, we were concerned with positional compromises made to reduce overlap between organs; teachers and MakerFaire attendees also expressed this concern. Finally, though we received positive feedback about the combination of automatic physiological sensing and on-body visualization, this feature was quite limited in Prototype 1—supporting only the heart.

Prototype 2: A New Lightweight design

Based on the above experiences, we began designing our second prototype (Figure 2b), focusing on improving the anatomical representations and reducing the weight/bulk of the shirt. Our primary concerns were on visual design, wearer comfort, and new animation approaches rather than physiological sensing. Consequently, Prototype 2 did not incorporate any physiological sensors; animations were simulated with artificial data. In contrast to Prototype 1, the anatomy was made with streamlined, flat (unstuffed) fabric organs cutout from anatomy templates. This new approach dramatically reduced weight and improved organ shape, size, proportionality, and placement (*i.e.*, organs could now appropriately overlap). We embedded a mix of LilyPad and Neopixel RGB LEDs into the heart and lungs, which were connected via conductive thread to a sewn-in Arduino



Figure 5: We demonstrated Prototype 1 and an early version of Prototype 2 at a MakerFaire exhibit. Though shirts were not worn by children, we observed interactions and elicited feedback from parents and teachers.

LilyPad. Unlike before, the lung visualizations were designed to represent *breathing*—the LEDs were intended to fill up and glow during inhalation and empty/fade during exhalation. Similar to Prototype 1, the digestive system was made solely of low-tech materials and did not animate or respond to user actions. To make the shirt easier to take on/off, we cut the back open and added snaps.

CI Session 2: Feedback Elicitation and Next Steps

For our second CI session (Figure 6), we had two primary goals: first, to get feedback on Prototypes 1 and 2 and, second, to conduct a co-design activity about how our shirts could be improved. For the first goal, two research assistants demonstrated the prototypes and elicited feedback. As Prototype 2 did not contain physiological sensors, the heart and lungs animated based on a fixed pulse and breathing rate. For the second goal, the co-design team was broken up into groups and was instructed to help design “the next generation of our shirt” using low-fidelity materials. After the design session, all groups rejoined to share their ideas and low-fidelity mockups with the team.

CI Outcomes. For the feedback elicitation, two co-design teams rotated through demonstrations of Prototype 1 and 2. At the Prototype 1 station, we observed physical activity, experimentation, and laughter. Each child wanted to try the pulse sensor and move around (*e.g.*, jump). Children not wearing the sensor would jump alongside. A few asked how the shirt worked. One child grabbed the small intestine and started unraveling it. For Prototype 2, there was less activity—probably because of the lack of sensing functionality; however, children still showed interest in the animations, the organs, and how the shirt was made. For the design activity, three of the four teams emphasized eating/digestion (Figure 6). One team, for example, thought of showing the small intestine as a “*gummy bear roller coaster*” and another designed a method of viewing food being processed and converted into waste. Others suggested updating the lungs so that they could physically inflate/deflate with breathing and help reveal differences between big and small breaths (similar to Schmidt’s puppets for asthma education [31]). Teams again added sound such as “heart pumping” and “stomach grumbling.”

Prototype 3: The current design

From these results, we designed and built our current prototype (Figure 2c), which is visually similar to Prototype 2 but differs in the following key ways:

Dynamically Removable Organs. While Prototype 2 had a more realistic portrayal of organs compared with Prototype

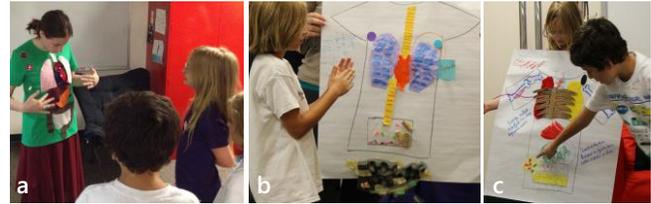


Figure 6: CI Session 2 included a (a) demonstration of Prototype 1 and 2 (2 shown) and (b-c) low-fidelity prototyping to design new shirt features.

1, overlapping organs caused occlusion problems. With Prototype 3, we designed a removable organ system using conductive magnets. The heart, lungs, liver, and a portion of the stomach can be removed and reattached dynamically by the wearer or his/her peers to examine different layers of the body (Figure 7). When detached, the organ stops “working” (animating) but automatically restarts when reattached. To help with reattachment, the shirt contains organ outlines and color-coded highlighting around each connection point. Each organ is also tagged with iron-on ink labels, which help with identification and learning.

