ABSTRACT

Title of Document:	BODYVIS: BODY LEARNING THROUGH WEARABLE SENSING AND VISUALIZATION
	Leyla Norooz, Master of Science, 2014
Directed By:	Dr. Jon Froehlich, Assistant Professor, Department of Computer Science, College of Information Studies

Unlike external body parts, organs are invisible and untouchable, making it difficult for children to learn their size, position, and function. With the advent of low-cost sensing, ubiquitous computation, and emerging e-textiles, new teaching approaches are developing that link the physical and virtual worlds. In this thesis, I report on the design and evaluation of several wearable e-textile prototypes —called BodyVis—that combine embedded sensing and interactive visualization to reveal otherwise “invisible” parts and functions of the human body. Key findings from an open-ended cooperative inquiry design session with children were used as guidelines in developing the first prototype. Versions of the second prototype were developed before and after a second cooperative inquiry design session. The final prototype was then evaluated through three design evaluation sessions. Three examples of use demonstrate the potential of BodyVis to engage, excite, and pique children’s curiosity in learning about the human body.

BODYVIS: BODY LEARNING THROUGH WEARABLE SENSING AND VISUALIZATION

By

Leyla Norooz

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Advisory Committee:
Dr. Jon Froehlich, Chair
Dr. Allison Druin
Dr. Tamara Clegg

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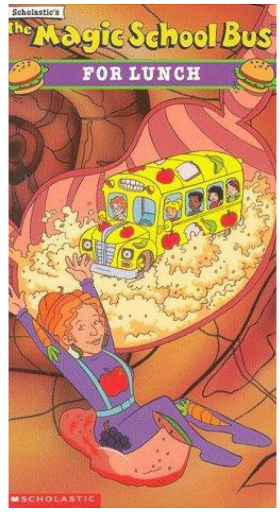


Figure 1: The Magic School Bus episode titled *For Lunch*.

My first memory of body learning in school was in the third grade when my teacher showed the class an episode of "The Magic School Bus" titled *For Lunch* (Figure 1). In this episode, Miss Frizzle takes her students on a wild adventure inside the human body where they get to experience the digestive system first hand. My jealousy blossomed as I, too, yearned to join this exciting class and get a first-hand look at the human body. Years later, I find myself still fascinated by the phenomenon that is the human body. Following a graduate course I took last year in *Tangible Interactive Computing* I became somewhat obsessed with the research behind wearable technology and e-textiles. Consequently, I began to wonder:

- What if we could build clothes that reveal the inner-workings of the human body?
- How could this change the way children understand and learn about their bodies and its connection to the physical world (e.g., eating, exercise)?
- How might children become engaged in body learning through wearable technology?
- Could we promote children's engagement in learning about their bodies through wearables, e-textiles, tangible interactions, and play?

Figure 2: The most current version of BodyVis (Prototype 2.1)

In this thesis, I report on the design, development, and evaluation of several wearable e-textile prototypes —called BodyVis—that combine embedded sensing and interactive visualization to reveal otherwise “invisible” parts and functions of the human body (Figure 2). As the BodyVis wearer engages in an activity, physiological phenomena are displayed on the wearable visualization in real-time, giving the wearer and the surrounding learners a real-time glimpse into the functioning of his/her own body. The wearer can remove his/her organs to explore their layering and later reattach them, solving the puzzle of the human body along the way. The overarching vision behind BodyVis is to transform how learners engage in learning and understanding body concepts.

1.1 Motivation

Learning about the position, structure, and function of internal body parts is challenging for children [74, 96, 110]. Although by age four most children have a fairly well-defined concept of their external body and the relationship between its parts, this is not the case with their inner body [110]. 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 (*e.g.,* [9])—to understand the internal workings of their bodies.

Traditionally, human anatomy (body form) and physiology (body function) are taught in pre-school and primary school education using a mixture of techniques including three-dimensional models and dolls, coloring and activity books, stories, audio-visuals, and video games [110]. Most schools include anatomy and physiology as part of their K-8 science curriculum, which is then extended through high school biology [68]. Teaching pre-school and primary school children about their anatomy and physiology can help with self-care and self-understanding and generally leads to greater compliance with health care regimens [96, 105]. For example, young children with asthma are more likely to take inhaled medications if they understand how their lungs function [96]. Other researchers emphasize the critical role of anatomy and physiology in teaching basic science (*e.g.*, biology) [38].

With the advent of low-cost sensing, ubiquitous computation, and emerging e-textiles, new teaching approaches are developing that link the physical and virtual worlds. While other efforts have explored the use of three-dimensional models and even fabric representations of anatomy (*e.g.*, iheartguts.com), BodyVis is the first exploration of a digitalized manifestation that actively visualizes and responds to the anatomy and physiology of the wearer [71].

1.2 Design Approach and Methods

Through a combination of cooperative inquiry, described in Chapter 3, and iterative design, I have developed two prototypes of BodyVis. The first was inspired by previous work in wearable e-textiles [112] and developed based on key findings from an open-ended cooperative inquiry design session with children. Versions of the second prototype were developed before and after a second cooperative inquiry design session. Key findings from this session were used to update the second prototype. The final prototype was then evaluated through design evaluation sessions with three groups of children (N=30) at local Boys and Girls clubs.

From the design evaluation sessions, I derived three examples of use, which suggest that BodyVis has the potential to engage, excite, and pique both wearers and non-wearers curiosity in body learning. Non-wearers showed greater signs of curiosity in comparison to engagement and excitement; these findings were reversed for wearers of the prototype. Three modes of engagement are presented based on the examples of use.

1.3 Research Contributions

In summary, the overarching contribution is the design, development, and evaluation of a novel way of engaging children in body learning through reactive wearable sensors and visualizations.

This thesis includes both formative and summative primary contributions. Towards the former, I offer new insights into how children think about visualizing their bodies and how this can be used to inform body-learning designs. Towards the latter, I offer an evaluated prototype design for children's body learning engagement. As a secondary contribution, I demonstrated that wearables and e-textiles may engage children in learning STEM topics.

1.4 Thesis Overview

I begin this thesis with a review of the literature on children's body knowledge, sensor-based learning, tangible interactive computing, e-textiles and wearables for learning, and learning theories. I describe the design goals and design approach for BodyVis. I then illustrate the design of each prototype by reporting key learnings from cooperative inquiry design sessions followed by a description of the prototype building process. I evaluate BodyVis by conducting design evaluation sessions with children, presenting three examples of use, and summarizing findings. Finally, I conclude with a discussion of my results, limitations, conclusions, and future work on BodyVis.

Chapter 2: Review of the Literature

In this chapter, I introduce various background research on sensor based learning, tangible interactive computing, body conceptions and body learning, e-textiles and wearables for learning, and learning theories.

2.1 Body Conceptions and Body Learning

As noted in the introduction, by age four most children have well-defined understandings of their external body and the relationships between body parts (*e.g.,* fingers to hand to arm); however, their conception of the inner-body is comparatively weaker [110]. Children between the ages of four and eight can recall approximately three to six internal body parts with those most commonly identified being the brain, heart, bones, and blood (*ibid*). However, children often misconceive of their size, shape, position, and function. For example, the heart is typically drawn as a playing card "valentine" heart (*e.g.,* [20, 40]) and the stomach is considered a respiratory mechanism because it moves in and out with breath (*e.g.,* [41]). In addition, few children have a clear idea of how food passes through their body and waste is eliminated [73]. Interestingly, though a review of 25 studies exploring children's conceptions of human anatomy and physiology found that knowledge generally increases with age [96], even studies of college-educated adults have found that some misconceptions can persist into adulthood [9].

Research in developmental psychology and education has shown that there are many benefits to children who understand basic anatomy and physiology. For example, children with higher "body literacy" have greater compliance with health care regimens, better self-care practices, and increased self-understanding [96, 105]. Schmidt (2001) showed, for instance, that young children with asthma are more likely to take inhaled medications if they understand how their lungs function. Other researchers emphasize the critical role of anatomy and physiology in teaching and understanding basic science (*e.g.,* biology) [38]

Most researchers emphasize that because internal organs are not visible or touchable, they are difficult for children to understand, observe, and experiment with in daily life (*e.g.,* [74]). Thus, pre-school and primary school methodologies often take a multi-sensory approach, which utilizes a student's multiple senses to receive, interpret, and respond to material about the human body. Vessey *et al.* [110] suggest using three-dimensional teaching aids such as anatomic dolls or models to accompany worksheets, stories, audio-visuals, and games (both board games and video games). Although few experimental studies exist on testing the effects of different teaching methods on children's body knowledge, two studies point to the benefits of using three-dimensional teaching aids specifically [95, 109]. From these studies, researchers recommend that teaching artifacts be engaging (*e.g.,* comprised of bright colors and different textures), realistic but approachable (*i.e.,* not "scary"), and interactive (*e.g.,* Schmidt [95] discovered that children learn more from interactive lungs than stationary ones).

2.2 Sensor Based Learning

Originally termed "microcomputer-based laboratories" (MBLs) and then later "probeware", sensor-based learning emerged in the 1980s to leverage the rise of the desktop computer along with emerging sensor technology to help children explore, experiment with, analyze, and visualize measured phenomena in the physical sciences (*e.g.*, among others: sound [104, 116], electricity [116], motion [8, 13, 21, 53, 69, 84, 94, 99, 103, 104, 116], humidity [108], and temperature [36, 53, 60, 70, 104, 116]). While probeware has been shown to facilitate content learning for a particular domain (*e.g.*, physics), it has also been useful for improving general scientific reasoning and analysis skills such as graph literacy [21, 36, 60, 70]. Researchers suggest that it is the real-time nature of probeware that accounts for the improvement in student understanding [13]; in other words, the tight coupling between the subject being examined in the real-world and the graphs being produced enhances learning.

Despite Tinker and Papert's [104] early vision of using sensor-based educational technology for young children to connect abstract measurements directly to the child's senses, most of the research studies examining the effect of probeware on science learning has focused on upper grade levels. Three recent exceptions include Zucker *et al.*'s large-scale study of probeware across 100 classrooms spanning both elementary (grades 3-5) and middle school (grades 6-8) levels [116] and two studies [21, 70] examining the benefits of probeware on fourth grade students' ability to understand and interpret graphs of scientific phenomena and to learn the physical science content itself. All three studies showed statistically significant learning improvements in the probeware conditions compared to conventional techniques, which was attributed to (i) real-time feedback, which allowed students to make concrete connections between the physical phenomena and graphical representations [21, 70]; (ii) the salience of various trends and events of the measured phenomena as manifest in the visualizations [116]; (iii) higher levels of engagement with science content perhaps due to increased understandability or simply the novelty of probeware [21]; (iv) and, finally, increased levels of observation, reflection, and discussion [21]. These benefits/findings are echoed with upper grade levels as well [36, 53, 90, 94, 99, 103].

The interest in sensor-based learning continues. A recent report prepared by the National Science Foundation Task Force on Cyberlearning identified sensor technologies as a significant field of research for future development of technologies [11]. The task force's interest stems from both the positive findings related to science learning from prior sensor-based educational work (*e.g.*, [1, 8, 36, 53, 56, 60, 67]) as well as the increased availability, affordability, and diversity of emerging sensor-based devices. Despite this sustained interest, there has been surprisingly little consideration of physiological and on-body sensors applied to learning contexts [59] and the work that does exist (*e.g.*, [57–59]) 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 [29, 97, 106] as well as human-computer interaction [18, 19, 37, 63], their potential to help children learn about their bodies remains largely unexplored. With the unprecedented growth of wearable physiological sensors, there is tremendous opportunity for building new body-sensing tools and activities to support learning. The BodyVis wearable prototypes represent a new generation of probeware where the "material" being measured is the human body and the visual representations span tangible models to large screen displays, which are all reactive to the wearer's physiology and movement in real-time.

Before going further, it is important to note that the mere presence of probeware in the classroom does not guarantee learning improvements; it must be paired with an appropriate, well-designed curriculum. For example, Nicolaou *et al.* [70] argue that "the combination of the MBLS with an inquiry-based curriculum should be regarded as a teaching and learning process with greater potential than any other traditional inquiry-based approach" (p. 93).

2.3 Tangible Interactive Computing

BodyVis also relates to *Tangible Interactive Computing or Tangible User Interfaces (TUIs)* as it combines physical representations of anatomy imbued with computation for animation and interactivity. TUIs seek to "seamlessly couple the dual world of bits and atoms" by embedding computation into physical objects [52, 107]. Tangible interfaces have been created and explored for a range of domains including programming [49, 65], playful construction [75, 83], architecture [76], urban design [5], and ambient rooms [52]. For example, Horn *et al.* [49] created a tangible computer programming system for the Boston Museum of Science where visitors could use wooden blocks to program robots. This hands-on approach is in great contrast to traditional programming paradigms with a mouse and keyboard; here, physical manipulations replace pressing buttons or rolling track balls and the *physical* experience of programming is highly visible and social.

Researchers in HCI and educational technology have suggested that tangible computing has great potential to support learning, as summarized by Antle and Wise [4], because they offer a natural and immediate form of interaction that is accessible to learners [61, 72], promote active and hands-on engagement [62, 79, 80, 87, 117], allow for exploration, expression, discovery, play, and reflection [34, 62, 82, 91], allow learning of abstract or complex concepts through concrete representations [3, 72, 87], and offer opportunities for collocated collaborative activity as the physical representations are accessible, viewable, and shared by all learners [3, 33, 78, 100].

Though conceptual and theoretical understandings of tangibles are still being developed (see [4, 61]), proponents of tangibles for learning point to the Montessori method for self-directed learning through the use of physical manipulatives as well as the benefits of *embodied interaction* [22], which foregrounds the role of the body, physical activity, and lived experience in cognition. For example, Antle [3] argues that tangible systems have the potential to engage children in active learning and that body movement, touching, and manipulating in the real world are valuable for cognitive development. Zuckerman *et al.* [117] emphasize that tangibles promote sensory engagement (*e.g.,* through touch, vision, hearing) and that this is the "natural way children learn in a constructive process" (p. 860). Others note that successful learning outcomes are not just dependent on motor and cognitive factors but also affective and motivational factors, which tangibles seem to support [3].

While tangible interfaces have been used to facilitate learning across a diverse array of topics from color-mixing [92] to language acquisition [50], the representational properties differ depending on the context—that is, the way in which physical forms and interactions are used to represent information differ depending on domain and purpose. Designing accurate and engaging representational forms for BodyVis is critical to its success as a learning platform. For TUI systems applied to storytelling [64, 98] and programming [49, 65, 117], physical and spatial attributes represent abstract and/or metaphorical properties and relationships. In contrast, tangible interfaces in the natural sciences such as molecular biology, chemistry, or astronomy often represent their microscopic or macroscopic counterparts as semi-realistic models imbued with computational behaviors, which provide dynamism and/or augmented information (*e.g.,* [35, 42, 114]). For example, Gillet *et al.* [42] combine 3D-printing of physical molecular models with virtual information overlays to show dynamic properties (*e.g.,* animated electrostatic fields that change shape as the molecules are manipulated). This work is similar in that I attempt to concretize the invisible structures and functions of the internal body by coupling tangible physical models (structure) with embodied digital forms (function).

In the domain of human biology specifically, I did not find any prior work in the tangible interactive space; however, a number of augmented reality systems [6] have been developed to allow users to "peer inside" a human body [7, 10, 66]. For example, recent preliminary work by Blum *et al.* combines a Kinect and a large screen display to create a "magic mirror" effect that overlays anatomical visualizations on the user's body [10, 66]. However, in contrast to my work, this research is targeted at medical students rather than children, and the biological representations are only accessible as three-dimensional projections on the large-screen display (*i.e.,* are not tangible) and do not react to the sensed physiology of the user.

