SharedPhys: Live Physiological Sensing, Whole-Body Interaction, and Large-Screen Visualizations to Support Shared Inquiry Experiences

Seokbin Kang[1], Leyla Norooz[2], Vanessa Oguamanam[1,2], Angelisa Plane[1], Tamara L. Clegg[2,3], Jon E. Froehlich[1]
Makeability Lab | Human-Computer Interaction Lab
Department of Computer Science[1], College of Information Studies[2], College of Education[3]
University of Maryland, College Park
{sbkang, leylan, vanogu, aplane, tclegg, jonf}@umd.edu

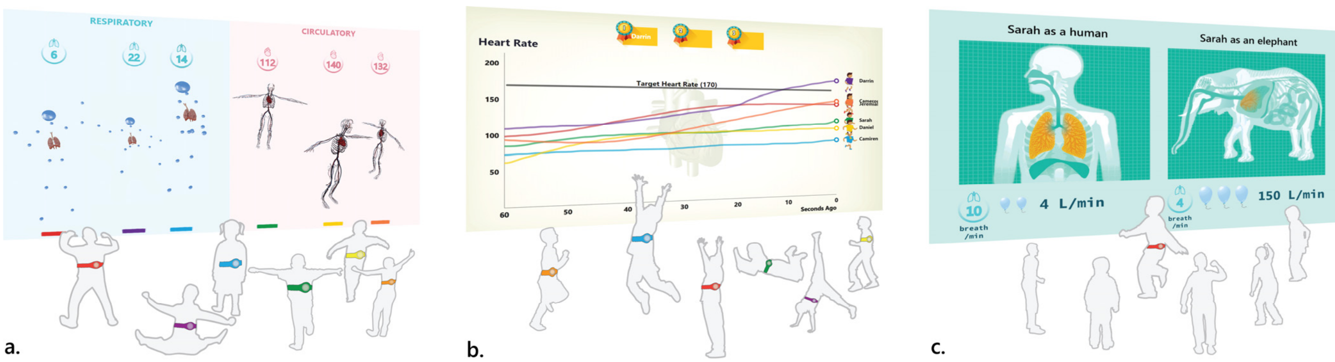

Figure 1: *SharedPhys* combines physiological sensing, whole-body interaction, and real-time large-screen visualizations to create new types of embodied interactions and learning experiences. Shown above, our three interactive SharedPhys prototypes: **(a)** Magic Mirror, **(b)** Moving Graphs, and **(c)** Animal Avatar.

ABSTRACT
We present and evaluate a new mixed-reality tool called *SharedPhys*, which tightly integrates real-time physiological sensing, whole-body interaction, and responsive large-screen visualizations to support new forms of embodied interaction and collaborative learning. While our primary content area is the human body—specifically, the respiratory and circulatory systems—we use the body and physical activity as a pathway to other STEM areas such as biology, health, and mathematics. We describe our participatory design process with 20 elementary school teachers, the development of three contrasting SharedPhys prototypes, and results from six exploratory evaluations in two after-school programs. Our findings suggest that the tight coupling between physical interaction, sensing, and visualization in a multi-user environment helps promote engagement, allows children to easily explore cause-and-effect relationships, supports and shapes social interactions, and promotes playful experiences.

Author Keywords
Physiological sensing; large-screen displays; mixed-reality; scientific inquiry; collaborative learning; STEM; wearables

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI).

INTRODUCTION
With the emergence of body-tracking technologies such as *Fitbit* and the *Microsoft Kinect*, there has been increased interest in exploring how *embodied interaction* [14] can enable and support new learning experiences [34]. Recent work by Lee *et al.*, for example, helps demonstrate the potential of wearable activity trackers and interactive visualizations to engage children in scientific inquiry that is authentic and life-relevant [36, 37]. Often citing the role of embodiment in cognition [56], others have explored utilizing the entire body through movement or gesture to support new forms of computer-mediated learning [31, 34]. Though a nascent area, research suggests that these whole-body interactions can help increase engagement [1, 62] and immersion [1, 69], support and shape social interaction [59, 69], and aid learning [31].

Building on the above work, this paper introduces and evaluates *SharedPhys*, which integrates live-streaming physiological sensors, whole-body interaction, and real-time large-screen visualizations to create a novel mixed-reality learning environment. With SharedPhys, children interact *physically*—both explicitly via body movement, gesture, and position as well as implicitly via their changing physiology. While prior work has explored body-centric inquiry (*e.g.,* [32, 36, 37]), the data collection and subsequent analyses are often disjoint and performed on a traditional computer setup. In contrast, our work simultaneously involves the body in data collection, interaction, and analysis creating new opportunities for feedback loops and playful experimentation. Similarly, while recent work has explored mixed-reality environments for collaborative learning, most have utilized simulations (*e.g.,* [12, 42, 47]) or artificial data (*e.g.,* [58]). Our work combines live streams of *real* body-data in a shared environment. We believe this tight coupling between physical action, physiological sensing, and live visualization offers new, rich possibilities for user interaction and learning experiences.

While our primary topic of exploration is the human body—specifically, the respiratory and circulatory systems—our overarching goal is to use the body and physical activity as an authentic platform for children to build science literacy skills and engage in meaningful scientific inquiry. As an initial investigation, our research questions are exploratory: In what ways do children interact and collaborate with real-time body data on large-screen displays? What aspects of our designs and activities seem to promote or hinder collaboration and inquiry? What are some design implications for tools that visualize real-time body data on large-screen displays*?*

To explore the potential of our approach, we pursued a three-part investigation. First, we conducted participatory design sessions with three groups of in-service elementary school teachers (*N*=20). These sessions helped to identify key characteristics for promoting learning engagement and inquiry such as *live sensor data*, *comparisons, physical movement,* and *collaborative activities*. Second, informed by these findings and by prior work (*e.g.,* [31, 34, 35, 55]), we designed and implemented three contrasting SharedPhys prototypes and learning activities. The prototypes explore different data representations, interaction paradigms, and levels of collaboration (Figure 1) within our design space: *Magic Mirror* uses an augmented-reality (AR) approach to allow children to see inside their functioning bodies; *Moving Graphs* transforms live sensor data into graph form, supporting *in situ* hypothesis generation and testing; and *Animal Avatar* enables children to become animals (*e.g.,* fish, chimpanzee) whose respiratory systems respond to the children's own sensed physiology.