Physiological Sensing. To expand BodyVis’ physiological sensing capabilities, we added the *Zephyr Bioharness 3* [40], which is a robust body-sensing platform traditionally used in sports training and the military. Multiple independent studies have demonstrated the BioHarness’ validity and reliability for measuring heart and respiratory rates [16,19]. Using a chest-worn strap, the Bioharness provides both physiological measures (*e.g.*, heartrate, breathing rate) as well as activity measures (*e.g.*, running, standing, walking). Currently, the strap is not directly sewn into the shirt and is put on independently. This decoupling between wearable sensor and visualization allowed for some unexpected explorations (as described in Study 2).

Touchscreen Stomach. For the stomach, we modified a small Android smartphone (Galaxy S3 Mini), which serves not only as the central processing unit for the shirt but also provides a flexible, programmable device for playing with sound, haptics, and visual output. The back panel and battery were removed from the device to decrease weight (from 113g to 82g). The phone’s power connectors were rewired to a battery pouch on the side of the shirt, which also contained an Arduino.

Eating/Digestion. We added a button called “snack time” near the neckline to trigger digestion animations. Once pushed, food (bolus) travels down the esophagus via animated Neopixel LEDs and into the stomach, which plays an animated video of chemical secretion, muscular contractions, and food breakdown. After 18 seconds, LED-based animations continue highlighting relevant organs (*e.g.*, the liver, pancreas, and gallbladder) and showing the continued movement of food (now chyme) from the small to the large intestine. At the end of digestion, a playful flatulence sound is emitted from the smartphone. Though digestion from mouth-to-anus in children takes ~30 hours [38], BodyVis portrays it in ~35 seconds. We return to representing the body’s timescales in the Discussion.

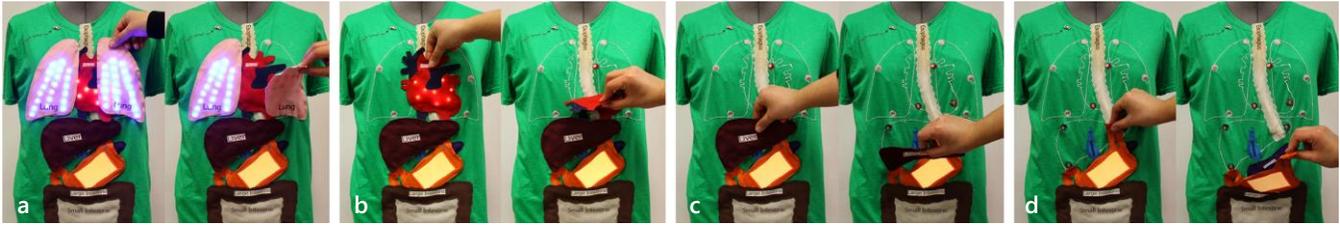


Figure 7: Using a conductive magnet approach, Prototype 3 allows for the dynamic removal and reattachment of the (a) lungs, (b) heart, (c) liver, and (d) part of the stomach, enabling learners to explore the multiple organ layers of the human body. See supplementary video for more details.

Prototype 3 System Architecture

Prototype 3 is comprised of four main technological components, which communicate over Bluetooth: (i) a Bioharness 3 that senses and transmits the wearer's biometric data to an Android smartphone (stomach); (ii) a custom BodyVis Android application that processes and wirelessly transmits the wearer's heart and breathing rate to a built-in Arduino; (iii) an Arduino that controls the LED-based animations; (iv) the "snack time" button that is hard-wired to the embedded Arduino. When pressed, digestion begins and the Arduino wirelessly communicates with the smartphone to trigger the stomach animation.

STUDY 1: TEACHER INTERVIEWS

To gain a better understanding of existing teaching methods, and to elicit feedback about BodyVis from trained educators, we conducted semi-structured interviews with seven elementary school teachers who teach anatomy. Our second study, described later, investigates children's responses and interactions with BodyVis.

Method

We recruited seven teachers (one male) through email lists, word-of-mouth, and contacts gained at MakerFaire. The participants taught science and health at elementary schools spanning 1st to 4th grade, and had a range of teaching experience from two to thirteen years. Three participants taught in the public school system; four in private school. Teacher interviews were broken into two parts: (i) a formative inquiry of teaching approaches for body learning, common body misconceptions in children, and learning challenges; and a (ii) a BodyVis design probe, where we solicited feedback to Prototypes 1 and 3. We allowed the teacher to interact with each prototype, and asked semi-structured questions including first impressions, uses in the classroom, and desired features. We also asked participants to envision scenarios with more than one BodyVis shirt.