2.4 E-textiles and Wearables for Learning

BodyVis focuses on using a wearable medium to teach children about their bodies. Similar to this thesis work, a growing number of researchers are exploring the use of e-textiles and wearable computing for teaching purposes. The LilyPad Arduino, a microcontroller initially designed to lower the bar when creating e-textiles for all levels of users and settings [15], has caused many researchers to think more critically about wearables for learning. A series of workshops tested the LilyPad's ability to engage children in computer science education [16]. The results of these workshops suggested that children can become "passionately engaged" in the medium of e-textiles while simultaneously learning computer science skills (p. 428 *ibid*).

Others have also conducted similar workshops with the intent to teach children about technology by allowing them to use electronics to enhance their arts and crafts (*e.g.,* [28]). Although they show that children become motivated to learn more about science technology through the use of e-textiles [17, 54], these studies do not explore the use of e-textiles in motivating children to learn anatomy, physiology, and/or biology. Some researchers, however, have explored physically engaging wearables to discover how people learn about their own bodies [113]. In order to engage and motivate children to learn these complex topics, an experience must be created for them that is relevant to their culture through crafts and technology [17].

2.5 Learning Theories

The theory of constructivism, first conceptualized by Jean Piaget, argues that children learn by constructing their own knowledge of concepts taught to them and through their own personal experiences [51]. This phenomenon occurs through children's personal discovery of relationships between concepts. In a classroom setting, for example, this type of learning may happen through experiments and real world problem solving. Previous research shows also that students learn and construct knowledge collaboratively with their peers and teachers, as argued in Vygotsky's theory of social constructivism [51, 77]. Therefore, in a classroom setting, children may collaborate with their peers through experimentation of real world problems and concepts to develop knowledge and learn about those concepts.

Although these peer and teacher collaborations aid in learning, children often fail to apply what they learn in school through textual information (*e.g.,* books) and classroom lectures outside of the typical classroom setting [12]. Many children learn best through a combination of methods in addition these traditional forms of teaching [39]. Theoreticians and educational reformers have agreed that in order to strengthen learning, teachers should emphasize on "engaging children in the learning process" (p. 79 [93]). These skills extend beyond recalling and stating correct answers; they require the involvement of children in exploring, solving, analyzing problems. By engaging in the learning process, children gain an experience that "provides a foundation for learning and gives it meaning" (p. 15 [81]).

Context is also important in children's understanding of new skills; "context" is defined holistically as the individuals that children interact with, what these individuals do and how they work [55]. Therefore it is important to immerse children in multiple learning environments to support their knowledge constructions both inside and outside of the classroom environment.

Chapter 3: Design Goals and Design Approach

In this chapter, I provide a summary of the design goals and approach toward developing BodyVis. I then elaborate on the design method known as *cooperative inquiry*, which I used in the design of BodyVis.

3.1 Design Goals

. I have six design goals for BodyVis, which were arrived at iteratively through the experience of making early prototypes and the cooperative inquiry sessions:

- **Engaging**: At its core, BodyVis should be designed to engage children in body learning and promote engagement of body learning through the shirt itself.
- **Exciting**: This design should attempt to excite children to help them become interested in how their bodies work and what actually happens inside our bodies.
- **Spark Curiosity**: This design should attempt to spark children's curiosity about their bodies. It should inspire them to ask questions about how their bodies work.
- **Playful**: Because children are naturally interested in playing with their toys, this design should attempt to be playful to further excite and interest children in the shirt itself, and consequently their bodies.
- **Lightweight**: To allow mobility and promote physical activity while wearing the shirt, the design should attempt to be as lightweight as possible.

- **Robust**: To ensure that the prototype will be durable enough for children to use, the design should attempt to be as robust as possible.

3.2 System Overview

Below, I list the minimum viable set of components that any instantiation of the BodyVis prototype must include:

- **Physical Models of Anatomy**: A BodyVis shirt should contain physical models of the human anatomy. Although these models will only be representations of internal organs, they should be as anatomically correct in shape as possible.
- **Sensing of Physiology**: The shirt should sense some of the users' physiology (*e.g.,* heart rate, breathing rate, swallowing). This allows for the developer to display the users' bio-data to the users through the shirt, allowing them to understand how their own bodies work.
- **Responsive Output**: Responsive output can be displayed via visuals (*e.g.,* lights, screens), haptics (*e.g.,* vibrations), and audio. This allows the developer to display the users' bio-data through different methods and give users a glimpse into their own bodies through the shirt.
- **Wearable Computer**: A wearable computer is required to gather bio-data from the sensors and control the responsive output in the shirt. This also allows for mobility of the shirt and promotes physical activities.

3.3 Design Approach

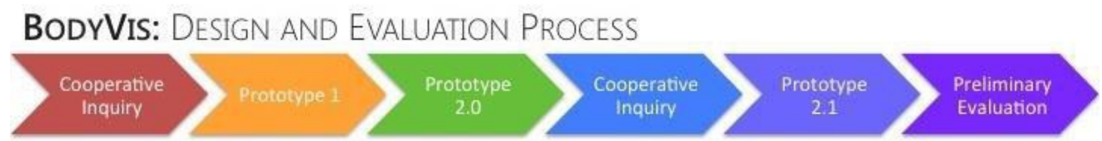


Figure 3: The design and evaluation process of BodyVis began with a cooperative inquiry session, followed by the development of Prototype 1 and Prototype 2.0. A second cooperative inquiry session was held using the first two prototypes. Following this session, Prototype 2.1 was developed and evaluated.

When building technologies for children it is important that we do so with the needs of children in mind [24]. As adults, we may have assumptions of the wants and needs of children towards technology, but we cannot know precisely what those wants and needs are until we work with them side-by-side [25]. Therefore, I chose to involve children in the design process (Figure 3), from the brainstorming and ideation phase to the final user testing of BodyVis. Based on these criteria, I followed the *cooperative inquiry* design method to build BodyVis with children via a group called Kidsteam.

3.3.1 Cooperative Inquiry

Cooperative inquiry with children first began when design methods typically

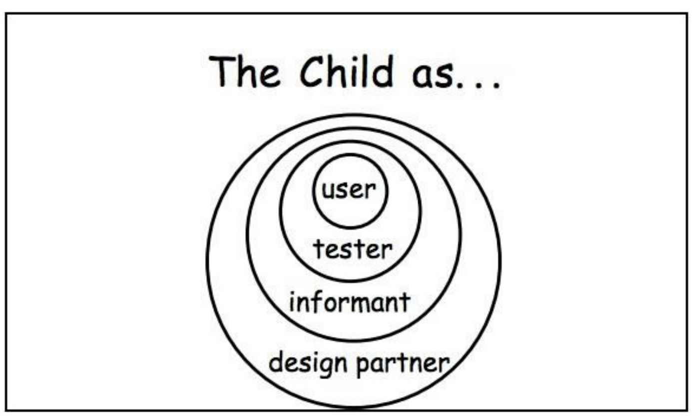


Figure 4: A diagram of the roles that children play when designing technologies. The user has the least amount of contribution in the design process while the design partner has the most. [25]

associated with adults (*e.g.,* participatory design, cooperative design, contextual inquiry) had to be tailored towards the needs of children [24]. In her early work on *cooperative inquiry*, Druin envisioned children working side-by-side with adults as design partners throughout the entire design process with maximum involvement (Figure 4) [24]. Druin describes her belief that "partnering with users is an important way to understand what is needed in developing new technologies" (p. 20 [24]).

Cooperative inquiry is defined as a design method with a set of prescribed techniques focused on the collaboration and partnership of adults and children in brainstorming, designing, developing, and testing new technologies for children with children [24, 25, 30, 46]. Here, children become design partners and equal stakeholders when designing new technologies [24]. Adults and children use materials such as art supplies (*e.g.,* yarn, felt, corks, popsicle sticks), transparencies, table-sized paper, and post-it notes [30, 45] to brainstorm, iterate, and evaluate different designs. Since its conception, this design method has become the product of much discussion [25, 26, 31, 44, 45] and has been applied in many different settings and contexts [88, 89, 102].

3.3.2 Kidsteam

The University of Maryland's Human-Computer Interaction Lab (HCIL) hosts weekly *cooperative inquiry* sessions, known as Kidsteam, with the same group members throughout the school year covering a range of design topics [46, 111]. child partners of Kidsteam visit the HCIL twice a week for an hour and a half each day to participate in *cooperative inquiry* sessions. During my design process, from the initial ideation phase to the testing and iteration of prototypes, I utilized two Kidsteam sessions (a session before developing Prototype 1 and another after developing Prototype 2.0) to explore potential design options and uncover current understandings of body structure and function amongst our group. Here, I briefly provide a general overview of Kidsteam while Chapters 4 and 5 discuss our specific usage of the *cooperative inquiry* method in the design of BodyVis.

Kidsteam consists of seven children between the ages of 7-11 (five girls, three boys) and seven adults between the ages of 20-49 (five female, two male). During the first session, all children had been participating for two months with the exception of a four-year member. Between my first and second sessions, a new female child replaced another and participated for 6 months before the second session.

Sessions begin with a "question of the day" [115]. This prompt serves both as a transitional point for the children to begin participating in the design process as well as a way of gathering data on preliminary thoughts and ideas about the target subject. The group then splits into sub-groups of adults and children where the partners work collaboratively using a design technique (a collection of techniques can be found in [30]). Prior to each session, the adult partners choose a design technique that will best answer the research question for that session. Each session ends with the sub-groups sharing their *big ideas* [30, 46], creations, results, and/or findings; all are given the opportunity to ask questions from their group-mates. *Big ideas* are those that are "surprising, most repeated among groups, or receive the most reaction from the whole team" (p. 39 [23]). An information frequency analysis is used to find recurring themes from the presented *big ideas*.

I utilized the main ideas and themes resulting from each of the Kidsteam sessions as guidelines for all iterations of BodyVis. Each of my sessions along with their results is described in further detail in Chapter 4 and Chapter 5 for Prototype 1 and 2, respectively.

Chapter 4: The Design of Prototype 1

In this chapter, I describe the details of the first Kidsteam session, the results obtained from the session, and how I developed the first BodyVis prototype.

4.1 Kidsteam Session

As discussed in Chapter 3, I utilized a cooperative inquiry session to uncover potential design options and gain insight on how children may understand the position, structure, and function of their internal organs. Before I began any development of the first BodyVis prototype, I worked with the Kidsteam children and adult partners to brainstorm design ideas.

4.1.1 Session Procedure

To ensure that the children would understand our session topic, I first asked for definitions of "anatomy." One of the children answered, "I think it's about the body." Once I provided the definition, I asked the question of the day: *What questions do you have about anatomy?* This question served as a transitional point for the children to begin participating in the design process.

Figure 6: Kidsteam members use *bags of stuff* to design t-shirts that represent their anatomy.

After each participant offered a response to the question of the day, I divided the room into sub-groups to engage in a low-tech prototyping activity called *bags of stuff*. Here, bags of art supplies are used to promote a structured way of brainstorming, creating, and sharing ideas [47]. Generally these bags consist of art supplies such as glue, string, markers, scissors, and paper; however, as these items can be tailored to specific projects, our bags consisted of textile supplies including yarn, felt, and pom-poms. I also provided white t-shirts for each child (Figure 6).

Figure 5: Kidsteam members display their t-shirt designs for BodyVis.

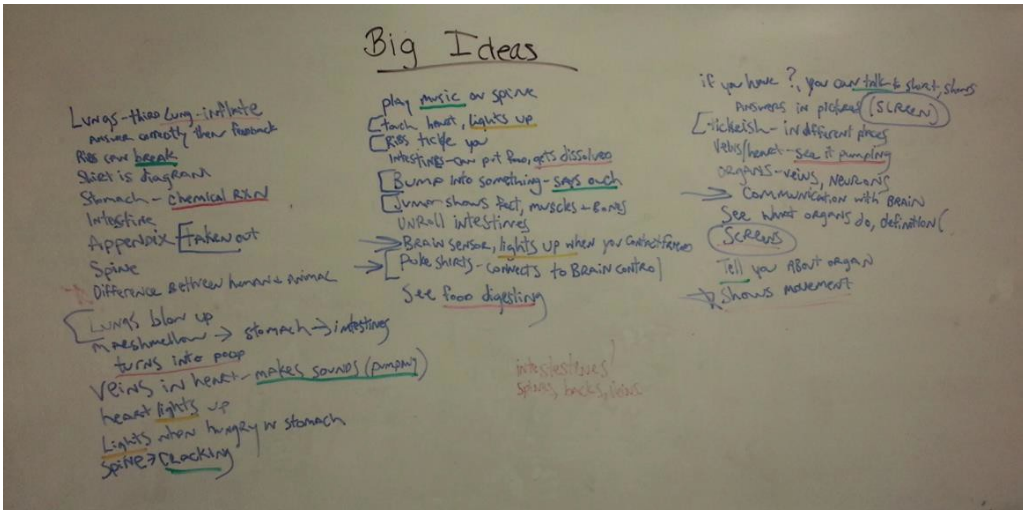


Figure 7: ***Big Ideas*** **are gathered from the session to find themes that emerge from designs. These themes are visible through color coded underlines, circles, brackets, and any other indicators of theme formation.**

The children were asked to create t-shirts that represented their anatomy using the provided supplies. They were given approximately 30 minutes to complete the task. Afterwards, each sub-group gathered together once again to share and present their designs (Figure 5). Following the *big ideas* approach [30, 46] (Figure 7), an adult partner helped synthesize and record surprising, repeated, and popular ideas on a whiteboard. Thus, ideas were analyzed and categorized *in situ* during the cooperative inquiry session itself. A short 20 minute debrief session also occurred amongst the research team.

4.1.2 Results

Though each sub-group in the cooperative inquiry session had unique design ideas, a set of overarching themes emerged around the use of color, sound, lights, and movement. Color was used to distinguish between organs and their function (*e.g.,* red for veins and the heart). For sound, I found that children used audio to increase the playfulness and reactivity of their shirts. For example, children designed breakable

Figure 8: On the left, a Kidsteam member uses her spine as a musical instrument. On the right, another member creates a method of "inflating" the lungs using a coffee stirrer straw (circled).

ribs and spines with "cracking" sound effects "talking" organs, and using the spine as a musical instrument (Figure 8). Lights were used mainly to indicate an action such as a pumping heart, hunger, or blood moving through veins. Finally, the most popular design theme was the use of movement. For example, children illustrated food traveling through the digestive system and dissolving in the stomach, physically pumping hearts, and "breathing" lungs (Figure 8). 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.

4.2 Creating Prototype 1

The first BodyVis prototype (Figure 9) was exploratory in nature. Because I was following an iterative approach, I created this prototype on the basis that I would be exploring different possibilities of designing future iterations. The results from the first Kidsteam session played a crucial role in how I created the first BodyVis prototype. Here I will illustrate the logistics of how I built the prototype and how the themes of color, light, sound, and movement were incorporated into my design.

4.2.1 System Overview

Prototype 1 was implemented following the minimum viable set of components presented in Chapter 3. In this subsection, I summarize these components before providing additional detail in the next section.

- **Physical Models of Anatomy**: The human anatomy is represented through physical "pillow" organs. Organs were created using two pieces of felt, cut into anatomically correct shapes, sewn together, and stuffed with pillow stuffing.
- **Sensing of Physiology**: In this prototype, the user's heart rate is sensed through a Pulse Sensor (www.pulsesensor.com).
- **Responsive Output**: LEDs embedded inside the heart pulsate on and off; the rate of this pulsation is controlled by the user's heart rate. Blue and red Electroluminescent (EL) wires are placed on the lungs to represent veins and blood flow inside the lungs. The rate of pulsation in these glowing wires is also controlled by the user's heart rate.