Finally, we conducted an exploratory evaluation of SharedPhys with six groups of children in two after-school programs (total *N*=69; ages 5-13). Qualitative findings from study sessions, pre- and post-study questionnaires, and program staff interviews demonstrate the potential of real-time body data and large-screen displays to engage children in physical interaction and new shared inquiry experiences. More specifically, our findings suggest that our integrated approach helps promote playful, data-driven inquiry (*e.g.,* rapidly iterating between hypothesis generation and testing) and alternative forms of social interaction and collaboration (*e.g.,* physical communication like body mimicry).

In summary, our contributions include: (i) the introduction of a new mixed-reality approach that combines on-body sensors and real-time, large-screen visualizations for physical, collaborative interaction and learning; (ii) findings from our participatory design sessions and six exploratory evaluations; and (iii) design reflections and directions for the emerging areas of mixed-reality environments to support embodied interaction and learning [40] and body-centric technologies for inquiry [32].

BACKGROUND AND RELATED WORK

We provide background on sensor-based learning, embodied interaction, and technologies for body learning.

Sensor-Based Learning

Originally called 'microcomputer-based laboratories' and later 'probeware,' sensor-based learning emerged in the 1980s to help children explore, experiment with, and analyze physical phenomena in new ways (*e.g.,* kinematics [41], electricity [77]). While most prior work has focused on learning benefits with older students in high-school and college (*e.g.*, [50, 64, 65, 71, 73]), three studies with younger children—our focus—also showed benefits [13, 53, 77]. Researchers suggest that it is the tight coupling between activity and the computer-based visualization that accounts for gains in understanding and engagement [13, 53].

Despite this long history, there has been surprisingly little consideration of physiological and wearable sensors applied to learning contexts [39]. Lee and colleagues suggest that the recent *Quantified Self Movement* and emerging commercial activity trackers such as Fitbit offer tremendous potential as learning technologies—particularly in support of scientific inquiry as the context is authentic with real-world relevance and the data is plentiful allowing for rich, diverse analysis [35–39]. While Lee *et al.'s* initial studies suggest positive learning outcomes both at the elementary [37, 39] and high school levels [38], the focus was on supporting inquiry and analysis skills (*e.g.,* graph literacy, elementary statistics). Moreover, the tasks involved pairs of students exploring retrospective activity data on individual computers. In contrast, we explore *whole-group* user interactions and learning activities mediated by novel interactive visualizations of *real-time* body-data.

Embodied Interaction and Learning

With SharedPhys, the body is both the primary form of interaction as well as the topic of inquiry. The role of the body in cognition has recently drawn increased attention in HCI [14, 28, 47] and the learning sciences [26, 33, 40]. This *embodied* perspective asserts that human cognition is deeply rooted in the body's interaction with the physical world [56]. Researchers have explored different forms of embodiment from using the hand as a mnemonic device [66] to using the entire body, often metaphorically through role-play, to represent molecules [63], electrical charges [68], or even CS concepts [3].With new body tracking technologies, these activities are increasingly computationally augmented—often forming a type of *mixed-reality environment* ("the merging of real and virtual worlds" [45]). With *Participatory Simulations* [11, 12, 15, 29], for example, learners become elements of a simulation via computer-augmented role-play.

As noted in the introduction, though an emerging area, prior work suggests that these computer-mediated, whole-body interactions can promote and support engagement [1, 62], immersion [69], sensorimotor development [30], social interaction [59, 69] as well as learning (see [31] for a review). Most closely related to our work are the tools *STEP* [12] and *SMALLab* [4, 26]. Both use body-tracking cameras and large-screen displays to support collaborative, embodied learning activities. Controlled evaluations of two SMALLab designs with high-school students showed greater learning gains compared with conventional instruction [26]. While highly related, SharedPhys is different in that it fluidly integrates body tracking *and* physiological sensing with a large-screen display enabling new types of embodied activities. For example, children can become body organs or even other animals (*e.g.,* grasshoppers, fish), which react not just to their movement but also their changing physiology.

Technology Tools to Support Body Learning

While SharedPhys is aimed at engaging children in a wide variety of STEM topics from biology and health to math and basic statistics, the primary content area is the human circulatory and respiratory system. A diverse set of body-learning technology tools have been developed, including collaborative simulations [24], touchscreen apps [49, 72], wearables [55], and AR [43, 48]; however, none integrate real-time physiological sensing, whole-body interaction, and collaborative large-screen visualizations as we do here. Most related to our work are *BodyVis* [54, 55] and *Mr. Vetro* [24]. BodyVis combines physiological sensing and reactive visualizations embedded in a 'smart' t-shirt; however, its LED-based visualizations provide only one representation of data, do not easily support temporal/social comparisons, and were not designed for whole-classroom interaction. With Mr. Vetro, students work in pairs to control individual organs on desktop computers and observe effects on a central simulation projected on a shared, large-screen display. Though initial study results are promising, Mr. Vetro uses a traditional computer-supported, collaborative learning approach—the children are not physically active in the simulation and their own body-data is not used.

Finally, while a number of recent AR systems have been developed to allow users to "peer inside" the human body (*e.g.,* [5, 21, 43, 48])—similar to our own Magic Mirror—these systems are not designed for children, are not collaborative, and, critically, do not react to the sensed physiology of the user. This *live* view of the body—the ability to see its changing physical structure, its constantly adapting physiology—affords new, rich interaction and learning opportunities, which we explore here.

PARTICIPATORY DESIGN WITH TEACHERS

To help design SharedPhys and corresponding learning activities, we conducted participatory design sessions with 20 in-service elementary school teachers (19 female) enrolled in a STEM M.Ed. program. At the beginning of the session, teachers were provided with a brief introduction and then split into three smaller groups of 6-7 for participatory design. The entire process took 2.5 hrs, with 20 mins for the introduction, 75 mins for the parallel design sessions, and 45 mins for an all-group, post-session discussion. As a formative design activity, our high-level goal was to involve experienced teachers in thinking of ways that the human body, wearables, and large-screen visualizations could be used to create new learning experiences.