Data and Analysis

On average, the interviews lasted 53 minutes ($SD=15$). Each interview was audio recorded and professionally transcribed. For the analysis, we pursued an iterative coding scheme with a mix of both deductive and inductive codes [6,18]. Our unit of analysis was a full response to a question. An initial codebook was derived based on topics in the body learning literature, our research questions, and our study protocol. A random transcript was then selected and coded by a single researcher. While coding, the codebook was updated to accommodate emergent themes and to clarify code descriptions. We had 16 codes in total, including learning potential, engagement, concerns (*e.g.*,

cost, distraction, privacy, robustness), learning activities, and design (*e.g.*, visual design, organ representations).

To establish inter-rater reliability (IRR), a second researcher used the codebook to independently code the same interview and the resulting codes were compared using Krippendorff's alpha (*average* $\alpha=0.77$; $SD=0.2$; *total disagreements*=22 out of 420 decisions). Krippendorff [20] suggests that scores of $\alpha < 0.667$ should be discarded or recoded. In our case, 6 of the 16 codes were < 0.667 . The two researchers met, resolved all 22 disagreements, and updated the codebook accordingly. Both researchers then independently coded a second random interview, establishing IRR ($\alpha=0.88$, $SD=0.19$). Finally, the first researcher coded the remaining five interviews.

Findings

We present frequent patterns and emergent themes.

Part One: Existing Teaching Practices

To inform their body learning curriculum, teachers used national science standards, district requirements (for the four public school teachers), and previous teaching materials at the school. Materials included a combination of books, videos, interactive software, smartboards, transparencies, museum field trips, and 3D models (*e.g.*, *Little Organ Annie*). To enhance learning and engagement, three teachers also incorporated physical activities—*e.g.*, T3 and T6 had children role-play as red and white blood cells in a magnified heart. T7 emphasized the importance of physicality in body learning: "I want them to use their bodies [to learn]... if we're talking about muscles, you want them to feel their muscles." Similarly, T5 noted that she did not use worksheets or books for body learning and relied exclusively on hands-on activities.

When asked about learning challenges, our findings were consistent with prior work (*e.g.*, [8,17,30]). Children struggled to understand that their bodies are comprised of smaller parts (organs, bones), how these organs operate, interact, and provide benefits to the body, how food is processed, and the location of certain organs (*e.g.*, T7 found that students could often find their hearts but not stomachs).

Part Two: BodyVis Design Probe

For the design probe, teachers generally reacted positively to BodyVis. Below, we organize our findings into four areas: learning potential, proposed learning activities, teacher concerns, and suggested improvements.

Learning Potential. All teachers were positive about BodyVis' potential as a body learning tool. Common

reasons included: its ability to engage children (6 teachers) and concretize otherwise invisible and/or abstract concepts (5), and the way the shirt responded to the wearer's body (4). BodyVis' use of on-body visualization to show the wearers' changing physiology, and its use of color, lights, and animations were identified as key to learner engagement. T3 described BodyVis as similar to a real life video game, and T2 emphasized the role of engagement:

"...the biggest thing is getting [the students] interested in [body learning]. And I think something like this would definitely get them interested and motivated to learn more about [their bodies]." (T2)

With regard to the concretization of abstract concepts, T2 provided a representative quote:

"I teach the age of students [3rd grade] that's very hard for them to think in the abstract. And the inside of your body is pretty abstract unless you can really see it and this is a great way for them to be able to really see it." (T2)

Similarly, T6 focused on how the animations overlaid on the wearer's externalized anatomy helped make invisible bodily actions more clear: "you can really see the pathway that food's taking, that air's taking, and their pulse." As with prior sensor-based learning approaches (e.g., [5]), the coupling between *action* and *feedback* was highlighted as a primary benefit. For example, T6 stated: "The biosensor again, that link with what's actually happening in one's own body is really fantastic." T5 also emphasized how the visualizations responded to one's own physiology:

"...[a book] describes it, the process, the steps, and then you watch a video but with this, you could actually connect to your body and see what happens in your body." (T5)

Finally, two teachers mentioned learning opportunities for STEM topics beyond body learning. T4 suggested math activities for measuring intestines and investigating pulse. T6 suggested providing a BodyVis API so students could add sensors and program new behaviors.