Figure 9: A snapshot of Prototype 1.

- **Wearable Computer**: An Arduino Uno is used in this prototype to read the sensing data and control the pulsation of the LEDs and EL wire.

4.2.2 A High Level View

As I am using a t-shirt as my visual medium, the areas of the human body that are covered include the *thoracic region* above the diaphragm and the *abdominal region* below it. For the thoracic cavity, I included the lungs, heart, and esophagus but not, currently, the trachea and the thymus gland. The abdominal cavity extends down to the pelvic cavity and includes most of the digestive organs including the esophagus, stomach, liver, gallbladder, pancreas, small intestine, and large intestine.

Currently none of the prototypes depict reproductive organs or human waste orifices. Vessey [110] warns that anatomical teaching aids can abstract complexity (*e.g.,* to simplify and capture interest) but should not create or reinforce children's false perceptions. Thus, I attempted to correctly shape and position each organ on the shirt though I did attempt to minimize overlap to avoid occlusion. Organs were created using two pieces of felt, cut into anatomically correct shapes, sewn together, and stuffed with pillow stuffing. This creates a plush, tangible aesthetic aimed at attracting a child's attention and touch.

Prototype 1 includes multiple bright colors, which was influenced by the Kidsteam session as well as related work (*e.g.,* [105, 110]). Because children in our cooperative inquiry group are often sensitive to perceived gender delineations, I selected a gender-neutral green color for the t-shirt itself (the base). The remaining colors balance the functional representation for each organ and overall visual aesthetic. Although some of the organ's colors are not anatomically correct, I believe that specific colors may help children remember the functionality and purpose of each individual organ. For example, one child in the cooperative inquiry session had a brown colored large intestine in her design, as it represented the final stage of the digestive system. She said, "That's where the poop comes out."

4.2.3 Heart and Lungs

The heart is a muscular organ that acts as a pump; it is located slightly left of center in the human chest and is about the size of a fist. The heart is divided into two parts. The division protects oxygen rich blood from mixing with oxygen poor blood [43]. In Prototype 1.0, the heart is comprised of red and blue felt to represent this division—*i.e.*, blood entering and leaving the heart. Embedded in the heart are six LEDs. These are placed on an inflexible perfboard and surrounded by soft stuffing

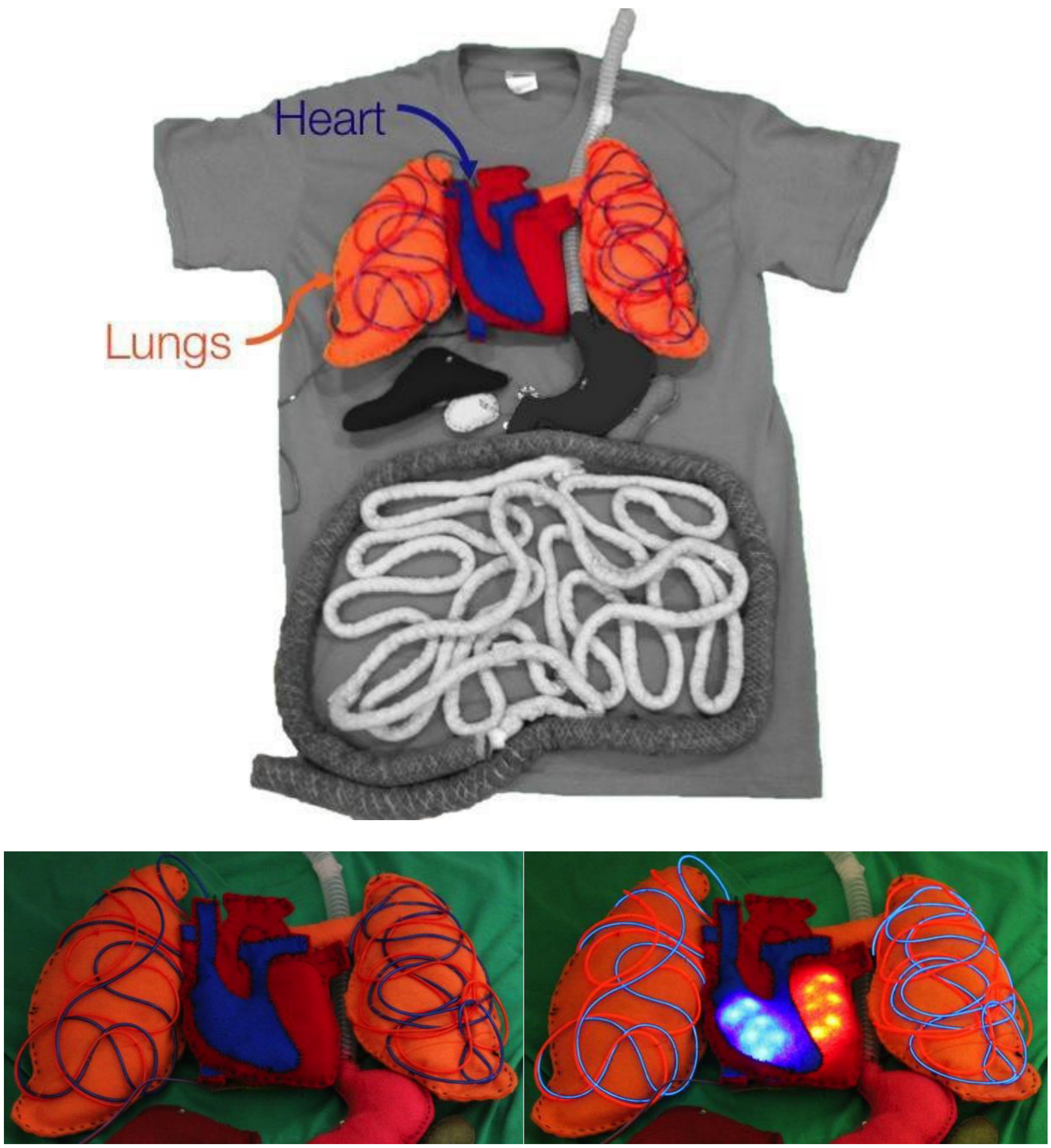


Figure 10: On top, the heart and lungs in Prototype 1. On bottom, a close-up of the fabric heart (red and blue) with embedded LEDs and lungs (orange) with vein accents made of EL wire.

and an outer layer of felt. Their colors correspond to the surrounding felt (blue or red). 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. The LEDs pulsate in accordance with the user's heart rate (Figure 10). This visualization represents the muscular movement as blood enters and leaves the heart. Through experimentation, I found that the pulse sensor functioned best when attached to the finger.

Lungs are sponge-like organs that are located to the left and right of the heart. Lungs fill up at inhalation and empty out at exhalation, carrying in oxygen from the air and letting out carbon dioxide from the body. Poorly oxygenated blood is carried into the lungs from the heart to pick up oxygen before it re-enters the heart and is

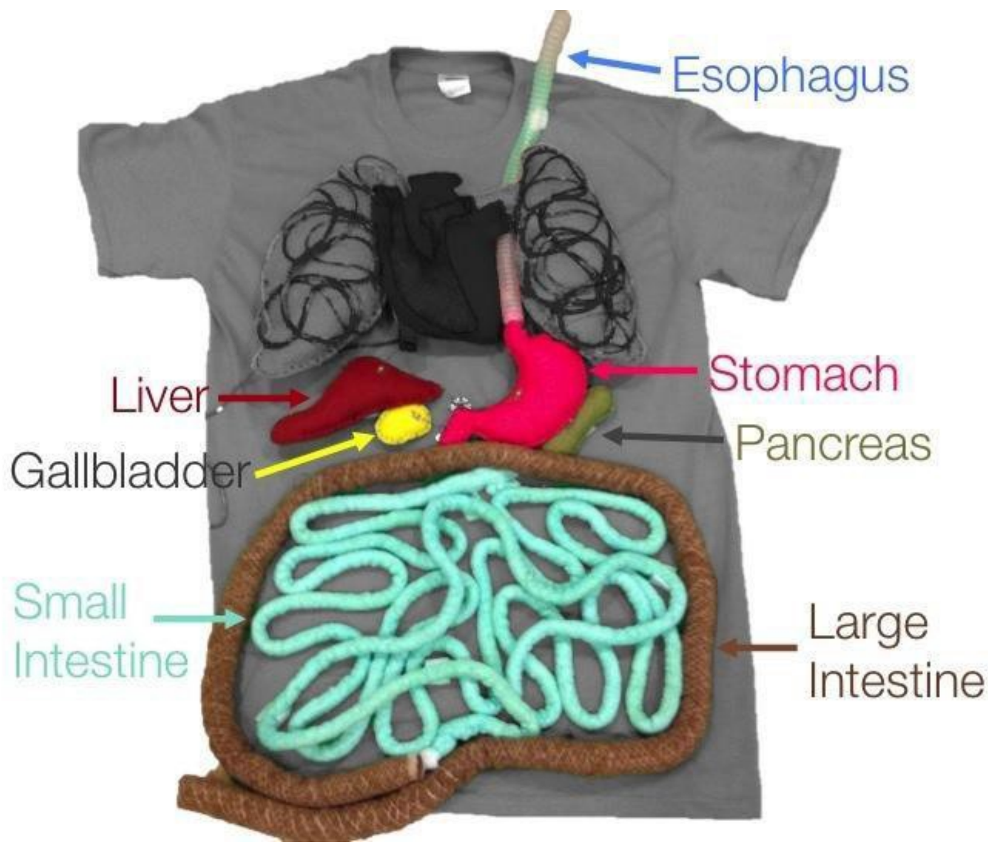


Figure 11: The digestive system in Prototype 1.

delivered to the body [43]. In Prototype 1, each of the lungs is attached to opposite ends of the heart. To illustrate the veins and blood flow in the lungs, I covered the lung surfaces with blue and red EL wire. These colors maintain the theme of blood entering and leaving the heart. Similar to the heart LEDs, the EL wire is connected to the Arduino and pulsates in accordance with the user's heart rate. This pulsation represents the blood flow in the user's lungs.

4.2.4 Digestive System

The digestive system consists of a series of organs that work together to retrieve nutrients and energy from eaten food. This system begins when food is swallowed and travels down the esophagus, a stretchy pipe that leads to the stomach. The stomach mixes, churns, and breaks down the food into a liquid mixture using the stomach walls and gastric juices before it empties the mixture out into the small intestine. The small intestine breaks down the food into smaller pieces, allowing the

Figure 12: The small intestine (in light blue) unravels to help illustrate its extensive length.

body to absorb nutrients from it. At the beginning of this procedure, the pancreas, liver, and gallbladder send juices to the small intestine to help this digestion and absorption of nutrients. The remainder of the food passes through the large intestine, where any water and remaining nutrients are removed. The waste from the food turns to a solid form before leaving the body through the rectum [43].

In Prototype 1, the digestive system (Figure 11) consists of the esophagus, stomach, liver, gallbladder, pancreas, small intestine, and large intestine. The esophagus was created using a grooved portion of a suction pump. This design was chosen due to its similar visual appearance of the human esophagus, which uses surrounding muscles to pinch inward and send food to the stomach. The esophagus is also visibly attached to the beginning of the stomach, which is made of stuffed fabric. Similarly, other digestive organs such as the liver, gallbladder, and the pancreas are built from colored fabric.

The fabric stomach is visibly attached to the small intestine, represented in blue. In the Kidsteam session, one child used strings of yarn to represent her small intestine and to highlight its surprising length. Consequently, I designed the small intestine using Velcro to detach and unravel from the shirt allowing children to fully investigate its length (Figure 12). Finally, the small intestine is visibly attached to the large intestine represented in brown.

4.3 Lessons Learned

Throughout the development and upon completion of this prototype, I faced several design challenges and learned several lessons about how to build this system.

In order to have a successful second Kidsteam session, I discovered that the prototype needed revising in several areas before moving forward.

As I informally tested the Prototype on myself and several others, it became apparent that the Pulse Sensor did not provide reliable feedback of the user's heart rate. Although the sensor correctly detected it, the user's heart rate was not consistently being detected. I began to explore different methods of sensing this data due to this challenge. This exploration later led me to a sensor that sensed both the user's heart rate and breathing rate (discussed in Chapter 5).

Although the first prototype is visually appealing, it does not provide enough visual feedback on the physiology of the human body. This particularly stands out when evaluating the results from the first Kidsteam session. Children were interested in receiving as much feedback as possible (*e.g.,* light, audio, movement), however this prototype provides minimal visual feedback in the form of light.

Additionally, I discovered that in order to provide further feedback to the user, I needed to include additional sensors. For example, a breathing rate monitor could regularly show the user a visual representation of how his or her lungs fill up and empty out.

Similar to lung visualizations, additional feedback to the user could have been provided through a visual representation of the digestive system. In this prototype, the digestive system served as placeholder for future iterations where I would add visual feedback to the system. Nonetheless, I recognized based on the Kidsteam results and my own experience in developing this prototype that visual and audio feedback would be necessary in the next prototype.

Figure 13: Over time, Prototype 1 (original on left) stretched due to the weight of the organs. On the right is a snapshot of Prototype 1 one year after completion.

Several weeks after the first prototype was completed, I discovered that the shirt began to stretch downwards due to the weight of the plush organs and caused it to double in size (Figure 13). The original size of the prototype was a Small adult size, which, at the time, was already slightly large for the target child users. Because my design goals included building a lightweight and robust system, I needed to overcome this challenge in the next iteration of the prototype. A simple solution was to use un-stuffed fabric organs to decrease the weight of the shirt. This solution also allowed for the easy overlap of organs, a design I did not implement in Prototype 1 to avoid occlusion of organs.

It became necessary to overcome these challenges before conducting a second Kidsteam session to gain optimal results. In the next chapter, I will explain how I utilized these lessons throughout two iterations to overcome previous challenges.

Chapter 5: The Design of Prototype 2

In this chapter I describe the details of how I developed BodyVis Prototype 2.0. I then describe the second Kidsteam session, where a set of overarching themes emerged around the use of sound, movement, and stomach animation. I end with a description of how I developed Prototype 2.1.

5.1 Creating Prototype 2.0

Prototype 2.0 began as the next iteration of BodyVis. Since new materials were being used to build it, similar to Prototype 1, it was very exploratory in nature. As such, this prototype became a method of learning new lessons to create the next working prototype (2.1) as opposed to a testable prototype. Consequently the sensing component of the system was not included in the design as time constraints and new design challenges required a re-implementation of this version of BodyVis. It is, however, important to discuss the method in which the prototype was created and the lessons learned throughout its implementation.

5.1.1 System Overview

Prototype 2.0 was implemented following the minimum viable set of components presented in Chapter 3. In this subsection, I summarize these components before providing additional detail in the next section.

- **Physical Models of Anatomy**: The human anatomy is represented through physical, flat fabric organs. Organs were created using two pieces of fabric, cut into anatomically correct shapes, and sewn together.

- **Sensing of Physiology**: Due to new design challenges and time constraints, this prototype did not have any sensors to sense the user's physiology.
- **Responsive Output**: LEDs are embedded inside the heart and show the path blood takes while inside it. LEDs are also embedded inside the lungs. These LEDs represent air flow inside the lungs by "filling up" and "emptying out".
- **Wearable Computer**: A LilyPad Arduino is used in this prototype to control the LEDs in the heart and lungs.

5.1.2 A High Level View

As described in Chapter 4, there were several design challenges in the first prototype that needed to be rectified before conducting a second Kidsteam session. These challenges included lack of visual feedback, lack of sensors, and weight problems. I tackled several of these challenges through various design decisions in Prototype 2.0.