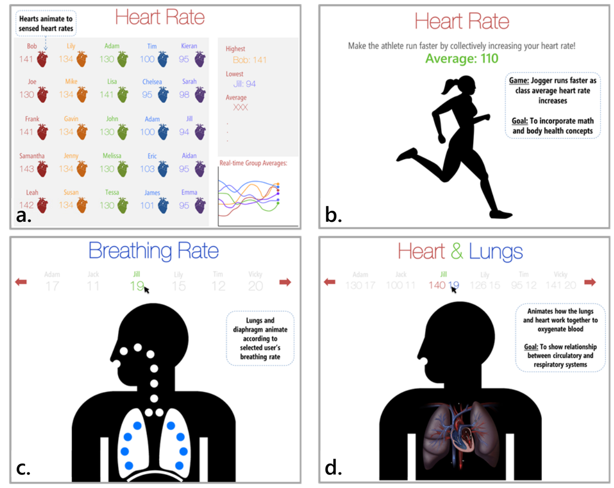

Figure 2: Four of the seven large-screen display mockups used in our participatory design sessions ranging from **(a)** whole-classroom visualizations of sensed heart rates to **(b)** target heart-rate mini-games. The bottom row shows more focused, anatomical views emphasizing **(c)** individual organs and **(d)** how organs work together. We explained that all mockups animate to sensed data.

For the participatory design sessions, teachers were provided with handouts of example inquiry questions and learning goals related to our design focus, which were explicitly aligned with *Next Generation Science Standards* (NGSS) [51, 52, 70]. Session facilitators used these examples as prompts to help teachers develop learning activities. Teachers were also given printouts of early design mockups (Figure 2) and materials for sketching and arranging ideas. At the end, teachers were asked to identify opportunities and challenges for using our proposed technology.

The design sessions and whole-group activities were video recorded and the audio transcribed. For analysis, we pursued an iterative coding scheme with a mix of both deductive and inductive codes [44, 67]. An initial codebook was defined based on our research goals and study protocol. Three researchers coded the sessions (one researcher per session). A fourth researcher then used constant comparison [6] to inductively identify themes within each code, first comparing within and then across sessions.

Participatory Design Ideas and Themes

Scientific Inquiry Activities. Teachers suggested a range of inquiry activities from structured, teacher-driven investigations to more open-ended approaches. For example, teachers discussed dividing the class into small groups where each group would perform an assigned activity (*e.g.,* standing, jumping jacks, running in place) and observe similarities/differences using the visualizations (similar to Figure 2a). Teachers also emphasized more open-ended activities such as involving children in the entire scientific process: posing their own questions, brainstorming physical activities, designing an investigation to test hypotheses using the sensors and visualizations, and drawing conclusions based on the data. In all groups, teachers mentioned inquiry activities that extended beyond a single classroom and into other classes (*e.g.,* physical education, music), recess, sporting events (*e.g.,* soccer practice), and even the home.

Body Systems and Organs. A subset of learning activities focused on helping children experience and learn about the form and function of the body. One group discussed an investigation of how individual organs react to different types of activities. The teachers would then facilitate a post-activity discussion about the causes/interactions between activities, organs, and observed physiology. Another activity involved children placing unlabeled organs onto their proper location on a model and discussing form and function related to the organs' position, size, and shape before investigating how those organs' actually functioned using sensed physiology. Finally, our teachers suggested activities to help children understand how bodies change as a result of a specific disease (*e.g.,* asthma), condition (*e.g.,* obesity), or external factor (*e.g.,* smoking, drinking caffeine).

Perceived benefits and challenges. In general, teachers were positive about utilizing wearables to aid learning: they felt that the live data, physical movement, and collaborative activities would help engage learners and that body-data could be used for cross-cutting concepts spanning topics (from math to health). Two groups also mentioned potential benefits for English language learners given the strongly visual and experiential nature of the designs. For concerns, teachers mentioned the cost, robustness, and maintenance requirements of the technology, possible issues with classroom management and setup time, and the potential for misconceptions with some visualizations (*e.g.,* if a simulation showed how heart rates increase due to smoking or drinking caffeine, children may assume the same benefits from physical activity.)

Summary of Participatory Design

In summary, our participatory design sessions helped demonstrate and verify teacher interest in using wearables and physiological sensing for collaborative learning. Their design ideas and activities leveraged key characteristics such as *physical movement*, *live data*, and *temporal* and *social comparisons* to engage children in both structured and open-ended investigations. Moreover, their feedback on our early mockups led directly to some final designs (*e.g.,* Moving Graphs is based on feedback to Figure 2a and b, Magic Mirror is based on feedback to Figure 2c and d).

DESIGN AND IMPLEMENTATION

Informed by our participatory design sessions as well as relevant prior work outlined above, we created an initial set of SharedPhys prototypes and learning activities—both were iterated via design critiques and pilot sessions. For our pilot sessions, we tested our designs and activities with one group of children (ages 7-11) and two groups of older students (from high school to university graduate level). Based on our pilot sessions, we developed a more proactive role for non-wearers, increased the amount of playfulness and game-like activities (*e.g.,* the addition of explicit goals and rewards), and allocated time to allow children to play and discover when first shown each prototype. Our final prototypes and learning activities are presented below.

Three Interactive Prototypes and Learning Activities

While each prototype has a different focus, the content is interlinked and builds progressively from basic human anatomy and physiology (Magic Mirror), to relationships with health and human activity (Moving Graphs), to a broader understanding of structures and processes across animals (Animal Avatar). Due to technological limitations, classroom management interests, and information display concerns, prototypes were limited to six simultaneous users. These six users are called *players* and wear on-body sensors that wirelessly transmit physiological data in real-time. The remaining children are *reporters*, who are tasked with helping the players as well as making observations, collecting data, and providing reports to the group. Some activities explicitly pair players and reporters together.

Prototype 1: Magic Mirror

Magic Mirror is designed to improve understanding of the human respiratory and circulatory systems, including: the position, shape, and size of relevant internal body parts, the function and purpose of those parts both individually and at the system-level, and how the two systems interact to provide oxygen to the body and expel carbon dioxide (CO_2). For the respiratory system, we included the lungs, thoracic diaphragm, and the airways (the nose, mouth, trachea). For the circulatory system, we focused on the heart, arteries, and veins. While selecting an appropriate level of detail is always a pedagogical challenge, our descriptions and abstractions were informed by our participatory design sessions as well as elementary school science textbooks such as [22]. The Magic Mirror prototype itself is comprised of three separate designs/activities. All designs use a depth camera and computer vision to actively track users' body movement, position, orientation, and gestures, which is seamlessly combined with the users' physiological data in real-time.