BodyVis Learning Activities. When asked to design learning activities for BodyVis, three strategies emerged: physical, movement-based activities (6); peer collaboration and comparison activities (5); and as a low-tech anatomical model (4). For physical activities, teachers stressed how students could explore their bodies responding to different actions (e.g., running vs. sitting) and contexts (e.g., going outside, to the cafeteria). Five of these teachers mentioned opportunities for collaborative learning as children could observe differences and similarities between their peers. Four teachers suggested using BodyVis as a static model. Here, students would identify and learn about organs before actually wearing the shirts.

Concerns and Suggested Improvements. We identified four primary concerns: robustness and maintenance (4), cost (3), potential to distract (3), and misrepresentation of organs (3). For robustness and maintenance, teachers stated concerns both for the technology and the material. For example, T1 said: "[if] one of the sensors stops working, how can we replace [it]." T2 worried "about pieces getting lost or torn." In terms of cost, T3 suggested there is a "real

market for [BodyVis]," but thought that poorer schools may struggle to afford multiple shirts; others worried about the maintenance costs. Teachers also related previous struggles with technology in the classroom. T2 found that technology can be both a "positive" and a "negative," and T6 suggested that for some students BodyVis could be "too distracting" especially "if they're used to worksheets." While teachers understood the role of simplification in focusing students' attention, three expressed concerns with our representations: e.g., T7 observed that neither prototype included a trachea, and T5 questioned the gallbladder's location with respect to the liver.

In terms of improvements, suggestions included adding: details to existing organs (3), greater controls for teachers (3), stronger links between organs and organs systems (2), and more multi-sensory feedback (2). For example, T6 wanted the lungs to show the "dispersion of gases into the alveoli" and suggested that we "show how different foods result in different things happening to your body" (e.g., high-sugar foods, caffeine). T4 suggested adding buttons on each organ, which would trigger audio explanations and T5 asked if each organ could play a movie like the stomach.

Summary of Study 1 Findings

Our Study 1 findings further motivate the need for interactive, physical, movement-based body learning tools and the potential benefits of BodyVis (e.g., increased learner engagement, concretization). Teacher concerns and suggested improvements will help direct future work.

STUDY 2: DESIGN DEPLOYMENTS

Three single-session field deployments were conducted in local after-school programs to explore children's reactions and interactions with BodyVis. These sessions were exploratory, aimed at uncovering how children approach, understand, and react to BodyVis (e.g., the questions it provokes, the social interactions that occur). See Figure 8.

Method

We recruited three after-school programs through mailing lists, word-of-mouth, and contacts acquired at MakerFaire. A total of 30 children (18 female, 12 male) aged 6-12 participated in the study. A team of two to three researchers worked with on-site staff to coordinate the sessions, which took place in large rooms with approximately 10 children per location. The study procedure included: introductions and a pre-study body knowledge questionnaire on anatomy and physiology (15 min); a 10-minute overview of BodyVis; a 30 minute interactive trial where three to four child volunteers tried on BodyVis and engaged in a small number of physical tasks; and a post-study questionnaire (15 min). Children also engaged in 15-minutes of free play with BodyVis at the end of each session. After each session, a 20-minute debrief occurred amongst the research staff and a summary of reflections and observations was composed. Parental consent and children's verbal assent were acquired, including permission to take photos and record audio/video, prior to the study.



Figure 8: In Study 2, we deployed BodyVis in three after-school programs. (a) Wearers engaged in various physical activities to see how their bodies would respond and (b) touched/removed their own organs. (c-d) Wearers and non-wearers interacted together; non-wearers suggested actions, conducted activities simultaneous with wearers, and touched/asked questions about the shirt and body functions. Unexpectedly, (e) children removed BodyVis organs and placed them on their own bodies, (f) investigated BodyVis even when it was placed on a mannequin, and (g) inquired about how the shirt works.

Data and Analysis

The sessions were audio and video recorded; however, only audio was available from the third site due to technical difficulties with the video camera. We began data analysis by reviewing session video, audio, notes, and summaries; this review was used to develop an initial codebook. Using audio and video data, one researcher coded for physical actions (e.g., gestures, interactions with the shirt, movements), emotional responses (e.g., volume of room, facial expressions), utterances (e.g., spoken questions and observations about the shirt, anatomy, and physiology), and design preferences (e.g., likes, dislikes, and design ideas). A second codebook was derived using open-coding to analyze children’s spoken questions. Two researchers coded this data (average $\alpha=0.85$; $SD=0.13$).