Similar to the first prototype, I began with the lungs, heart, and esophagus in the *thoracic region* above the diaphragm and the esophagus, stomach, liver, gallbladder, pancreas, small intestine, and large intestine in the *abdominal region* below it. I attempted to minimize the weight of the shirt by using flat, 2D fabric organs as opposed to the plush, 3D organs I created in Prototype 1. Once again I attempted to correctly shape and position each organ on the shirt; however, unlike Prototype 1, I did not attempt to

Figure 14: Organs were traced out on fabric before being cut out.

Figure 15: A snapshot of Prototype 2.0.

minimize overlap of the organs because I had smaller, lighter organs that could easily overlap. Thus, I could correctly portray the overlap of organs in the human body in a manner that I could not show in Prototype 1.

Organs were created using two pieces of flat, 2D fabric cut into anatomically correct shapes and sewn together (Figure 14). This design change created a tradeoff as the prototype lost its tangible, plush aesthetic but allowed for overlap of organs and minimized the weight. Finally, I added buttons on the backside of the shirt to ease the process of wearing and removing the shirt for the user. Similar to Prototype 1, I included multiple bright colored organs influenced by the initial Kidsteam session and a gender-neutral green color for the t-shirt itself.

Figure 16: A snapshot of the heart and lungs in Prototype 2.0 (left) and a close up of the heart and lungs visualization (right). Here, the lungs are fully "inflated" as indicated by all the lit LEDs.

5.1.3 Heart and Lungs

The heart and lungs are powered and controlled via a Lilypad Arduino (www.lilypadarduino.org). The Arduino is connected to each lung and heart via 3 layers of conductive thread twisted together for minimal resistance, covered with non-conductive thread to prevent shorts.

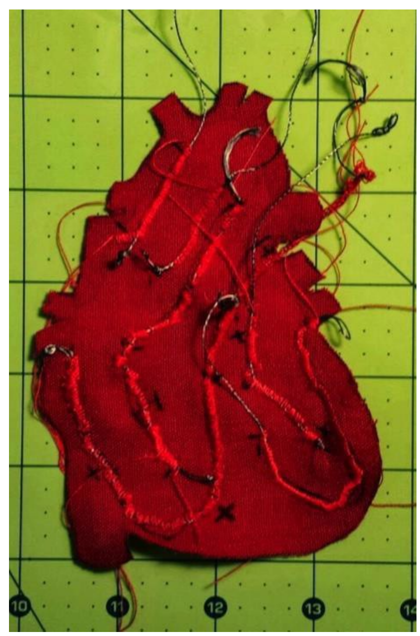


Figure 17: The heart contains LED pixels connected by conductive thread (silver thread), held down and protected by non-conductive thread (red thread).

The heart is comprised of red and blue fabric to represent the division of the

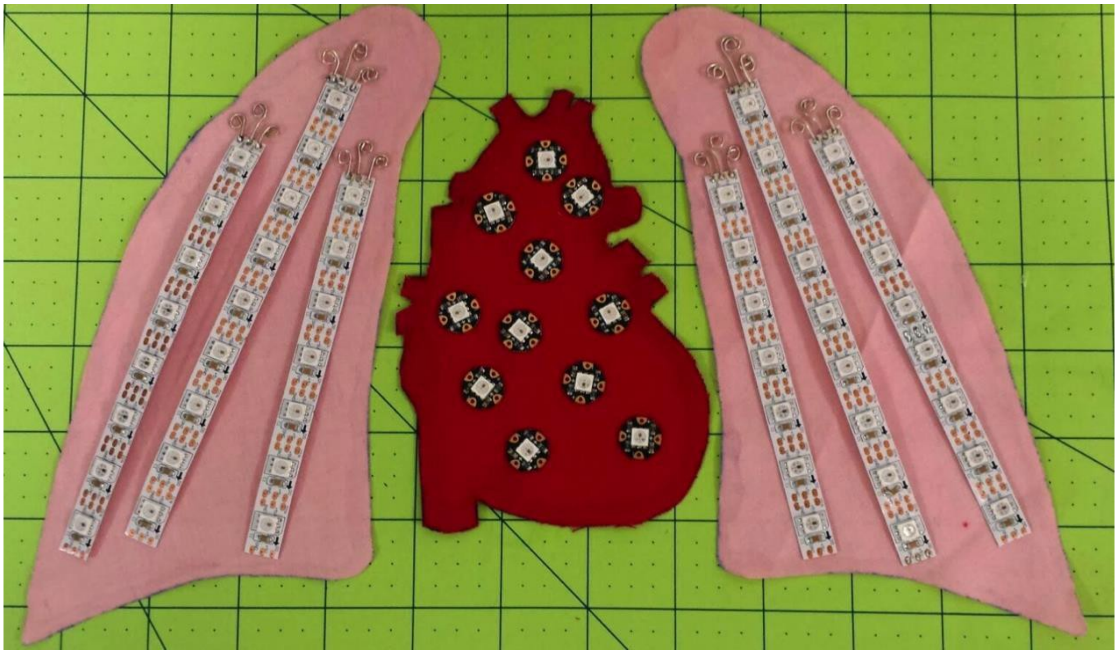


Figure 18: Inside of the heart and lungs are LED pixels and strips, respectively.

heart. Embedded in the heart are eleven Neopixel LEDs (Figure 18). These are wired together using three layers of conductive thread twisted together for minimal resistance, covered with non-conductive thread to prevent shorts (Figure 17). Unlike Prototype 1, where the visualization in the heart represents its muscle movement, the visualization in the heart of Prototype 2.0 represents blood entering and leaving the heart using the corresponding colors (blue and red).

In Prototype 2.0, each lung is attached to opposite ends of the heart. Embedded inside each lung are three Neopixel LED strips (Figure 18). These strips are wired together using insulated wire and are wired to the Arduino using conductive thread. Unlike Prototype 1, where the visualization in the lungs represents blood flow, the visualization in the lungs of Prototype 2.0 represents airflow. In this visualization, as air enters and inflates the lungs, the LEDs in each strip turn on upwards one by one until all the LEDs in the strip are on. As air leaves and deflates the lungs, the LEDs in each strip turn off downwards one by one until all the LEDs in the strip are off (Figure 16).

As this prototype was exploratory in nature, I experimented with the new visualizations in the heart and lungs to illustrate a different representation of these organs. The heart and lungs did not visualize sensing data from the user; instead they became a canvas to experiment different visualizations and representations for future iterations of the prototype.

5.1.4 Digestive System

The digestive system (Figure 19) consists of the esophagus, stomach, liver, gallbladder, pancreas, small intestine, and large intestine. These organs were created using 2D fabric sewn onto the shirt. Due to design consistency, the esophagus was created using 2D fabric as opposed to the grooved portion of a suction pump used in Prototype 1. The esophagus is visibly attached to the beginning of the stomach, represented in orange. Similarly, other digestive organs such as the liver, gallbladder, and the pancreas are built from colored fabric. The fabric stomach is visibly attached to the small intestine, represented in blue and gray. Again, due to design consistency, the small intestine was created using 2D fabric as opposed to a detachable one. Finally, the small intestine is visibly attached to the large intestine represented in brown.

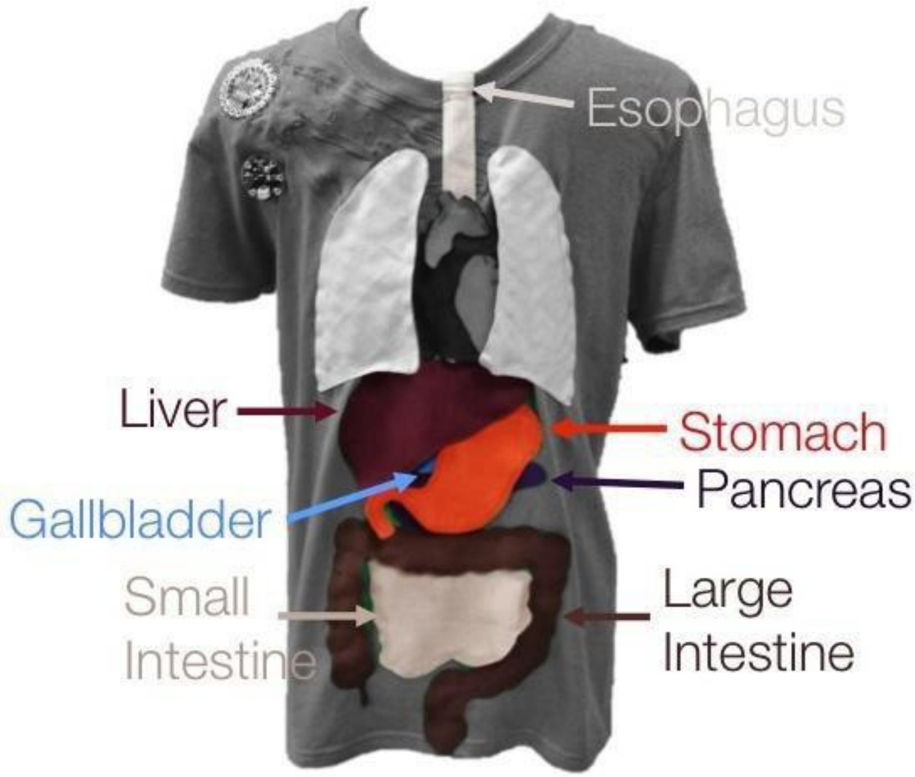


Figure 19: A snapshot of the digestive system in Prototype 2.0.

The digestive system was created without functionality in this prototype due to time constraints towards the second Kidsteam session and additional flaws discovered when using conductive thread. These flaws were revised in Prototype 2.1, described later in this Chapter.

Figure 20: Demoing Prototype 1 (left) and 2.0 (right) for Kidsteam.

5.2 Kidsteam Session

Following my method of including children as design partners in my design process, I utilized a second cooperative inquiry session with Kidsteam to gain insight on children's opinions of Prototype 1, Prototype 2.0, and design ideas for future iterations.

5.2.1 Session Procedure

In this session, I utilized a combination of three *cooperative inquiry* design techniques:

- *Bags of stuff*: This low-tech prototype technique uses bags of art supplies to promote a structured way of creating and sharing ideas among groups [30, 47].
- *Big Paper*: Table-sized paper is given to each group to promote the generation of ideas through drawing [45].
- *Mixing Ideas*: Group members mix and merge individual ideas to form bigger and collaborative ideas [30, 45].

Figure 21: A Kidsteam member uses materials from the *bags of stuff* to design her version of BodyVis.

Seven children and six adults participated in this session. All but one of the children in this session participated in the first session. I began this session with the question of the day: *What organ in your body would you like to know more about?* This question served as a transitional point for the children to begin participating in the design process. I then asked the children to briefly describe the events that took place in the first session to refresh their memory and to inform the new child design partner.

After each participant offered a response to the question of the day, I divided the room into two groups. Each group received a demo of Prototype 1 and Prototype 2.0 as well as an opportunity to ask questions and interact with the prototypes (Figure 20). They were given approximately 15 minutes for this demo session. The team was then divided into sub-groups to engage in three techniques: *bags of stuff*, *big paper*,

Figure 22: A Kidsteam member shares her group's design while an adult partner records *Big Ideas* from the design on a whiteboard.

and *mixing ideas*. Each sub-group was given *bags of stuff* and *big paper*; once again these bags consisted of textile supplies including yarn, felt, and pom-poms.

The children were then asked to design the next iteration of BodyVis on *big paper* using *bags of stuff* by *mixing ideas* from Prototype 1 and Prototoype 2.0 that they particularly enjoyed (Figure 21).They were also asked to add new design ideas when they believed it missing from or necessary in the prototypes. They were given approximately 30 minutes to complete the task. Afterwards, each sub-group gathered together once again to share and present their designs. Following the *big ideas* approach [30, 46], an adult partner helped synthesize and record surprising, repeated, and popular ideas on a whiteboard (Figure 22). Thus, ideas were analyzed and categorized *in situ* during the cooperative inquiry session itself, from which several themes were identified among the ideas of the groups. A short 20 minute debrief session also occurred amongst the research team.

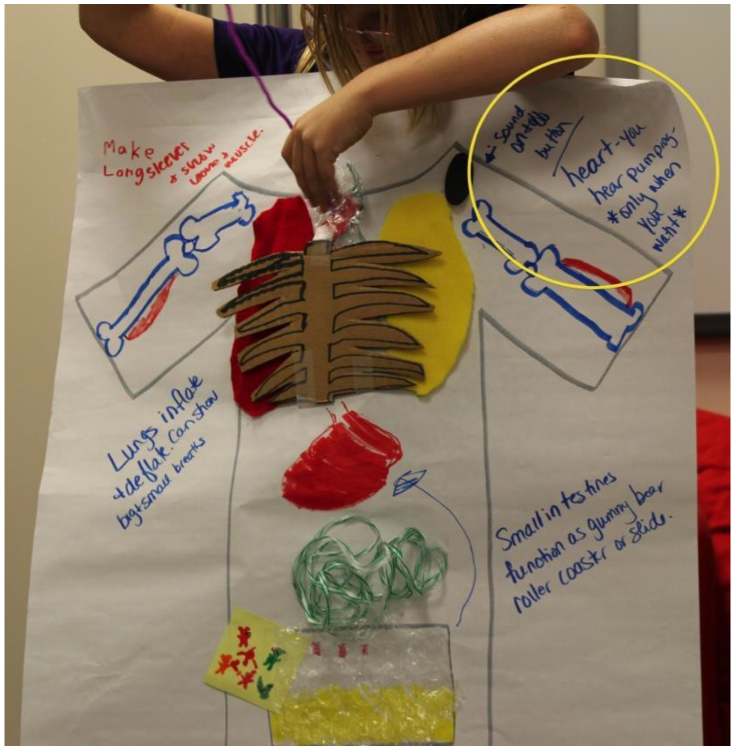


Figure 23: These group members designed a "heart you hear pumping" and the ability to control sound affects (circled in yellow).

5.2.2 Results

Though each sub-group in the cooperative inquiry session had unique design ideas, a set of overarching themes emerged around the use of sound, movement, and stomach animation. For sound, I found that children used audio to increase the playfulness and reactivity of their shirts. For example, children several groups designed their hearts and lungs with sound affects to hear "heart pumping" and "breathing" (Figure 23). Similar to the results of the first Kidsteam session,

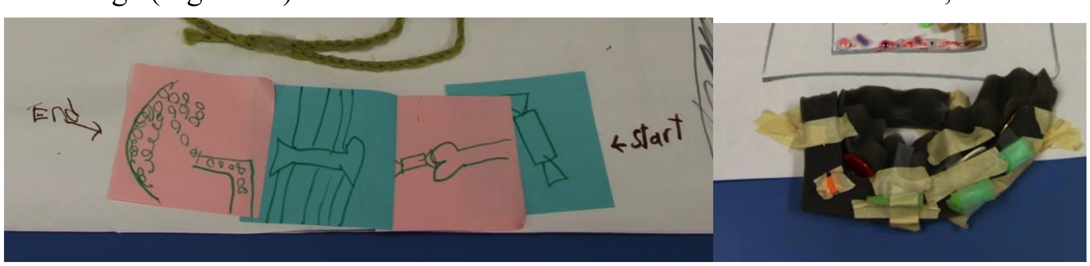


Figure 24: On the left, one group designed a method of viewing the digestion of food from start to finish (right to left in the image). On the right, another group designed a method of viewing food converting into waste in the intestines.

movement was a popular design theme. For example, children illustrated, in great detail, food traveling and breaking down through the digestive system (Figure 24) and physically "breathing" lungs. In this session, children were particularly interested in the breakdown of food inside the stomach. All groups included a visualization of food breakdown inside the stomach. In general, there was more emphasis on the design of the digestive system in each group as opposed to the heart and lungs. When I questioned the children regarding this matter, they responded that they "liked the design" of the heart and lungs.