MM1: Live Mirror. MM1 uses an AR approach: children are mirrored by on-screen human avatars that expose otherwise invisible body parts, which animate in real-time based on sensed physiology (Figure 1a). This provides the sensation of peering inside one's own body and seeing functioning organs. For example, lungs inflate and deflate and the diaphragm relaxes and contracts based on the child's sensed breathing rate. Because of the body's layered nature, we visualize different organs and body parts depending on the users' physical position in the interaction space—the left side is reserved for the respiratory system and the right for the circulatory system. Above each avatar, a number and graphic shows the current breathing or heart rate for that

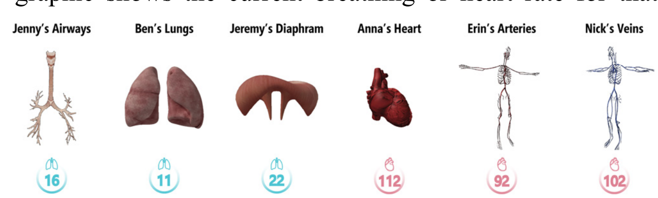

Figure 3: With MM2a, children become individual organs, which rotate/move with the user's body and animate based on their sensed physiology. In the actual design, each organ is shown separately along with a brief textual description.

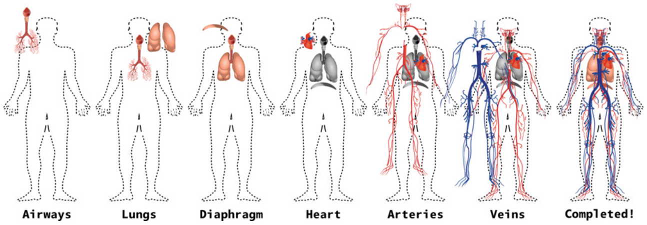

Figure 4: With the *placement puzzle* (MM2b), children move their bodies to place body parts in the correct location on an outlined human form.

player. As with an ordinary mirror, users can zoom in/out by moving closer to or away from the screen and can see a different part of their body by changing orientation.

MM2: Becoming an Organ & Placement Game. In MM2, players become individual parts to better understand their role and position in the body. There are two separate interaction screens. In the first screen (Figure 3), the active player becomes a randomly assigned body part from the circulatory or respiratory system. This part is rendered as a 3D anatomical model that, as before, animates based on the active player's sensed physiology. To help build engagement and a sense of ownership, the body part is labeled with the player's name (*e.g.,* "*Erin's Heart*") and moves with the player's body. A textual description of the body part's function and purpose is also provided (not shown in Figure).

The second screen is a mini-game (Figure 4), called the *placement puzzle,* where players physically move to place their body part on a virtual human. If incorrect, an error sound plays and the player gets to try again. Otherwise, a reward animation and sound effect play, and the next player begins the first screen. Correctly placed body parts persist for all future players in the group so the body systems build up over time. After each system is built, reporters summarize their findings about each body part/organ.

MM3: Body Systems Game. Finally, in MM3, players engage in a mini-game to help reinforce and assess conceptual understandings of the relationship between organs and their respective systems (Figure 5). Similar to MM1, all players interact with the screen simultaneously, which is again split into halves: left for circulatory, right for respiratory. Like in MM2, players are represented as body part models that compose these two systems. The goal is for all players to move their model (by moving themselves) to the appropriate side of the screen. When all players are in the correct position, a reward animation and sound effect play.

Prototype 2: Moving Graphs

While Magic Mirror emphasizes the structure, function, and purpose of the circulatory and respiratory systems, Moving Graphs focuses on the relationship between these systems and physical activity (*e.g., "What happens to my heart when I run and why?"*). Secondary goals include building STEM skills related to graph literacy and basic statistics, as well as scientific inquiry skills (making observations, testing hypotheses, and performing analyses). Moving Graphs uses a line graph to depict real-time heart rates from the six players over the last 60 seconds (Figure 1b). Lines are color

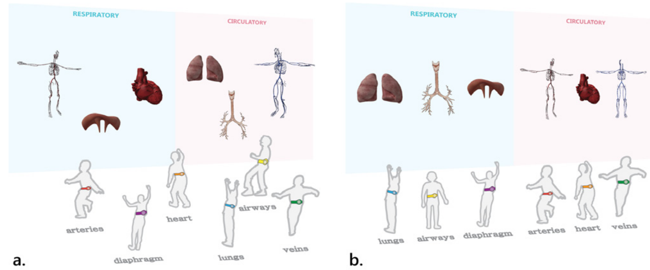

Figure 5: In MM3, children must move their assigned body part (a 3D model) to the correct side of the screen: respiratory (left side in blue) or circulatory (right in red). Above, **(a)** beginning and **(b)** ending game states.

coded by player. To the right of each line, players' names appear next along with an animation of a character running—the animation speeds up in proportion to heart rate. Moving Graphs enables both temporal comparisons (*e.g.,* "*How is my heart rate changing over time?*") and social comparisons (*e.g.,* "*How does my heart rate compare to Maya's*?"). It includes two activities with the same basic visualization.

MG1: Physically Testing Hypothesis. Following a brief introduction to the Moving Graphs visualization, we turn off the display, place reporters and players in teams of 2-3, and ask them to brainstorm and write-down activities that make heart rates slow down and speed up—Figure 6. After five minutes, each group shares one slow-down activity and one speed-up activity. Both players and reporters then return to the large-screen display to test their hypotheses. For the speed-up activities, the facilitator sets a target heart rate on the screen—roughly 20-30% above the players' cumulative resting average. Players are told to reach the target as fast as they can using their brainstormed activities. Award animations, sound effects, and virtual ribbons are provided to the first three players over the target. At the end of the activity, facilitators provide a series of provocations for discussion, such as: "*What's happening in the body to increase your heart rate? Why does this happen?"*

MG2: Basic Statistics. In MG2, we introduce the notion of *average*. We first ask the group to describe what 'average' means to them. We then show a slightly modified line-graph visualization that includes a seventh, thicker line, which depicts the real-time group average (Figure 7). The class is asked how to move the average up or down, and the players test their responses (*e.g., "What happens to the average if one player is physically active? How about three players?"*).