Findings

We focus on common reactions and patterns of behavior that occurred across the three deployment sites.

Overall Reactions. Generally, children reacted positively to our prototype. As intended, the shirt elicited questions and observations about the body: “Does the liver keep your water?”, “His heart is getting faster and faster!”, “Is that what’s happening inside me?”, and “We’re looking inside his stomach!” It also promoted body movement and inquiry (“I wonder what would happen if...”) and engaged children in thinking about, discussing, and playing with their bodies. Wearers appeared to experience a strong connection between the shirt visualizations and their own bodies. One child, for example, pressed the snack time button after each bite of his apple. Some vocalized disgust at first (“ewww”) and older children (e.g., 10-12 years) seemed less interested; however, this changed after interactions began. A few found the BioHarness uncomfortable (“it’s itchy”).

Wearers and Non-Wearers. Though we were initially concerned with deploying a single prototype for groups of 8-12 children, wearers and non-wearers worked together to explore, play, and interact with BodyVis. While most children volunteered to wear the shirt, we could only accommodate four per site due to time constraints. However, non-wearers remained engaged throughout. They would shout out activities to the wearer (e.g., jumping jacks, push-ups, “run around us like duck-duck-goose”), remark on physiological changes (e.g., “[his lungs] are going faster” and “His heart is beating really slow”),

remove and reattach BodyVis organs, and press the “snack time” button. Because wearers could not always see the shirt, non-wearers would inform them about changes and also help them reattach organs in the proper place (e.g., “follow the color, the outlines, the magnets”). Children would also discuss and answer each other’s questions. For example, one participant asked, “What are those yellow things [in the stomach]?” Another answered: “acid.”

Removing/Reattaching Organs. The ability to remove and reattach organs allowed children to explore the layered nature of their bodies (e.g., “What’s under the heart?”) and also resulted in unexpected inquiry and play. For example, when a wearer removed his lung, a child asked, “How’s he going to breathe?” Another joked: “You’re dead now!” In one session, a wearer decided to role-play as a doctor and performed surgery on herself. Children also experimented with removing organs and reattaching them in the wrong place. One non-wearer positioned the liver as the right lung but found that the lights did not turn on. She said “that’s not right!” and put the liver back in its correct position.

Common Questions/Observations. BodyVis elicited a wide range of observations and questions. Children made observations on changing physiology, the state of the wearer’s body, and inferences about how the shirt works (e.g., “Oh, these are magnets”). Children questioned the role of certain organs, the effect of actions on the body, and how the shirt was made and how it functions. More specifically, for the body-related questions, children asked “what happens if” inquiries (e.g., “What happens if [the heart] stops beating?”), verification questions (“Is that what’s happening inside me?”), questions about organs and their functions (e.g., “what the heck is that?” while pointing to the pancreas) and questions about the shirt’s abilities “What if I put that on, and I’m drinking this [water], would it detect where it’s going?” Though our Study 1 teachers thought that their students would be curious about the shirts’ construction and operation, we were surprised with how common these questions were in our deployments. At each session, children also asked to look inside the shirt to see its wiring and microcontroller (Figure 8g).

Disembodied BodyVis. At the end of each session BodyVis was placed on a mannequin (Figure 8f). Children would approach the mannequin and touch, play with, and explore BodyVis. At the end of one session, a non-wearer

asked to wear the BioHarness. With BodyVis still on the mannequin, she performed a number of physical actions to see what would happen. Other children joined her and mimicked her behavior. So, while the coupling between sensing and visualization seems important—*i.e.*, visualizing one’s changing physiology in real-time on the body—there may be interesting opportunities for visual manifestations that are physically disconnected from the sensed body (*e.g.*, a mixed reality approach where the wearer’s physiology is overlaid on a virtual avatar).