5.3 Creating Prototype 2.1

The results from the second Kidsteam session in addition to my experience building Prototype 2.0 played a crucial role in how I created Prototype 2.1. Here I will illustrate the logistics of how I built the prototype and how the themes of sound, movement, and stomach animation were incorporated into my design.

5.3.1 System Overview

Prototype 2.1 was implemented following the minimum viable set of components presented in Chapter 3. In this subsection, I summarize these components before providing additional detail in the next section.

- **Physical Models of Anatomy**: The human anatomy is represented through physical, flat fabric organs. Organs were created using two pieces of fabric, cut into anatomically correct shapes, and sewn together.

Figure 25: A snapshot of Prototype 2.1.

- **Sensing of Physiology**: A chest strap sensor, called the Zephyr Bioharness (www.bioharness.com/products/bioharness-3/), was used to sense the user's heart rate and breathing rate.
- **Responsive Output**: LEDs are embedded inside all the organs, minus the stomach, which contains an android phone's screen to display visual animations of stomach digestion. Audio output is also presented in this prototype.
- **Wearable Computer**: An Arduino Uno is used in this prototype as the main computer to control the LEDs in the organs. The android phone in the stomach communicates with the Bioharness and sends its bio-data to the Arduino to control the LEDs.

5.3.2 A High Level View

During the development and upon completion of Prototype 2.0, I discovered that with the sophisticated amount of wiring that BodyVis requires, conductive thread poses many issues ranging from risk of shorts, risk of faulty connections to the Arduino, and risk of insufficient power delivery to LED components.

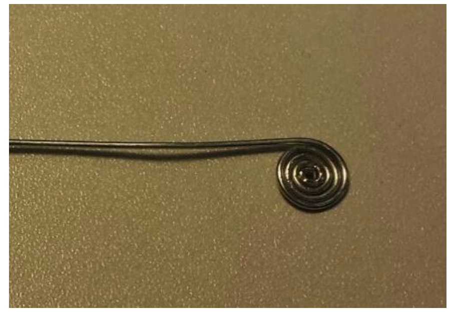


Figure 26: Solid core wire is bent into a spiral shape and used as a point of contact between each removable organ and the shirt.

In order to maintain the weight of the shirt at a low level while also avoiding these risks, I updated my design for Prototype 2.1 to use stranded insulated wire that mimics the flexibility and weightlessness of conductive thread.

In addition, an important design update in Prototype 2.1 is the ability to remove several organs (heart, lungs, liver, and a portion of the stomach) from the

Figure 27: The back of the heart (left) contains three spiraled wires that, when attached to the shirt, turn on its visualization. The heart's points of contact on the shirt (right) can be located using the red "highlighters" and white outline.

shirt to illustrate the overlapping of organs inside the body (Figure 28). This design uses magnets to connect these organs to the shirt. To deliver power and data, a point of contact is made between each organ and the shirt using spiraled wires (Figure 26). These spiraled wires complete the circuit of each organ when it connects with the corresponding spiraled wire on the shirt (Figure 27). This design is identical to connecting two pieces of wire together to complete a circuit. A magnet is located behind each spiraled wire, separated by a layer of fabric, to connect the organs to the shirt.

Figure 28: Magnets are used to connect the removable organs to the shirt.

When detaching the removable organs from the shirt it is sometimes difficult to identify where they must be reattached. I produced two designs to address this issue. First, I placed color-coded “highlighters” around each wire spiral on the shirt to guide reattachment of organs (Figure 27). These highlighters are small fabric circles that surround each wire spiral and correspond in color with the correct organ. For example, the heart has three points of contact with the shirt through the spiral wires. Because the heart is red, users can find these points of contact by locating the red highlighters on the shirt. Next, I used white fabric paint to draw outlines of each detachable organ on the shirt (Figure 27). This provides additional guidance on where to reattach organs on the shirt. These outlines are located under each organ. For example, when a removable organ is detached, its outline is revealed on the shirt.

Prototype 2.1 encompasses the same organs and materials used to create Prototype 2.0, but differs in visual appearance and functionality. Prototype 2.1 has significantly more visual and auditory feedback in comparison to Prototype 2.0. All organs provide visual feedback via LEDs, the stomach provides visual feedback via the screen of an Android phone, the digestive system provides audio feedback, and each organ is labeled to help the user know what each organ is named (Figure 25). These organs are powered and controlled using an Arduino Uno, a Bluetooth shield, and an Android phone.

Figure 29: Prototype 2.1 now uses insulated stranded wire as opposed to conductive thread in the heart and lungs.

5.3.3 Heart and Lungs

Embedded in the heart are eight Neopixel LEDs. These are wired together using stranded insulated wire to provide maximum flexibility. The visualization of the LEDs mimic the heart physically “beating” as blood enters and leaves using red colors by pulsating on and off (Figure 31).

The lungs were created identical to Prototype 2.0 with the exception of using stranded insulated wire to connect them to the Arduino (Figure 29). The visualization was slightly altered to account for a fading in and out affect when the lungs inflate and deflate, respectively (Figure 31).

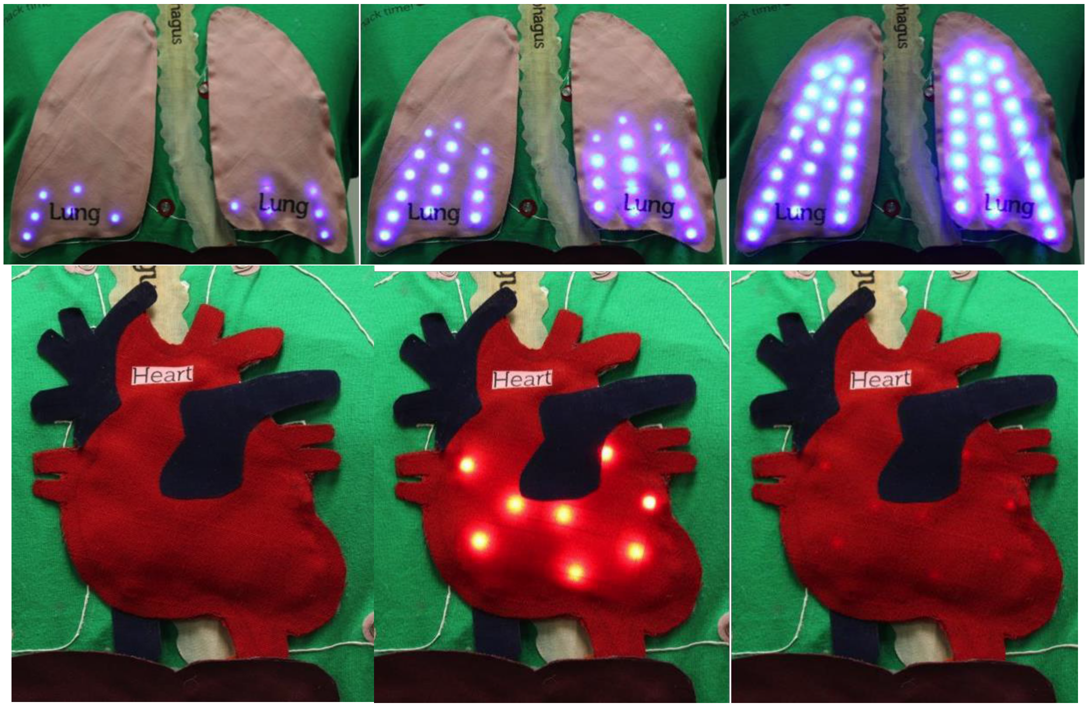


Figure 31: Lungs "inflate" when the LEDs fade on upwards (top left to right), and vice versa when they "deflate." The LEDs in the heart abruptly turn on and fade off to mimic a heartbeat (bottom left to right).

The speed of the visualizations in the heart and lungs are calculated using a Zephyr Bioharness (http://bioharness.com/products/bioharness-3/) underneath the shirt (Figure 30). The Bioharness detects the user's heart rate and breathing rate, transmits the data to a custom-written app in an Android phone embedded in the stomach. The phone translates this data and transmits it to the Arduino (Figure 32). The custom-written Arduino program then sets the rate at which the heart "beats" and the lungs "breathe" to mimic the user's live heart rate and breathing rate. To reduce the weight of the shirt, the Arduino

Figure 30: The Zephyr Bioharness as it should be worn.

and its battery pack are stored in a pouch inside the shirt that hangs from the user's shoulder, similar to a shoulder bag. The Android phones battery pack is also stored in this pouch through an extended wire.

Figure 32: The Bioharness (shown on top of shirt for clarity), Android phone (Galaxy S3 Mini), and Arduino (in pouch) are embedded into the shirt (on top). The Bioharness sends bio-data to the Android phone via Bluetooth; the phone translates this data and sends it to the Arduino via Bluetooth; the Arduino is wired to and controls the LEDs in the organs (on bottom).

5.3.4 Digestive System

The primary change in the digestive system consists of the visual and auditory feedback conveyed through the addition of a modified Android smartphone in the

Figure 33: The "snack time" button triggers the digestive system shown here.

stomach and embedded LEDs in the remaining digestive system organs. The visualization begins with a push of the "Snack time!" button (Figure 33). The esophagus, which consists of a Neopixel LED strip covered with fabric, lights up to illustrate the movement of food traveling down (Figure 34).

The stomach is made of an Android phone with a fabric stomach shape surrounding it. When the food reaches the stomach, the phone plays an animation of the digestive process inside the stomach. During my design evaluation sessions, I gave each child apples to eat to better conceptualize the digestive process. This decision led me to illustrate the breakdown of an apple inside the stomach. This animation illustrates the apple entering the stomach, acid breaking down the apple,

Figure 34: A full cycle of the digestive system visualization from top left to right, bottom left to right. See Figure 35 for the stomach animation.

the stomach walls churning the apple, and finally the apple leaving the stomach (Figure 35). This animation builds in the theme of movement and stomach animation from the second Kidsteam session. The liver, pancreas, and gallbladder begin to glow on at the start of the stomach animation. These organs are made with Neopixel LEDs covered with fabric.

Similar to the esophagus, the small and large intestines are made of LED strips with fabric covering them. When the food reaches the small intestine, the LEDs light up to show the movement of food traveling through it. This visualization continues through the small intestine. At the end of this cycle, when the food reaches the end of the large intestine, a flatulence sound is emitted from the Android phone.

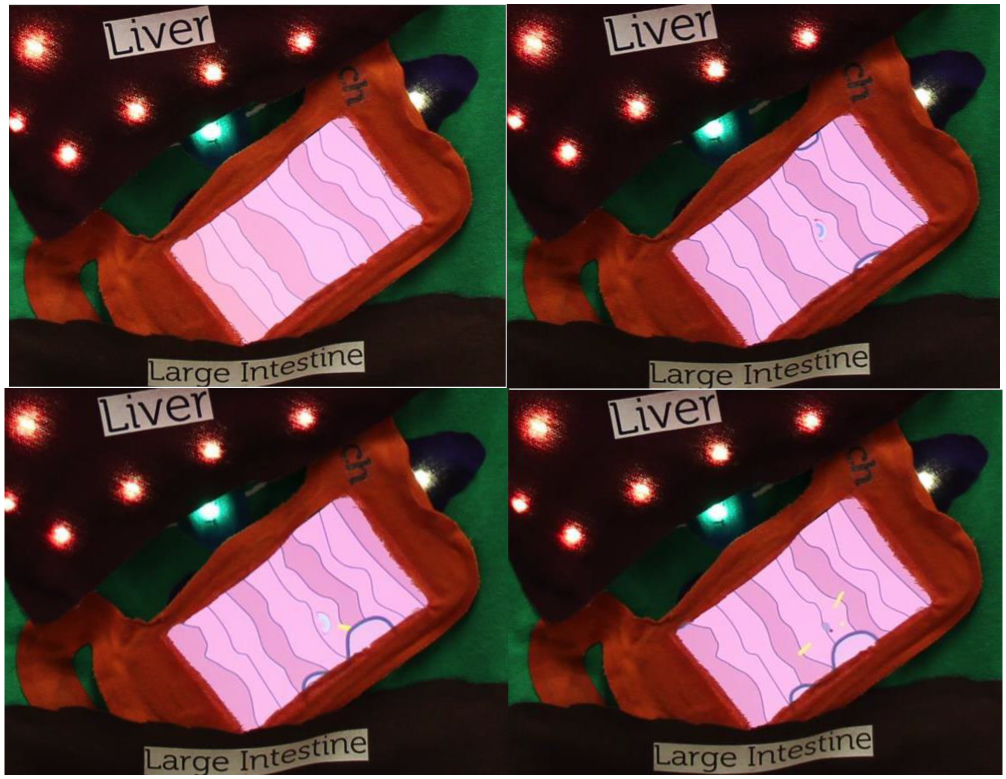


Figure 35: The stomach animation illustrates an apple entering the stomach (top), the stomach walls churning the apple, and yellow acid (bottom) breaking down the apple.

This incorporates the theme of sound from the second Kidsteam session and also captures the playful spirit that our children co-designers suggested. At this point, the liver, pancreas, and gallbladder fade off.

Chapter 6: Design Evaluation and Results

In this chapter, I first describe the technique used to evaluate BodyVis. I then present three participants as examples of BodyVis use, describing each participant's experience with the prototype. Finally, I present a summary of common and distinct behaviors exhibited between the participants.

6.1 Evaluation Technique

Three individual sessions took place to conduct design evaluations for Prototype 2.1 of BodyVis. Each evaluation was comprised of four parts: (i) an introduction and a brief pre-study anatomy/physiology knowledge questionnaire, lasting approximately 15-20 minutes; (ii) a 10 minute demonstration of the BodyVis prototypes; (iii) a 30 minute interactive trial with the shirts where participant volunteers tried on the prototype and engaged in a small number of simple tasks to elicit certain behavior from the wearable prototypes; (iv) a brief post-questionnaire lasting approximately 20 minutes. Each study session lasted approximately 90 minutes in total. Please see Appendix A for the pre-study questionnaire, example tasks, and the post-study questionnaire.

Each session began with "circle time," a technique adopted from Kidsteam sessions used to ease participants into comfortably working with adults and into the session [115]. At the beginning of circle time, each participant was given a bag of apples to eat. To break the ice, participants took turns introducing themselves and answering the "question of the day": *What do you think is happening to the apples inside your body?*

Figure 36: Many Boys and Girls Clubs have designated STEM rooms supplied with computers.

After circle time, participants completed a pre-study questionnaire, based on standard methodology for evaluating children's understanding of body concepts [85, 86], which gathered information about the participants' knowledge on heart, lung, and stomach functionality. Participants were also asked to draw and label any internal organs they were familiar with on the survey. This information provided preliminary insight on the level of knowledge the participants had regarding their internal bodies. Following the survey, the participants watched a brief demonstration of the prototype.

To reduce the researcher:participant ratio, the room was split into two sub-groups. The first group was allowed to play on their own time while the second group participated in the evaluation of the prototype. Two to three participants volunteered from each sub-group to wear the prototype while others observed. Participants were taken to the restroom to privately wear the Bioharness with the help of a female researcher. Before and after each participant tried on the prototype, all areas of the Bioharness that make contact with the skin were wiped down with a disinfecting wipe. Each participant who wore the prototype was given several tasks to perform while observers answered questions I asked them regarding the shirt, asked questions of their own, and often provided additional tasks for the wearer. For example, to increase the wearer's heart and breathing rate, participants were asked to perform several jumping jacks. As a second example: to see how the esophagus, stomach, and digestive system function, the participant was given another pack of apples to eat. Each session ended with a brief post-study questionnaire that mimicked the pre-study questionnaire.

In each session, I presented myself as a researcher to the participants. I conducted and led each session, assigned tasks to the participants, aided participants with their questionnaires at their request, and visibly recorded noteworthy events throughout the session. I also presented myself to the participants as the designer and developer of BodyVis.