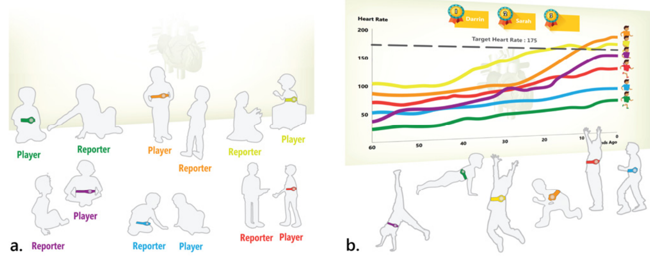

Figure 6: For MG1, players and reporters partner into teams to **(a)** brainstorm activities that affect their heart and **(b)** test those activities using a live heart-rate visualization. Virtual ribbons are awarded to those that reach the target rate first.

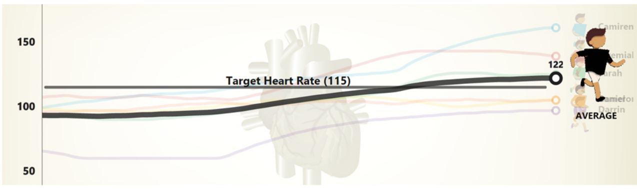

Figure 7: With MG2, players and reporters work together to affect the group's *average* heart rate represented by the thick black line and 'giant' runner. The underlying individual heart rates are still visible in the background.

Prototype 3: Animal Avatar

Our third and final design, Animal Avatar (Figure 1c), is intended to broaden understanding of biological systems across animals and has only one design/activity. Players begin by selecting one of six animals: an *elephant*, a *chimpanzee*, a *fish*, a *grasshopper*, a *chicken*, or a *human child* (Figure 8). Players are then asked to think about and role-play their animal through movement and sounds. The prototype uses a quiz show paradigm: the display shows a question about one of the six animals and the children are asked to collectively respond. For example, "*Which animal can inhale and exhale from their nose at the same time?"* and *"Which animal uses holes along their body to breathe?"*

With the correct answer, the associated player role-plays that animal to the center of the room (*e.g.,* hopping like a grasshopper). A second interface then displays a human on the left and the player's embodied animal on the right (Figure 1c). For both, the respiratory systems are visible and animating with the player's sensed physiology (Figure 9). Crucially, the animal's breathing is automatically adapted from the child's data using equations from biology and physiology [7, 16, 19, 25, 46, 74]. For example, the elephant breathes at ~25% of the player's sensed breathing rate but with much larger volume [7, 46]. We also display real-time breathing rate and volume data to help further enable cross-species comparison. Facilitators encourage players and reporters to make observations about similarities and differences, which are supplemented with prepared facts.

Implementation

SharedPhys is comprised of three parts: (i) physiological and body-tracking sensors, (ii) backend infrastructure and control interfaces, and (iii) the three interactive prototypes.

Figure 8: In Animal Avatar, players role-play one of six animals. Anatomical visualizations are shown on the screen, which react to the user's sensed physiology and are adapted into the selected animal's form.

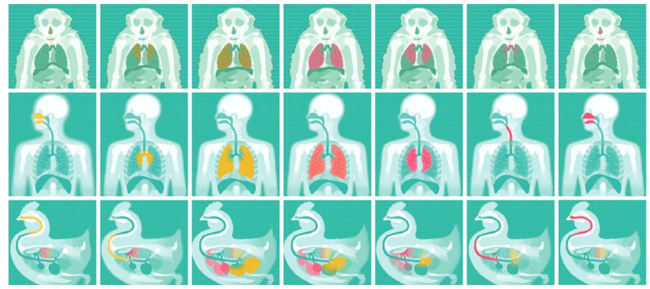

Figure 9: Sample animation frames (of ~23 total for each animal) for the chimpanzee, human, and chicken. The animations use color as well as organ and body movement to show breathing (*e.g.,* lungs inflate, diaphragm contracts).

A single laptop is used to communicate with the sensors, upload data to the backend, control the visualizations, and project the visualizations on a large-screen display.

Sensors. For our physiological sensors, we use the *Zephyr BioHarness 3* [76], a robust body-sensing platform designed for sports training and the military. Multiple independent studies have demonstrated the BioHarness' validity and reliability for measuring heart and respiratory rates [20, 27]. The BioHarness uses a flexible, chest-worn strap to sense physiological measures such as heartrate, breathing rate, ECG, and body temperature. This data is wirelessly transmitted at 1 Hz via Bluetooth. We modified the chest-worn strap to fit children's bodies. For our body tracking sensor, we use the *Microsoft Kinect for Windows v2*. The Kinect v2 is limited to recognizing six simultaneous users.

Backend. A host application written in C/C++ for Windows establishes and maintains Bluetooth connections with the BioHarness sensors, parses the BioHarness data packets, and uploads the data to a backend database. The data is shared directly with Magic Mirror via interprocess communication but via a web service for Moving Graphs and Animal Avatar. A control interface along with an instructor-facing web app were created to manage the visualization screens and monitor system health (*e.g.,* sensor connectivity).

Interactive Designs. Moving Graphs and Animal Avatar are web-based visualizations implemented in D3 (d3js.org). Magic Mirror is a standalone Windows application implemented in Visual C++ and Orge3D (orgre3d.org). The reward animations used in Moving Graphs and Magic Mirror were created in Adobe After Effects, and the sound effects are from soundrangers.com. The animal respiratory animations were made in Adobe Illustrator and After Effects based on original animations by Eleanor Lutz [2].

EVALUATION

To qualitatively explore and solicit feedback on our prototypes and to uncover particularly promising activities/designs that could be refined in future work, we conducted six exploratory evaluations of SharedPhys in two local after-school programs.

Method

Across the six sessions, a total of 69 children participated (42 boys, 27 girls) aged 5-13 (*M*=8.8; *SD*=2.1). Sessions were roughly broken down by age, based on pre-arranged 'teams' at our program sites. While we did not customize our prototypes or learning activities based on age, instructors did adapt their language for younger and older groups. The average session size had 11.5 children (*SD*=3.8; *Min*=5, *Max*=17). In the session with five participants, a program staff member stepped in for the sixth player slot. Players were selected by asking for volunteers and randomly selecting three boys and three girls. Prior to the study, parental consent was acquired, including permission to take photos and record audio/video. In total, six program staff helped across the six sessions. Three had professional teaching experience. Two research team members served as 'instructors' during the session.