Pre- and Post- Questionnaires. Though our primary intent was not to assess learning, we did examine children’s pre- and post-body knowledge using body map drawings, a common assessment approach (*e.g.*, [8,11,12,35]). We analyzed organ layering, shape, position, and the addition of organs. Of the 30 participants, 22 drew at least one new organ in their post-study body maps, 17 corrected positions, 12 properly adjusted organ layers, and 10 improved organ shapes. However, 16 participants had at least one shape that was incorrect on their pre-study drawing and it remained incorrect post-study, 3 added an organ but in the wrong position, and 3 had removed organs that were correct originally. Some children remained confused about heart and lung function. Without a more rigorous evaluation (*e.g.*, with control conditions), we cannot make strong claims about these results; however, BodyVis does appear to have a positive influence on body knowledge.

DISCUSSION

As the first work exploring the combination of on-body sensing with wearable e-textile visualizations for body learning, we were encouraged by both teacher and children reactions. Below, we reflect on our study methods and findings and describe limitations and future work.

Representing the Body. Science education has diverse representational forms that abstract reality to simplify concepts and capture learner interest (*e.g.*, atomic models). Throughout the BodyVis design process we explored different ways of representing the body, not all of which were successful (*e.g.*, the heavy plush organs, EL wire for lung veins). More work is needed to understand tradeoffs between guiding a child’s attention, simplifying concepts, and allowing for the accurate construction of knowledge. One design goal that we did not fully explore was combining haptics with visualization (*e.g.*, vibration for stomach rumbling, heartbeat); this may improve the wearer’s connection to the shirt and increase engagement. Additionally, we did not address portraying the body’s different timescales (*e.g.*, pulse *vs.* digestion). We have discussed including a “fast forward” button on the touchscreen stomach to provide additional context (*e.g.*, to describe digestion length). Surprisingly, one teacher thought of these abstractions as learning opportunities:

“Because this one shows it to you in under a minute, I would have [the students] compare and contrast to it and research the actual time it takes for the food to travel [through you].” (T4)

This emphasizes the important interconnections between technology innovations and the design of learning activities.

Learning Potential. As initial research, our focus was on qualitatively assessing BodyVis rather than conducting controlled pedagogical studies. Still, our findings suggest that BodyVis has the potential to support learning and body inquiry. Teachers emphasized its ability to engage learners, concretize abstract concepts, and enable new types of learning activities. With Study 2, we observed behavior that our teachers predicted: children were active, curious, and engaged in inquiry—both about their bodies and the construction of the shirt. Still, more work is needed to examine how BodyVis affects learning. We have begun collaborating with an educational researcher with a focus on understanding how BodyVis can be used and evaluated in both formal and informal learning contexts.

Privacy and Discomfort. BodyVis is designed to facilitate social interaction and collaborative inquiry among children. As found in Study 2, non-wearers and wearers worked together to explore their bodies. These interactions included touching and comments about the body, which may make a child feel uncomfortable. This tension is one reason we pursued an iterative, participatory design approach. While these concerns did not emerge in either study, this is a critical design issue that will require continued awareness.

Cooperative Inquiry. It may seem dichotomous to work with children as co-designers on a subject in which the literature suggests they are not experts; however, their role was not to design scientifically accurate body representations but rather to help us gain a better understanding of a child’s perspectives, ideas, and desires. The designs generated underscored the importance of multi-modal feedback (*e.g.*, sound, visuals), of bright distinctive colors, and of low-fi and high-fi interactivity (*e.g.*, the unraveling intestine in Prototype 1). In addition, CI includes an intergenerational mix of design partners, so adults could assist children who encountered foreign concepts.

Limitations and Future Work

We deployed BodyVis in a constrained fashion: single-session studies that were researcher facilitated. This study design is susceptible to novelty effects as well as biases that result from the designers conducting the deployments. For the teacher interviews, we had a small number of participants and the focus was on initial reactions rather than views developed from actual use. Still, the combination of methods used—iterative design, the MakerFaire exhibit, interviews, and deployments—help mitigate the effects of any one technique. Our primary future work includes: (i) improving and extending BodyVis representations; (ii) developing new physiological sensors; (iii) expanding to other parts of the body. Other long-term goals include allowing learners to investigate their bodies more broadly, exploring body systems in everyday contexts (*e.g.*, soccer matches), and making BodyVis “hackable”—allowing children to customize their BodyVis shirts.

CONCLUSION

This paper contributes new knowledge to the field of wearables and tangibles for learning. The BodyVis system demonstrated a potential to help children understand their anatomy and physiology. Our findings show that this wearable tool engages children and that teachers believe it could be an educational aid. Our vision is to transform how learners engage with and understand body concepts and to identify how wearables can be designed to support scientific inquiry and life-relevant learning more generally.

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