Three groups of children between the ages of 6-12 were recruited to participate in three design evaluation sessions in February and March 2014. Each session took place in a Boys and Girls Club of America center. These clubs provide after-school programs for children and are often partnered with the STEM Education Coalition to promote the education of STEM topics outside of the school setting (Figure 36). Participants' parents were notified of the opportunity to participate in the study via the STEM coordinator of the Boys and Girls Clubs. Children were required to receive parental consent to participate as well as provide verbal consent before beginning the study.

6.2 Participants

Participants' ages ranged from 6-12 years of age. A total of 12 male and 18 female children participated in all sessions combined. In each session, there were three different types of participants:

- **Wearers**: These participants wore the prototype while simultaneously interacting with it.
- **Non-wearers**: These participants interacted with the prototype while another participant wore it.
- **Teachers/facilitators**: These participants facilitated groups of children while they were outside of the session.

In this evaluation, I only evaluate and report on the wearers and non-wearers of the prototype, as I am primarily interested in the interactions that children had with the prototype. In the next section, I present one participant from each evaluation session as an example of how BodyVis was used.

6.3 Examples of Use

In each session, participants exhibited several behaviors that were present across all sessions; many participants, however, also exhibited unique behaviors. Each example of use presented here exhibits some of these common behaviors as well as several unique ones. As BodyVis' original target users are second and third grade children (about 7-8 years of age), three participants (one from each session) in this age ranger were chosen as examples of use. Their results cannot be generalized to all children, however they exhibit characteristics that may be present in other users of BodyVis

These example participants are both wearers and non-wearers of BodyVis. I begin with a detailed description of each participant's experience with BodyVis, followed by a summary of common and distinct behaviors exhibited between the participants. Data presented here comes from photographs, audio, and video recordings from each session. All participants have been given pseudonyms for anonymity.

6.3.1 Jim: A Wearer

Jim is an 8-year-old boy in the third grade. The day of the design evaluation session was his first day at the Boys and Girls club. Jim arrived thirty minutes before the session began and spent his time playing on the computer in the STEM lab (Figure 37).

Figure 37: Jim works on the computer alone before the session begins (left). He watches his heart "beating" and his lungs "breathing" as he wears the Bioharness and another participant wears the prototype (right).

As the session began, Jim took a seat next to one of the team members. On his turn during circle time, Jim quietly introduced himself and stated that he did not know the answer to the question of the day (regarding what happens to an apple slice once swallowed inside the body). After patiently listening to everyone introduce themselves, Jim walked over to a table on his own to fill out the pre-study questionnaire and later followed other participants onto the floor for the demonstration portion of the session.

The shirt was revealed with the lights off; participants were told that lights inside the shirt would turn on and display body visualizations. Jim, intrigued with this information, jumped up from his seat on the floor to move closer to the front of the room where the prototype was being demoed.

Jim was in the first group of participants to wear and experience the prototype. A volunteer was needed to wear the Bioharness, and while others were preoccupied with the shifting of children in the room and settling down for the next segment of the session, Jim exclaimed, "*I'll do it!*" Jim was told that he would be taken to the restroom to wear the Bioharness; once again he bounced out of his seat. Eager to test the prototype, Jim began to remove his sweater to wear the Bioharness. A team member stopped him from unclothing further and escorted him to the restroom. Jim

Figure 38: Jim, on his own, finds and begins eating a muffin.

re-entered the room and watched as another participant wore the shirt, asking if he could "*zip it up*." A non-wearer directed Jim's attention towards the heart, saying "*your heart is beating really fast, Jim*!" Jim was told to perform several jumping jacks, but instead began to run laps around the room while other participants cheered him on. Next, he performed several jumping jacks, again following the consensus of other participants. With a smile on his face, Jim returned to the prototype, breathing heavily, listening to other participants as they pointed out that "*his heart is getting faster and faster*" (Figure 37).

Figure 39: Jim watches the digestive system visualization after realizing the heart is removable. Other participants point to where the food is currently located in the digestive system.

Jim asked if he could wear the shirt instead of watching it, and was allowed to do so. He began to show more of his eagerness by attempting to zip up the shirt on his own, a difficult task as it is located on the backside. Immediately after the prototype turned on, Jim began to walk around the room, intrigued at his autonomy. Jim was handed a bag of apples to eat and told to press the snack time button. He watched as the visualizations on the shirt showed him where the food was traveling in his body. Jim finished the bag of apples and decided to take matters into his own hands, walked over to his desk, and picked up a blueberry muffin and began eating (Figure 38). He pressed the snack time button once again, looked down at the shirt, and watched the muffin move through his digestive system. Despite the fact that several non-wearers crowded around him and played with the prototype while he was wearing it, Jim continued to take bites of his muffin and press the snack time button. At one instance, a non-wearer removed an organ from the prototype. Discovering this new ability, Jim took a bite of his muffin, removed the heart from the prototype, and once again watched the visualization of the digestive system (Figure 39). Jim removed the shirt and returned to his desk to complete the post-study questionnaire. At the end of the session, Jim stayed in the room with several other interested participants to ask questions and further explore with the shirt while my team cleaned up.

6.3.2 Emma: A Non-Wearer

Emma is a 7-year old girl in the first grade. She regularly visits the Boys and Girls on Saturdays. As the session began, Emma took a seat next to her friend and quietly talked as the apples were passed around. During circle time, she excitedly discussed the answer to the question of the day with her friend while others began to introduce themselves. Emma introduced herself on her turn and responded to the questions of the day: "*It digests.*" After listening to everyone introduce themselves, Emma walked over to a table with her friend to fill out the pre-study questionnaire and later followed other participants onto the floor for the demonstration portion of the session.

Figure 40: Emma (in pink) wears the removable organs on her own body (left). Even though she is not wearing the Bioharness, Emma jumps along with another participant (in gray) who is wearing the Bioharness (right).

Emma listened to the explanation of the purpose of the session. The prototype was revealed and Emma immediately pointed to the heart and said, "*Look at the heart! ... Look at its lungs*." Further along the start of the session, the prototype was turned on revealing the LED visualizations. Emma gasped at this revelation and clapped with a smile on her face.

Emma was placed in the second group of participants to test the prototype and was sent out of the room to wait her turn. While outside, she noticed a participant going to the restroom to wear the Bioharness and returning to the room. Although it was not her turn to test the prototype, Emma returned to the room with her friend to view the prototype in action. She and her friend sat on the floor, eagerly waiting for the next participant to wear the prototype. They began discussing with other non-wearers what might happen next, contemplating what may happen if they wear the shirt, and pointing at the prototype and whispering about it. When the prototype began reflecting the Bioharness data, Emma pointed out that the heart is beating. The wearer was then instructed to remove a lung. Emma's eyed widened as she asked, "*How is he going to breathe?*" Her eyes were kept locked on the prototype as the next lung and the heart were removed as well. At one point she held her hand to her mouth, possibly due to fear for the participant's life.

Next, the participant wearing the prototype was told to press the snack time button. Emma patiently watched as the visualization began, and quickly reacted when the food reached the stomach, exclaiming to others to look at the apple and asking, "*That's what's happening inside me?*" At this point, another participant volunteered to test the prototype. Emma was told that she would be able to explore with the prototype at the end of the session; this excited her as she wanted a chance to "*play doctor*" with the prototype.

The next participant began by pressing the snack time button to experience the digestive system visualization. Emma expressed her feelings towards this decision by clapping her hands and repeating that it was snack time. Another participant was asked to remove the removable organs from the prototype to reveal the organs underneath. The participant removed the lungs followed by the heart; Emma humorously exclaimed that the wearer was now "*dead*". After each organ removal, Emma gasped and moved closer to the prototype. Near the end of this portion of the session, I asked if other participants wished to try removing some organs. Emma volunteered and began removing each organ one by one, naming each organ along the

Figure 41: Emma (in pink) explores the wiring of the prototype.

way. She realized that the organs were removable because they were magnetic after some exploration of the liver.

Following the post-study questionnaire, Emma and her friend unexpectedly returned to the prototype for some additional exploration. Emma removed one of the lungs and placed it on her chest where her own lungs were located. Her friend picked up the remaining removable organs and placed it on Emma in the correct locations on her body (Figure 40). During this period, another participant asked to wear the Bioharness and watch the prototype function while it was on the mannequin. This participant began to do several jumping jacks while watching the prototype. Even though they were not wearing the Bioharness, Emma and several other participants began jumping along (Figure 40). Emma, like several other participants, wanted to know how the prototype functioned. I explained how I built the shirt and showed

Figure 42: Emma experiments with the prototype by attaching the liver onto the chest where the lung should be.

them the wiring on the inside (Figure 41). After some exploration and questions, Emma asked to play with the prototype a while longer. She began removing and reattaching organs; this gave her the idea to reattach the organs in incorrect locations. Emma switched one of the lungs with the liver and discovered that the lights no longer turned on (Figure 42). She smiled at this revelation, stating, "*That's not right.*" Emma removed the lungs from the prototype and placed it on the researcher helping her, exploring and playing with other organs along the way. Emma finally left the room when it was time for my team and I to leave.

Figure 43: Kate jogs in place to view the effects on the prototype.

6.3.3 Kate: A Wearer

Kate is an 8-year old girl in the third grade. She regularly visits the Boys and Girls club after school before her parents pick her up. Kate was out of school and playing with other children an hour before the session began.

As the session began, Kate took a seat next to one of the team members. On her turn during circle time, Kate introduced herself and stated that the apple "turns to mush" in her stomach. After listening to everyone introduce themselves, Kate walked over to a table to fill out the pre-study questionnaire and later followed other participants onto the floor for the demonstration portion of the session.

Figure 44: Kate removes the lungs to explore the organs underneath.

Kate patiently heard the purpose of the session; she let out an “*Ooh!*” as the prototype was revealed. At this point, the lights on the prototype were not on, but she patiently listened to me describe how it works. Kate was hesitant at first to try on the prototype even after she saw it turn on, but then shyly volunteered to be the first tester. Kate was taken to the restroom to wear the Bioharness. While she was away, the other participants were given a longer demo to experience the digestive system visualization. She returned shortly to the exclaims of her friends telling her “*your heart was beating fast and then it was slow!*” as the prototype paired with the Bioharness while she walked towards the room. Kate smiled and proceeded to wear the prototype. I began to jog, prompting her to jog with me to perform the first task (Figure 43). Kate jogged in place, and was then told to jump on her own several times to observe her heart. Kate became encouraged to jog in place on her own several

Figure 45: Kate (in red) laughs and points at the participant wearing the shirt while holding the heart in her hand.

seconds longer when others continuously made observations about her heart and lungs, smiling as she did so. At the end of this task I joking told her I was tired from jogging, to which she responded, "*I'm not tired.*" She was then told to remove the lungs and observe the prototype without them. Kate removed the lungs and smiled as she observed them front to back before she looked back down at the heart (Figure 44).

Several of the participants pointed out that Kate had not yet experienced the digestive system visualization and wished for her to see it. Kate was given an apple to eat and pressed the snack time button. Before the visualization completed its cycle, another participant told Kate what she would soon experience. Kate observed the digestive system and laughed at the flatulence sound, saying, "*That's funny!*" Because our time was limited, Kate was only able to watch the visualization once on her turn. She removed the prototype to give another participant, Jessie, a turn. Concerned for

Figure 46: Kate (in red) helps another participant reattach the liver.

the Jessie's comfort, Kate asked Jessie if she was sure she wanted to try it on as the Bioharness was "*really itchy in the back.*" Despite this comment, Jessie decided to test the prototype.

Kate was now a spectator participant. She giggled as she watched Jessie put on the shirt, telling her she had "*real big lungs*." Before Jessie was given any tasks, a participant asked if they could experience the digestive system visualization once again. Jessie was told to remove her lungs and heart; Kate volunteered to hold the heart while Jessie was given an apple to eat (Figure 45). Kate patiently watched as the visualization neared the end of the cycle. Once again, Kate, along with all the participants, laughed loudly at the flatulence sound. Kate exclaimed, "*You farted, Jessie!*"

Figure 47: Kate removes the heart and tells everyone she is "half dead" (left). She then removes the remainder of her organs and lies down on the floor claiming she is dead (right).

Jessie was told to remove the liver and examine what was underneath. Upon reattaching the liver, Jessie had problems finding its location on the shirt. Kate jumped up with an "*Oh! Oh! Oh! I got it*," and volunteered to help find its location. Kate noticed some of the highlighters on the shirt and silently told Jessie "*it [the liver] matches with the color*" of the highlighters (Figure 46). I asked Kate to tell everyone how she knew where to place the liver, to which she responded, "*Follow the outline … the color, the outlines, the magnets.*"

A third participant, Lana, was given the opportunity to try the prototype on. While Lana went to the restroom, I asked the participants if they wanted to play with the prototype without the Bioharness. Kate, wanting to volunteer again, shouted out "*Me! Me! Me!*" She quickly decided her friend, Jane, should have a turn and said, "*Oh, I think Jane should go. Jane, you try … Jane, try to do the fart thingy!*" Jane, seemingly shy to test this out, declined to volunteer. With this decline, Kate said, "*I would like to [try]! I like the fart thingy.*" Kate tried on the shirt once again, this time given the opportunity to explore the prototype on her own as she had already performed the tasks from our protocol. Kate first removed the heart and gasped, "*I'm dead! I've got no heart*" (Figure 47). She began to role-play as a doctor trying to fix the heart. This removal of a vital organ was seemingly quite interesting for Kate. She began a series of exclamations as others laughed at her explorations: "*I'm dead, but I'm really alive … Jessie, I'm holding my heart!*" Kate observed that she was "*half dead half alive*". To remedy this condition, Kate removed the remainder of her organs and said, "*now I'm totally dead*" as she lied down on her back on the floor (Figure 47).

Kate now wished to experience the digestive system visualization one again. She was given an apple, pressed the snack time button, giggled as the visualization reached the end, and laughed once more at the flatulence sound (Figure 48). To prepare them for Lana's tasks, I asked the participants what they wanted Lana to do

Figure 48: Kate laughs at the flatulence sound (left). She dances around the room to demonstrate the tasks that the next participant should perform (right).

while wearing the prototype. Kate demonstrated by skipping, jogging, and dancing around the room with the shirt (Figure 48).

Figure 49: Kate (in red) instructs Lana (wearing the prototype) to lift her leg at the flatulence sound. They both laugh at this sound effect.

Lana returned and began to wear the prototype. At this point, none of the removable organs were on the prototype. Kate explained to Lana, "*Now you're dead, so now we're going to make you alive again…because you don't have any [organs].*" Jane, who shied away from wearing the prototype before, decided to help Kate put the organs back on the prototype. At first Jane had trouble locating where to reattach the heart, but with Kate's help, who told her to "*follow the red bands [highlighters]*", she was able to reattach the heart in the correct position. The participants reattached all the organs, and now wished to watch the digestive system visualization once more. Kate wondered if she could customize this action with the help of Lana. Kate instructed Lana to lift her leg up on Kate's command. Kate narrated parts of the digestive system as Lana watched the visualization reach the end of its cycle. On Kate's command, Lana lifted her leg up seconds before the flatulence sound; all the

Figure 50: Kate returns once again at the end of the session to detach and reattach several organs.

participants laughed at this new interaction (Figure 49). Kate and Lana continued doing this two additional times, until it was time to complete the post-study questionnaire. Kate completed the questionnaire and spent several minutes detaching and reattaching several organs one final time before her parent took her home (Figure 50).