Each session lasted approximately two hours and included: (i) a 25-minute introduction with a brief overview, a pre-study questionnaire, an icebreaker, and assigning volunteers to player and reporter roles; (ii) a 15-minute setup period where staff helped players put on their BioHarnesses while reporters were assigned specific body parts to keep track of and asked to fill out preliminary notes based on current understanding; (iii) an hour session with SharedPhys; and (iv) a 15-minute concluding activity with a post-study questionnaire and snack. To gather additional perspectives, we also conducted individual, semi-structured interviews with the six staff who helped facilitate sessions. Interviews lasted ~10 minutes and were also video recorded.

Data and Analysis

We use three primary sources for our analysis: the pre- and post-questionnaires, video recordings of the sessions, and the program staff interviews. Multiple video cameras were setup in the classrooms to capture facial expressions, physical movements, and social interactions as well as interactions with the large-screen display. The pre-questionnaire contained: body map drawing activities where children were asked to draw the respiratory and circulatory systems (a standard assessment approach [17, 61, 75]), questions on the purpose and function of these systems and related organs, and questions that required reading/analyzing a line graph. The post-questionnaire included questions about the SharedPhys prototypes and the child's overall experience. To gain a preliminary understanding of learning potential, some pre-questionnaire questions were also repeated.

To evaluate children's interactions and engagement, we analyzed the video data and pre- and post-questionnaires. For the video analysis, we followed Chi's eight-step process [10] using a mixed deductive and inductive approach. A single researcher developed an initial codebook based on prior work in learning engagement [9, 60], our study goals, and watching a single video. Three researchers then met and simultaneously coded a second video, concurrently updating the codebook. Finally, two researchers coded all six videos independently, developed summaries, and then met to discuss and co-interpret the data. A final summary with examples was also co-written. The video data was used to analyze interaction and behavioral indicators of engagement [60] such as body position, gaze, facial expressions, and verbalizations. The questionnaires were used to analyze more psychological indicators (*e.g.,* self-reported interest).

For the six staff interviews, we used an analysis similar to the participatory design sessions. An initial codebook was derived from study goals (*e.g.,* engagement, social interaction, perceptions). Two researchers independently coded all six transcribed interviews and resolved disagreements through consensus. To further condense themes across interviews, one researcher did a final, inductive coding pass using constant comparison [6]. For the body map drawings, two researchers independently coded the label, shape, position, and existence of circulatory and respiratory body parts in the pre- and post- questionnaires. In total, 68 questionnaire pairs were analyzed resulting in 3264 total codes (240 disagreements). Cohen's Kappa was used to verify high inter-rater reliability (κ = 0.92). All 240 disagreements were resolved through consensus.

Findings

We report on findings related to physical and social interactions, the impact of games, indicators of enjoyment, reported design preferences, and learning potential as well as perspectives from the six program staff. We refer to quotes from questionnaire data as: (*PId*, *Gender=[Male, Female]*, *Age*, *Role=[Player, Reporter]*); we are not able to attribute quotes from the videos. While 69 children participated, only 68 completed the post- questionnaire.

Physical Interactions

Our visualizations, system interactions, and learning activities engaged participants' bodies through movement, gesture, and exercise (Figure 10). When each design was first shown, players immediately began experimenting physically, typically before instruction. This was most prevalent in Magic Mirror and Moving Graphs. In Magic Mirror, players voluntarily moved their bodies left and right, often breaking into dance and jumping, to view their bodies and organs from different perspectives (Figure 10a). Players quickly discovered that they could move closer to the screen to 'zoom in' on their bodies, which created waves of back and forth movement as well as comments of delight and disgust "*Oh my gosh!*", "*Wee my head is huge! OK, now I'm getting creeped out!*" Reporters were far less physically active than players, perhaps because they were tasked with collecting observations or because of the mirrored 1:1 nature of the visualization. One exception was during mini-games where reporters would shout and gesture to help players win.

With Moving Graphs, players instantly started moving fast—jogging in place, jumping jacks—as soon as the graph was displayed. During hypothesis testing and the competitions, players were extremely focused—making very few utterances; however, reporters would shout encouragement and instruction: *"Keep going!" "Look at how high your heart rate is!" "Amanda, try push-ups!"* Compared with the other two prototypes, reporters were far more likely to

Figure 10: (a) Zooming into Magic Mirror to get a closer look at animating lungs; **(b)** gesturing and shouting to help a player in the placement puzzle; **(c-e)** testing activity hypotheses with Moving Graphs; and **(f-g)** acting like a fish and a chimpanzee in Animal Avatar.

engage in physical activity themselves, often matching players' movement (Figure 10d). When testing slow-down and speed-up activities, players would begin with the activity that s/he brainstormed with their reporter partner but then quickly switch to the activity that seemed to work best so that by the end, most players were doing the same activity.

Overall, there was less physical movement with Animal Avatar except for the animal role-play perhaps because this interface did not require explicit, computer-mediated physical interaction or because of its turn-taking nature. However, players would breathe in and out deeply or very fast to see how this would influence the respiratory animations in their animals. The role-play (Figure 10f and 10g) and tight, responsive coupling between player and animal did seem to increase engagement; however, some players/reporters seemed to lose interest when their animal was not active.

Social Interactions

We focus on two categories of observed social interaction: within-group (*e.g.,* player-to-player) and across-group (*e.g.,* player-to-reporter). Most verbal within-group interaction occurred between reporters who helped each other take notes, stay on task (*e.g.,* "*Lucas, you're the lungs!"*), or repeat things that were not originally heard. In contrast, players were more focused on themselves and their live data representations. Consequently, there was less *explicit* interaction between players; however, players would interact implicitly as they observed other players' actions and their effect on visualizations, and then try to replicate them.

For cross-group social interaction, reporters were much more vocal in interacting with players than players with reporters; however, players would often respond *physically* to reporters by changing their interaction or movement. For example, in Magic Mirror, reporters proposed different movements to try in the mirror and shouted suggestions or mimicked actions for solving the placement puzzle (Figure 10b). In Moving Graphs, reporters would often engage in their own exercises or match their partner and would shout encouragement and suggestions (as noted above). For Animal Avatar, some players were shy about role-playing, so reporters would help make animal sounds and actions.