6.4 <u>Results</u>

Several commonalities emerged in the behaviors of these examples of use that corresponded with three of the design goals presented in Chapter 3: engagement, excitement, and curiosity. Although these themes are not generalizable to all users of BodyVis, the examples presented here suggest that BodyVis has the potential to engage, excite, and spark children's curiosity in body learning. Results also suggest that non-wearers can potentially be engaged in body learning while interacting with BodyVis, although additional evaluation is needed.

6.4.1 Engagement

Engagement was depicted through a series of characteristics: active participation in utilizing the prototype, touching the prototype, performing physical activities, and making vocal observations about the prototype. Here I will illustrate how each participant exhibited engagement with the prototype.

Jim

When Jim first wore the Bioharness, he ran several laps around the room and quickly returned to watch the visualizations on the prototype. While doing so, he also performed several jumping jacks and watched as his heart and breathing rate began to increase; Jim was engaged with the prototype's visual feedback of his physical activities.

Jim pressed the snack time button and watched the digestive system visualization a total of 5 times in the 4 minutes he was wearing the prototype. Each visualization cycle lasts approximately 50 seconds, which shows that Jim pressed the snack time button every time the digestive system visualization ended. Jim was constantly engaged in watching the visualizations on the shirt while he was wearing the prototype.

Jim was never distracted away from the prototype. He never vocally complained or voluntarily left the session. While Jim was wearing the prototype, several of the other participants gathered closely around him and began to talk loudly and remove organs from the prototype. All the while, Jim was staring down at the digestive system visualizations as the food he was eating traveled through his body.

Emma

Emma was vocally observant of many events that took place during the session. She consistently pointed at the prototype and stated what was happening, whether it was the heart beating, the lungs breathing, or the wearer being "dead." Her attention was on the prototype whenever a visualization took place.

Although she was engaged during the session, Emma was most engaged when she was personally interacting with the prototype after the session ended. During this period, Emma explored with the prototype by removing several organs and placing it on her own body. She also participated in performing several jumping jacks while another participant wore the Bioharness. These actions show Emma actively participating with the prototype despite the fact that she was not wearing it.

Kate

Kate often made vocal observations that hinted at her engagement with the prototype. For example, while exploring the liver she discovered that the highlighters' colors correspond with the organ colors and vocally expressed this observation. When another participant had trouble reattaching the heart to the shirt, Kate informed her to follow the outlines of the heart on the shirt and to follow the highlighter colors. Kate also narrated the digestive system visualization for a participant, keeping them both engaged in watching the visualization.

Kate was continuously interacting with the prototype throughout the sessions. For example, she removed different organs and pretended she was partially alive. She also removed every organ all at once and observed that she was no longer living. Kate's experimentations with the organs and constant vocal observations show that she was continuously participating in exploring the prototype.

6.4.2 Excitement

Excitement is depicted through a participant's willingness to volunteer, performing tasks without receiving prompts, raised voices, and the desire to experience a particular event multiple times. Here I will illustrate how each participant exhibited excitement for the prototype.

Jim

Jim was one of the first participants to volunteer to wear the prototype and Bioharness. In fact, he volunteered several times to wear the Bioharness and the prototype. His eagerness and excitement was clear from the beginning when he began to remove his sweater and was stopped from unclothing further by my team members. Jim volunteered to perform tasks without being asked to do so. This was apparent in several of his actions:

1) Jim was eager to zip up a fellow participant to optimize the speed of the session. Later on, he wanted to zip up the shirt while he was wearing it himself, a difficult task to perform as the zip is on the backside of the prototype.

2) Although he was told to do jumping jacks, through the encouragement of other participants, Jim ran several laps around the room to raise his heart and breathing rate.
3) When Jim wore the prototype, he voluntarily found a muffin and began to eat it, press the snack time button, and watch the digestive system visualization.
4) Before even being asked to remove organs, Jim removed the heart from the prototype and once again watched the digestive system visualization.

Emma

Emma was eager to begin testing the prototype before her turn. She quickly returned to the room after she was sent outside to wait. Several times throughout the session her voice raised in exclamation as she made observations about visualizations on the prototype (*e.g.,* claiming that the wearer was "dead", loudly repeating observations). She also clapped her hands whenever she was particularly interested in an event that would soon take place (*e.g.,* snack time).

Emma never wore the prototype, however she did express interest in playing with it several times. She volunteered to remove several of the detachable organs to examine them more closely. Emma also asked if she could "play doctor" when the session was over. After the post-study questionnaire she returned to the prototype and asked if she could play a few minutes longer.

Kate

Kate showed signs of excitement primarily through her constant willingness to volunteer. Although initially shy, Kate was the first to volunteer to wear the prototype. She continued to volunteer for various tasks throughout the session; these tasks ranged from wearing the prototype to holding organs while others explored the prototype to helping her fellow participants reattach organs. Another indicator of Kate's excitement is her constantly raised voice. Kate often shouted her desire to volunteer to wear the prototype. She was told twice to give others a turn to wear or interact with the prototype.

Finally, Kate's excitement extended into her desire to perform tasks without being asked to do so. When she was given the opportunity to explore with the prototype, Kate wanted to "play dead" with the prototype by removing the heart. She also wanted to experience the snack time visualization several times to assist a fellow participant in customizing the end result of the cycle. Kate performed this task at least three times before the session was over.

6.4.3 Curiosity

Curiosity is depicted through a participant's strong desire to know how the prototype functions, what the prototype is doing, what a visualization implies, or any other inquiries regarding the prototype. Here I will illustrate how each participant exhibited curiosity for the prototype.

<u>Jim</u>

Jim was not very vocal throughout the session. He relied mostly on other participants to ask questions about the prototype. However, his curiosity sparked while he was physically wearing the prototype. Jim watched the digestive system visualization three times while the heart and liver covered other organs in the digestive system. At times the LED indicating the path of the food in the digestive system would disappear under other organs. A non-wearer then removed an organ from the prototype; Jim realized that the heart was removable and removed it to reveal the full digestive system underneath. Jim pressed the snack time button twice after removing the heart to watch the visualization in full, unobstructed view.

Emma

Emma's curiosity sparked when she saw the first person wearing the prototype. She and her friend began discussing what may happen if they wore the prototype themselves, whispering in one another's ear and pointing at the prototype. As other participants explored the functionalities of the prototype, removed organs, and watched the visualizations, Emma often asked questions such as "How is he going to breathe?" and "That's what's happening inside me?" She was additionally interested in seeing the effects of incorrectly reattaching the removable organs to the prototype. This action probably resulted from her curiosity of how other organs on the prototype functioned without the presence of the heart.

Emma's curiosity extended to the anatomy of the prototype itself. She was not only interested in what she saw on the outside but also what existed on the inside of the prototype. Emma wanted to know how the prototype functioned, what made it turn on, and how I built it. She spent several minutes asking questions about the development process as she explored the wiring within the prototype.

Kate

Kate showed almost no signs of curiosity. Although she was thoroughly engaged with and excited about the prototype, she rarely asked questions regarding how it worked or what was happening. In contrast, she made many observations and discoveries on her own that she relayed to other participants in the session who showed signs of curiosity.

Chapter 7: Discussion, Future Work, and Conclusion

This research is the first exploration of a digitalized manifestation that actively visualizes and responds to the anatomy and physiology of the wearer. Though the prototypes discussed in this thesis are preliminary, the Boys and Girls deployments help demonstrate BodyVis' potential as a way to engage, excite, and promote curiosity in children about the body.

7.1 <u>**Discussion**</u>

Findings from both Kidsteam sessions were valuable guidelines in designing BodyVis. These findings showed that children were interested in color, sound, light, movement, and stomach animation. In each design evaluation session participants focused a great deal on the LED visualizations with particular interest on the digestive system. The constant repetition of pressing the snack time button suggests that children were potentially interested in the sound, lights, and movement presented in the digestive visualization. In Kate's example, she and several other participants patiently watched the visualization reach its end several times with hopes of customizing the sound effects of the prototype with their own actions (*ie*. lifting a leg at the flatulence sound). This aspect of play and exploration of the prototype was largely what led to the engagement of children in the body learning process.

An important discovery during the evaluation sessions was that of the engagement of both the wearer and non-wearers of the prototype. Although some non-wearers were, admittedly, not engaged, most exhibited signs of engagement. Similarly, some participants showed interest in the prototype even while it was on display on the mannequin. During the end of each study session, the prototype was placed on a mannequin and some participants would experiment with removing organs, reattaching them in different locations, and placing them on their *own* bodies. The connection that children made between the prototype and their own bodies, even while it was on display, was surprising at times. This connection was seen in Jim's example during as he felt a strong connection between his own body and the visualizations on the prototype when he ate his apples and muffin. Kate also explored with placing organs on correct areas of her own body. The participants' engagement in the prototype while on display may be due to the prototype's ability to offer the user an interactive experience, even when no one is wearing it, through the detachable organs.

An unexpected interactive element that emerged from the sessions was the non-wearers' ability to guide the wearer's actions. For example, both Jim and Kate performed physical activities such as running, dancing, and jumping jacks as a result of the non-wearers' enthusiastic guidance to perform them. This relationship between the wearer and the non-wearers shows that a teacher with only one BodyVis shirt may, perhaps, be able to promote engagement and interactivity in body learning for all students in the class. Emma's shows an example of this through her curiosity about her body throughout the session. She was often surprised that what she was seeing on the prototype was a representation of her own body.

A related additional unexpected discovery from the sessions was the emergent peer tutoring that occurred among participants (*e.g.,* participants began aiding each other in reattaching removable organs). Kate's actions exemplify this: several times in the session, she taught other participants how they could find the correct location of each organ on the shirt. This discovery presents new avenues for future work with BodyVis in the classroom through peer tutoring

7.1.1 Modes of Engagement

The three examples of use presented in Chapter 6 show some commonalities in their engagement, excitement, and curiosity for the prototype, but illustrate three different modes of engagement: experimenting, questioning, and mentoring. These modes show different ways in which the participants engage with BodyVis.

Experimenting

This mode was most exhibited through Jim. Jim experimented with the prototype primarily when he was exploring the digestive system visualization. He showed a desire to experiment with this visualization in different ways, including eating different foods and watching the visualization with and without specific organs on the shirt.

Perhaps it was the connection Jim felt between his own body and the illustrations on the prototype that led him to this experimentation. The ability to manipulate the shirt by detaching and reattaching organs may have also led him, as well as other participants, to this mode of engagement. For example, Kate experimented with detaching only her heart to see if the lungs would still function, and similarly detached only her lungs to see if she would still be able to breathe. This experimentation often led to different modes of engagement, such as questioning.

Questioning

This mode was most exhibited through Emma. Although she was a non-wearer participant in her session, Emma was inclined to ask many questions about what the shirt was doing, whether or not the representations on the shirt reflected her own anatomy and physiology, and how the prototype was built.

Other participants, primarily non-wearers, exhibited this mode of engagement as well. This questioning may be due to a number of factors:

- Participants' curiosity towards a novel device
- Participants' curiosity towards the reality of the representations presented on the prototype
- Non-wearer's inability to interact with the shirt due to crowding around the wearer
- The physical presence of the designer and developer of the prototype in the session

These factors are among many that were seen in participants of each session.

Mentoring

This mode was most exhibited through Kate. Kate was interested in mentoring other wearer's experiences and interactions with the prototype. She offered her aid regardless of whether or not the wearers requested it. Kate, similar to several other participants, helped the wearer reattach organs to the shirt. She proceeded by mentoring the wearer on how to relocate the correct area of reattachment.

Kate also customized other wearer's interactions with the prototype. For example, she mentored a wearer to lift her leg at the flatulence sound to make it appear as though the wearer was producing the sound. Once again, a connection is seen here between the wearer's own body and the illustrations of the prototype.

7.1.2 Going Under the Hood

One of the most unexpected, and possibly most significant, observations from the evaluation sessions was the participants' desire to know how the prototype works, how it was built, and how it functioned. At the request of the participants, I dedicated several minutes in each session to show them the wiring under the shirt and the Arduino running the prototype's visualizations. This "show-and-tell" seemed to spark the interest of many participants—they asked if I programmed the visualizations, built the prototype by hand, and how I knew what to do. Many questions were related to basic concepts of computer science (*e.g.,* programming) and electrical engineering (*e.g.,* building the prototype), especially when participants were able to see the Arduino and wires. Children are generally accustomed to using everyday technology such as computers, tablets, and smartphones without asking questions about how they work. Therefore, it is important to understand the reasoning behind the participants desired to "go under the hood" to understand how the prototype was built and functions, and to explore the implications of these desires. Although a formal interview was not conducted with the children to understand the reason behind this questioning, several factors may allude to why the participants were eager to go under the hood.

BodyVis shows the user a glimpse of its inner workings when organs are detached. The user can essentially take apart pieces of the prototype without breaking it and simultaneously understand some of how the prototype works. The participants generally seemed to understand, after removing one organ, that power reaches each organ when it is attached to the shirt. It may be their ability to manipulate and the shirt and view what is underneath that encouraged some participants to ask questions.

BodyVis uses everyday fabrics and clothing to display bio-data to the user. Another factor in the participants' questioning may be the novelty of experiencing technology embedded into their everyday objects. In these evaluations, participants were presented with clothing already embedded with technology, but previous work has shown that crafts and computational textiles can engage children in learning topics, such as computer science, when children embed their own technology into everyday objects [16]. In the future, one may use a hat, for example, to display brain activity data. This use of an everyday object may promote further questioning of how the device functions.

The ability to talk to the designer and developer of such a device may have encouraged the participants to ask questions. Generally children are handed mass-produced technology to use without ever meeting, corresponding with, or talking to the team behind the development those products. In these sessions, the participants were given that opportunity. Several participants in each session seemed surprised when I told them I built the prototype myself; this generally happened after they saw the wires inside the shirt. Participants may have felt surprised because the tangled wires intimidated or overwhelmed them, causing them to believe that the development of such a device is a difficult task.

Additionally, the participants may have been surprised to see that the designer, developer, and engineer of BodyVis is female. Children often believe certain science courses are better suited for males than females, and female children often believe the stereotype that scientists are male [2, 14, 32, 48]. Although the participants did not verbally confirm this, it is possible that the break in this stereotype and ability to talk to a female engineer was a factor in the children's desire to ask questions about whether or not I personally built the prototype.

Participants in the sessions did not wish to simply be a user, but rather they wanted to understand how BodyVis worked. The implications behind this desire to go under the hood may suggest ways in which we can encourage children to tinker and make on their own, and consequently pique children's interest in STEM topics.

7.2 Contributions

The overarching contribution of this thesis is the design, development, and evaluation of a novel way of engaging children in body learning through reactive wearable sensors and visualizations. This thesis provides both formative and summative contributions.

7.2.1 Formative Contributions

This thesis offers new insights into how children think about visualizing their bodies and how this can be used to inform body-learning designs. These insights are formed by two Kidsteam sessions and the themes that emerged from each session. Collectively these themes suggest that body-learning designs should include color, sound, light, movement, and a detailed representation of stomach animation.

7.2.2 Summative Contributions

This thesis offers preliminary evaluations of a prototype for children's body learning engagement. Through our initial deployments at three Boys and Girls clubs, I show that BodyVis has the potential to engage, excite, and spark curiosity in children to learn about their anatomy and physiology.

7.2.3 Secondary Contributions

As a secondary contribution, I demonstrated that wearables and e-textiles may engage children in learning STEM topics. Participants in the sessions did not wish to simply be a user, but rather they wanted to understand how BodyVis was programmed, built, and how it functioned.

7.3 Limitations

There is a novelty effect with BodyVis as it embeds technology into an everyday object. This may have been a factor in the some of the participants' interest in the prototype. Moreover, a researcher bias existed when conducting the evaluation sessions. I assigned tasks to the participants as opposed to allowing them to explore with the prototype and observing their actions.

Each prototype in the iterative design process had its own set of limitations. For the most part, the limitations in Prototype 1, discussed in Chapter 4, were overcome in Prototype 2. Prototype 2, however, had its own challenges. For example, Prototype 1 offered a tactile, plush interactive experience to users whereas Prototype 2 removes this 3D feature to prevent from organ occlusion.

The development of any BodyVis prototype requires making a choice in how each organ will be represented. In Prototype 1, for example, the visualization in the lungs represented blood flow in the lungs, whereas in Prototype 2.1 the visualization represented airflow in the lungs. There is an inevitable tradeoff between selecting an accurate visual and behavioral representation of each organ and the approachability/understandability of that representation—indeed, these sorts of tradeoffs are well-known in the education literature [27, 110]. Moreover, a more detailed and realistic rendering of each organ would require a far more complex physical and electronic design. For example, the four chambers of the heart are not visualized in the prototypes nor is the flexing/contracting motion of the heart muscle. Adding an LED array that could visualize the opening and closing of the heart ventricles would greatly increase the complexity of the design. Alternatively, as new wearable displays emerge (*e.g.,* T-Shirt OS [101]), the heart (or even all internal organs) could be represented by a high density, flexible LED array.

Prototype 2 automatically senses heart rate and breathing rate, but does not sense real time locations of food in the body. This design was specifically not implemented because it takes an average of 24 hours for food to travel through the digestive system. For the purpose of this research, it is not feasible to allow the digestive system visualization to cycle over 24 hours. However, if such a feature were implemented, it would display a more anatomically correct visualization of each organ and offer live data throughout the prototype. Again, this relates to how to properly represent body form and function with our anatomical models and responsive visualizations.

In the next section I will discuss how these limitations can be overcome in future work and how other avenues of research can be explored using BodyVis.

7.4 Future Work

BodyVis is a tool developed to engage children in body learning through wearable sensing and visualization. I would like to explore different representations of the current BodyVis organs as there is an inevitable tradeoff in any representation of these organs. In Prototype 1, for example, the visualization in the lungs represented blood flow throughout the lungs, whereas in Prototype 2.1, the visualization represented airflow. It may, however, be possible to increase the understandability of these organs by creating multiple representations of them, providing additional haptic and audio feedback, exploring different visualizations, or attempting to improve the realism of the current models.

One can also envision using different medium of clothing to display anatomy

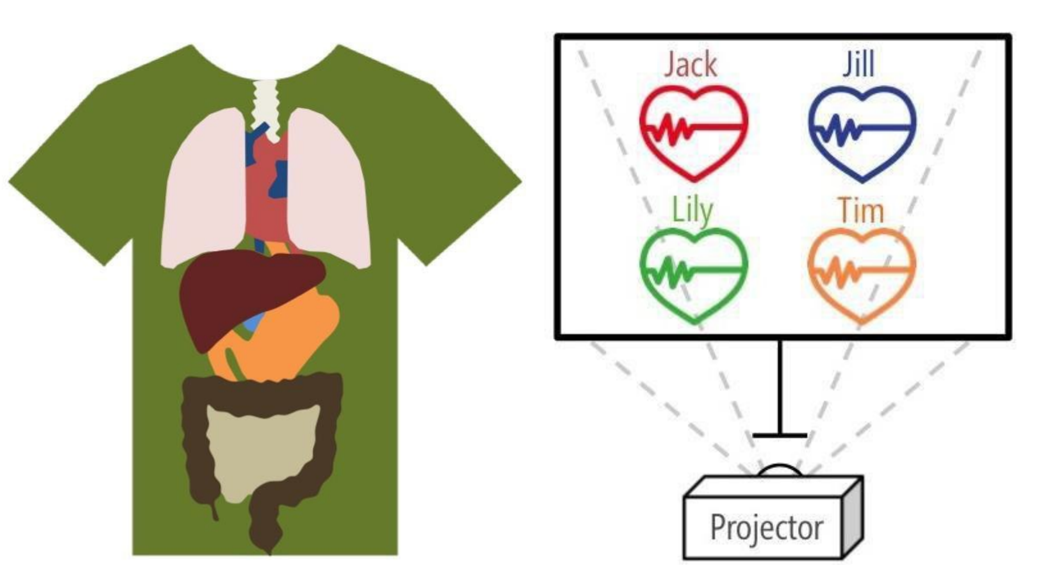


Figure 51: A shared view tool allows a classroom to view every student's bio data simultaneously

and physiology. For example, a hat can be designed using the guidelines from the Kidsteam sessions to display brain activity. Pants can be designed to show the anatomy and physiology of legs and feet. A full body suit can show multiple organs and their relationships to one another simultaneously.

Although the evaluations presented in this thesis show that both wearers and spectators of BodyVis can potentially be engaged in body learning, it will be of interest to evaluate classroom settings where every child is in possession of a prototype. Interactions in these settings may differ when children can view both their own physiology as well as their peers'. In the future, one may explore the use of BodyVis to support scientific inquiry skills in the classroom and support life-relevant learning more generally Figure 51. These interactions can promote social constructivist approaches to learning by encouraging peer-to-peer and collaborative learning.

Figure 52: BodyVis scrubs may aid in public health settings.

BodyVis may also be used in the public health setting, specifically for children. These organs can easily be implemented onto pediatric scrubs (Figure 52). Pediatricians may use BodyVis scrubs to educate children about their bodies, ease children into learning about diseases and illnesses, and allow children to feel more comfortable in a doctor's office. BodyVis may also be altered to show illnesses in the body through "sick" organs (*eg*. damaged lungs from smoking) to further aid not only children, but also adults in learning about their bodies.

Finally, I would like to implement a Do-It-Yourself (DIY) tutorial for schoolteachers to create their own versions of BodyVis to share with their community and to help improve the education of anatomy and physiology for primary school children. This tutorial may also help promote computer science and electrical engineering education for children.

7.5 Conclusion

In this thesis I have introduced BodyVis, a wearable e-textile shirt that combines embedded sensing and interactive visualization to reveal otherwise "invisible" parts and functions of the human body. BodyVis aims to transform how learners engage in learning and understanding body concepts. Two prototypes were designed using thematic guidelines from two cooperative inquiry sessions with children. The updated prototype was tested in three design evaluation sessions, and an example of use was presented from each session. Findings from these sessions showed that BodyVis has the potential to engage, excite, and pique both wearers and non-wearers curiosity in body learning. The work presented in this thesis is exploratory in nature and is an initial step towards developing a product that can engage children in body learning. Further evaluations and iterations are necessary to address the presented challenges and limitations.

Appendices

Appendix A: Design Evaluation Sessions

I. Minor Assent Script

My name is [researcher's name]. Today we're going to ask you to play and interact with some new kinds of shirts that are meant to help teach you about your internal body parts like your lungs, heart, and stomach.

Is it OK with you if we record what you say using a video camera so we can look back at what you did later? Your name will never be connected to any information we get from the recordings.

Great, we'll get started then. If at any point you want to stop for any reason, or want to stop the recordings, let us know and we'll stop.

II. Pre-Study Questionnaire

Hi!

How old are you? ____________________

What grade are you in? ________________

Are you a boy or a girl? _________________

What do you think your **heart** does?

____

____

What do you think your **lungs** do?

____

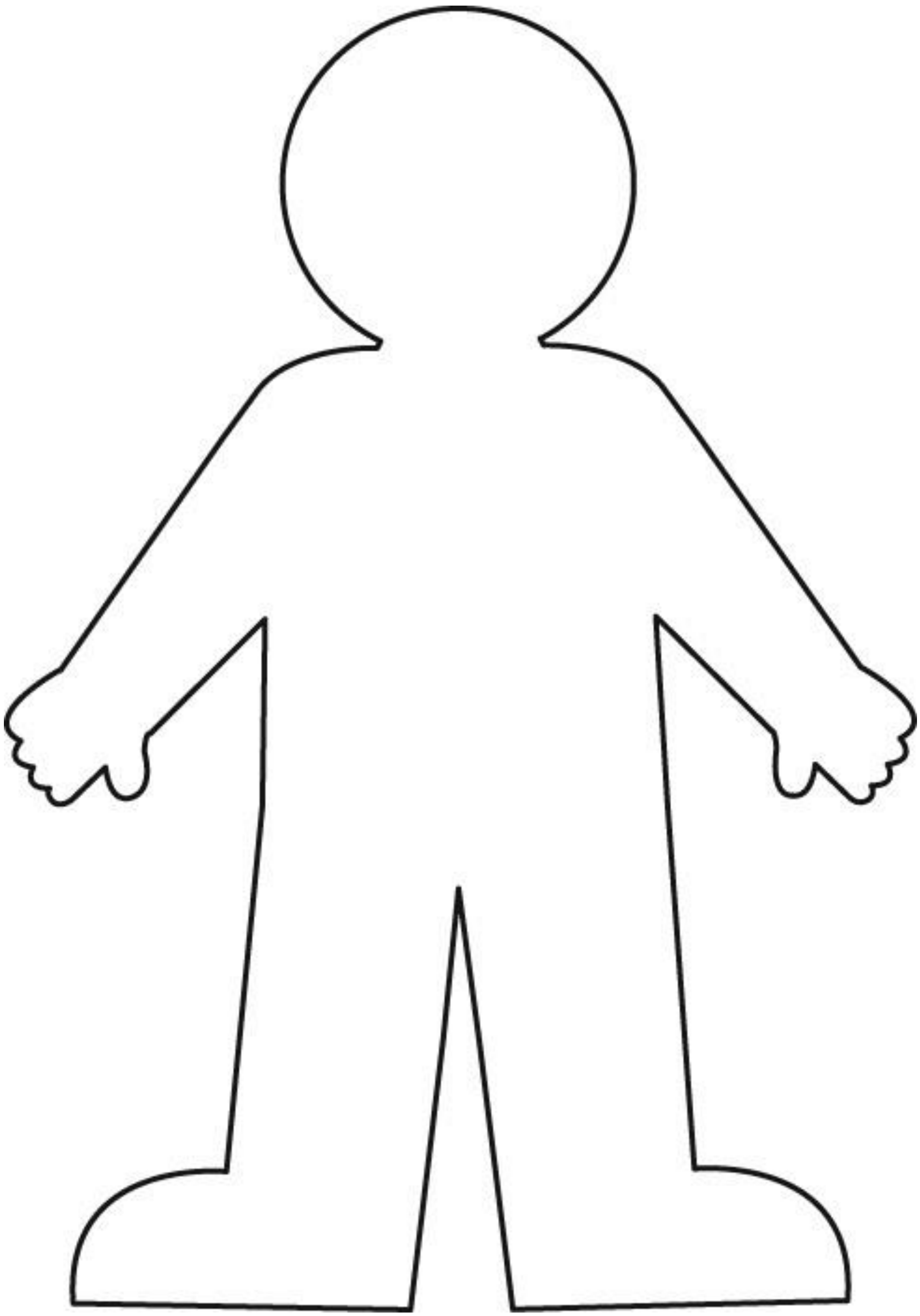
____

What do you think your **stomach** does?

____

____

Draw all the organs inside your body that you know. Label them and draw them the way you think they look. Be as specific as you can.



III. Participant Tasks

1. Find your heart. Describe what happens in your heart.
2. Find your lungs. Describe what happens in your lungs.
3. Swallow some [saliva/water/participant's own food]. Watch it move through your digestive system.
    a. Find the starting point of the digestive system.
    b. Find the organs that are always working when you swallow something.
    c. Find the ending point of the digestive system.
    d. Describe what happened when you swallowed.
    e. Name all the organs that are in the digestive system. Describe what happens in each organ.
4. Let's do some jumping jacks. (Jumping jacks for a couple seconds.) Now take a look at your body. Find/identify anything that changed.
5. Take a couple deep breaths. Watch your lungs as you do. Describe what happens.

IV. Post-study Questionnaire

What do you think your **heart** does?

____

____

What do you think your **lungs** do?

____

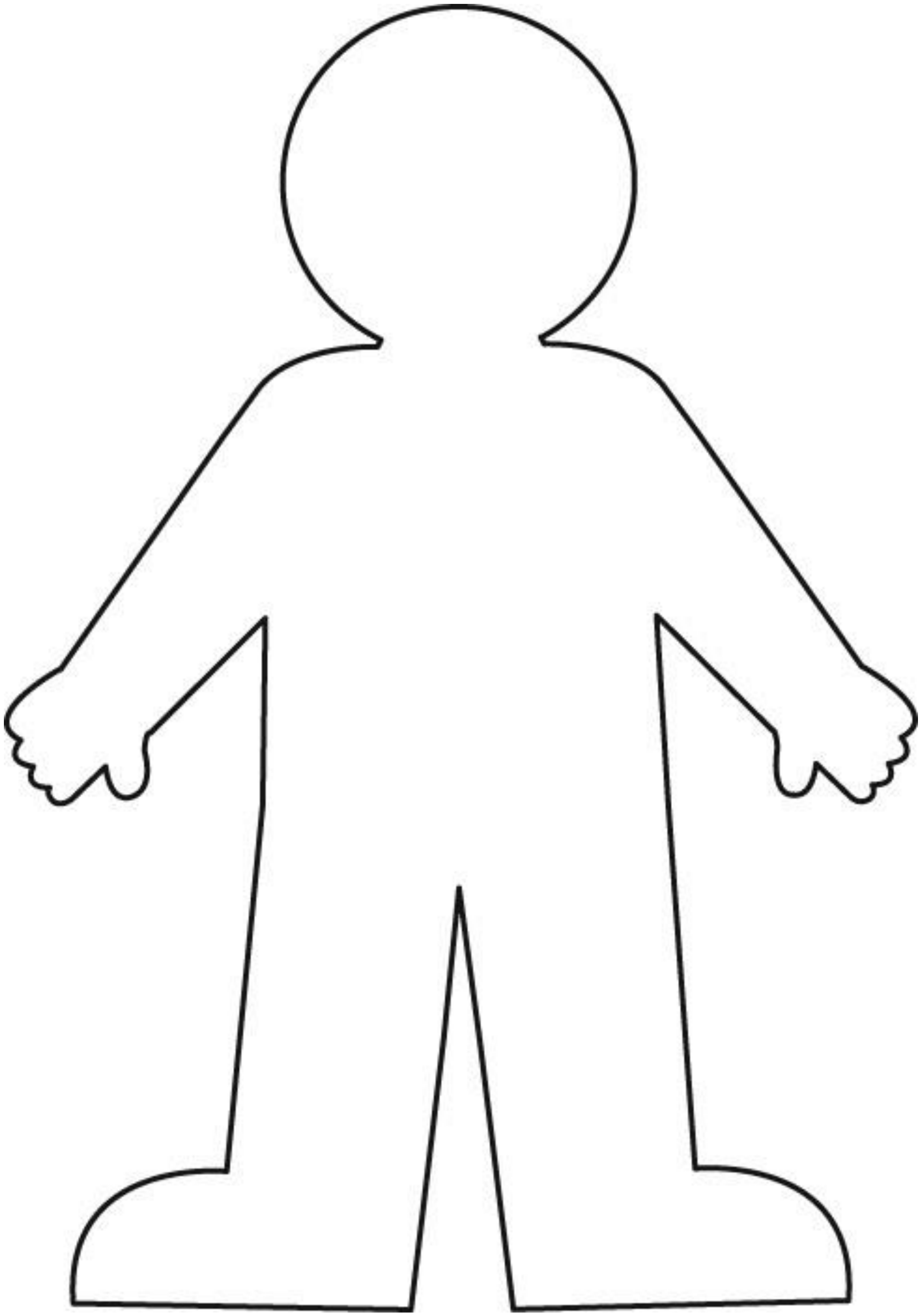
____

What do you think your **stomach** does?

____

____

Draw all the organs inside your body that you know. Label them and draw them the way you think they look. Be as specific as you can.



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