Games

Similar to prior work in whole-body interaction [59, 62], we found that games were successful in building engagement. This finding extended even to reporters who were not wearing sensors and whose data was not being visualized. While reporters did seem less involved in some designs, their engagement often peaked during games and competitions. With the placement puzzle (MM2), for example, reporters would shout and raise their arms to help players place their body parts. The most physical activity—for both reporters and players—was during the Moving Graphs competitions. Here, all participants would engage in some form of physical exercise and experimentation even though only players' data was represented on screen.

Enjoyment

In our video analysis, we found many indicators of enjoyment from positive facial expressions and excited utterances to active attention and participation. Indeed, on the post-questionnaire, most children (91%) indicated having fun during the session. Reasons included being able to move a lot, being able to see internal parts of the body actually working, and enjoying learning about the body. One participant said "*I haven't had this much fun basically all summer*" (P66, M, 13, P). Of the five participants that reported *not* having fun, three were reporters and two were players. Two of these reporters stated they would have had more fun if they wore the sensor, one player indicated not liking any of the activities. The remaining two provided no explanation. As an additional indicator of enjoyment: while 39.7% participants felt that '*learning about my body and body organs*' was '*very interesting*' on the pre-questionnaire, this increased to 56.1% on the post-questionnaire.

Design Preference.

When asked to select a favorite prototype, Magic Mirror was most preferred, selected by 28 participants (41%), followed by Moving Graphs (35%) and Animal Avatar (24%). Reasons for selecting Magic Mirror, included: enjoying how it mimicked the body, its use of physical interaction, and being able to see inside one's body. For example, one child said "*I loved how it copied me"* (P36, F, 10, P) and another: "*It shows what the inside of your body looks like and how it moves"* (P37, M, 13, R). For those that selected Moving Graphs, common reasons included being able to compare heart rates, the type and amount of physical activity required by the prototype, and the competitions. For example, "*it shows the different heart rates between people*" (P30, F, 12, R), "*I like pushups and running"* (P2, M, 5, P), and "*It was fun competing"* (P25, M, 10, P). Finally, for those that selected Animal Avatar, children emphasized the comparison between animals and humans, enjoying seeing how different animals breathed, and being generally interested in animals. For example, "*it is cool seeing how fast or slow you would breathe as an animal"* (P59, F, 9, R) and "*it made us know [sic] that elephants breathe more air and that you breathe more when you are young"* (P12, M, 12, R).

Despite differences in age (from 5-13), we did not observe significant behavioral differences across sessions in our video analysis. However, we found that younger children (age 5-8, *N*=33) selected Magic Mirror most frequently as their favorite (51.5%) followed by Animal Avatar (27.3%) and Moving Graphs (21.2%). For older participants (age 9-13, *N*=35), Moving Graphs was most preferred (48.6%) then Magic Mirror (31.4%) and Animal Avatar (20%). However, a chi-square test comparing these two age groups ($X^2_{(2,N=68)} = 5.84$, $p = .059$) was not significant at $p < 0.05$. More work is needed to explore this trend.

Learning Potential

Though the primary intent of our study was not to assess learning, we did compare pre- and post-questionnaire data to gain a preliminary idea of effectiveness. Participant body map scores improved between the pre- and post-questionnaires, from *M*=8.5 (*SD*=4.9) to *M*=12.0 (*SD*=7.0) out of 24. This improvement was statistically significant as shown by a paired t-test (t_{67}=4.89, *p*<.001)[1]. Overall, the greatest gains were observed in shape (62% of the participants), existence (60%), and position (51%). While a total of 45 participants increased their scores (66%), a surprisingly high number (28%; *N*=19) decreased. In examining this further, we found that a few children had done relatively well on the pre-questionnaire but did not fill out the post-questionnaire or wrote *"I don't know,"* perhaps due to fatigue.

We also assessed the five questions that were repeated on the pre- and post-questionnaires, including three multiple-choice questions that required analyzing a line graph and two fill-in-the-blank questions about the circulatory and respiratory systems. Overall, participant scores increased from *M=1.8* (*SD*=1.4) to *M=2.0* (*SD*=1.4) out of 5, however, this difference was not statistically significant. Most gains were on the body-system questions—29% of participants improved while 3% performed worse.

Program Staff Interviews

With regards to the perspectives and reactions of the six program staff, generally all were positive about the potential of SharedPhys to engage children in learning. Noted benefits included: the authentic connection between body data and activities, the importance of physicality and mimicry (*e.g.,* live 3D anatomical models of the body), and SharedPhys' ability to make STEM-related learning relevant and fun. For example, one facilitator, a former teacher, felt that the graphing in SharedPhys "*was very authentic… it just really made the math alive*" (S5). Most facilitators emphasized the tight coupling between the physiological data and our visualizations in building engagement and relevance: "*It's one thing to show a picture of the respiratory system, it's another thing to have them see their own"* (S2) and *"The cause and effect relationship, the interactivity… all those things make much more personal education… just learning on a deeper level."* (S5). Two staff mentioned that SharedPhys was able to engage children who otherwise struggled to pay attention during prior STEM activities: "*they were on task, well behaved… that was awesome*" (S6).

When asked about player and reporter roles, most (5/6) staff members felt that it was *not* necessary for everyone in a class to wear a sensor, though they felt that everyone should have the opportunity. Two staff reasoned that players were not as focused on learning concepts as reporters. Another felt that it would be too hard to visualize more than six wearers' data at once. The one staff member (S6) who thought *everyone* should wear a sensor felt that players were far more "*involved and on task*" than reporters.

Finally, several staff members shared pedagogical suggestions and design ideas for SharedPhys, including adjusting the complexity of content based on age and developmental stage, spreading the use of the tool out over multiple days/weeks, and allowing reporters and players to more easily switch roles. Similar to our participatory design sessions, staff raised concerns about cost and durability but also the need for professional development and the overhead required to setup and use our tools.

DISCUSSION

This paper contributes to two growing but nascent areas of research: (i) mixed-reality environments to support embodied interaction and learning [40] and (ii) body-centric technologies for inquiry [32, 34]. Specifically, we investigated the potential of integrating live physiological sensing, whole-body interaction, and large-screen visualizations in a multi-user environment to support and promote new forms of interaction and shared inquiry experiences. Our findings suggest that the tight coupling between physical interaction, physiological sensing, and responsive visualizations helps promote engagement, allows children to easily explore cause-and-effect relationships, supports and shapes social interactions, and creates a fun, playful experience. As an exploratory, qualitative study, our findings also help provide design guidance and ideas for future work.

Design preferences. Children's preferences were fairly evenly split across the three prototypes, though there was a clear trend toward designs that required higher levels of physical interaction. Preferences also point to the promise of using AR for body inquiry. With Magic Mirror and Animal Avatar, for example, children liked to see avatar versions of themselves with real-time animations of functioning body parts. Future designs could include interconnections between body organs, higher-fidelity models, or other parts of the body (*e.g.,* how muscles work [23]). With Animal Avatar specifically, children seemed deeply interested in cross-species comparisons and were struck by how their physiology manifested in other animals; however, the

[1] This data met the normality assumption: Shapiro-Wilk result was *W*=0.98, *p=ns*.

sequential nature of the design and lack of explicit physical interaction limited engagement. We envision a hybrid approach where children can become other animals in a Magic Mirror-like design. Finally, our findings highlight the value of games and competitions to help promote collaboration and build collective investment between wearers and non-wearers (echoing [8]).

Wearers *vs.* non-wearers. To promote equitability and engagement, we initially envisioned that *all* children would simultaneously wear sensors. As such, we were surprised to find no differences in reported 'fun' between wearers (players) and non-wearers (reporters) and that most program staff (5/6) felt that sensors for all children were not necessary. Indeed, our study identified benefits to both roles. Wearers had greater control and a more direct connection to the data, whereas non-wearers had more time to reflect, observe others, and record observations—while still engaging physically by mimicking or demonstrating suggested movements. For future designs, we recommend both incorporating activities that help children slow down and reflect on their learning [18] and allowing children to easily switch between wearer and non-wearer roles (echoing [69]'s notion of 'social balance').

Physiological sensing. While we believe there is rich potential in using physiological sensing in mixed-reality environments, sensors can be expensive and require time to put on/take off (making it difficult to switch wearers). In addition, most wearables are not designed specifically for children. We modified the BioHarness's chest strap to fit a child's body, but at least one child in each session complained of discomfort. While less invasive sensors are available (*e.g.,* the wrist-based *Fitbit Charge HR* or camera-based techniques [57]), they often provide only one measure (*e.g.,* heart rate), are less accurate, or do not provide a programming API. Future designs should consider expense, accuracy, invasiveness, and switching overhead along with user interaction and learning goals. As mentioned above, expense can be mitigated by having fewer devices and allowing children to switch.

Social interactions. Social interactions between learners are often characterized by verbal or text communication or, more recently, via digital media (*e.g.,* [42]); however, we observed important non-verbal forms as well. Leveraging whole-body interaction in the shared mixed-reality environment, children communicated with their bodies both explicitly and implicitly. Explicit communication often meant physically demonstrating a suggested activity or helping to encourage a player. More implicitly, children would observe other children's physical actions to learn new ways of interacting with the system and to gain a better understanding of their own performance. This was most striking with Moving Graphs where, by the end, most children had converged on the same one or two activities that seemed to work best. This convergence helps demonstrate the visibility of action in a shared, mixed-reality space and how social observation and modeling can potentially lead to learning.

Benefits and drawbacks. Our findings suggest that SharedPhys's tight coupling of action and visualization is approachable, engaging, and helps promote collaborative data-driven inquiry. In contrast to prior work [37–39], SharedPhys supports body inquiry experiences via whole-body interaction in a *shared* environment, enabling and shaping collective investigations. Still, there are challenges. First, the real-time, collaborative nature of the activities forces all children to engage at the same pace. Second, as noted previously, vigorous physical interaction sometimes limited opportunities for reflection. Third, physical, body-centric activities have the potential to raise sensitive issues such as fitness level and body shape. While this last concern did not arise in our study, future designs should consider how to mitigate this potential problem. Finally, to address issues due to the real-time nature of our approach, we suggest including complementary retrospective tools (as in [36–38]) for reviewing and (re)analyzing the real-time data.

Study Limitations. We deployed and studied three contrasting prototypes using a single-session study design. While useful for identifying promising activities and design elements, studying initial impressions, and uncovering usability issues, the study design is susceptible to novelty effects. The session length may also have been long for some children, who appeared to tire. More in-depth studies are necessary for evaluating longer-term usage patterns and learning benefits. Still, the combination of methods used—participatory design, tool evaluation with 69 children, and staff interviews—helps mitigate the limitations of any one technique. We are currently working with two site partners to examine longitudinal uses of physiological sensing and visualizations in informal and formal learning contexts.

CONCLUSION

We pursued a multi-stage, mixed-methods approach to evaluating the potential of live physiological sensors, whole-body interaction, and large-screen visualizations to engage children in playful, collective inquiry. Participatory design with teachers helped (i) demonstrate and verify interest in utilizing body sensors and live multi-user visualizations to support learning; (ii) provide design and group learning activity suggestions; and (iii) identify key characteristics for promoting engagement and inquiry. The design and evaluation of three contrasting SharedPhys prototypes helps map out and probe an initial design space for mixed-reality environments that utilize live physiological data for body-centric inquiry. Our findings suggest benefits in the tight coupling between action and visualization, the social interactions afforded by a multi-user mixed-reality environment, and in the interplay between wearers and non-wearers.

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REFERENCES

[1] Adachi, T., Goseki, M., Muratsu, K., Mizoguchi, H., Namatame, M., Sugimoto, M., Kusunoki, F., Yamaguchi, E., Inagaki, S. and Takeda, Y. 2013. Human SUGOROKU: Full-body Interaction System for Students to Learn Vegetation Succession. *Proceedings of the 12th International Conference on Interaction Design and Children* (New York, NY, USA, 2013), 364–367.

[2] An Animated Guide to Breathing: *http://tabletopwhale.com/2014/10/24/3-different-ways-to-breathe.html*. Accessed: 2014-10-24.

[3] Begel, A., Garcia, D.D. and Wolfman, S.A. 2004. Kinesthetic learning in the classroom. *ACM SIGCSE Bulletin*. 36, 1 (Mar. 2004), 183.

[4] Birchfield, D., Thornburg, H., Megowan-Romanowicz, M.C., Hatton, S., Mechtley, B., Dolgov, I. and Burleson, W. 2008. Embodiment, multimodality, and composition: convergent themes across HCI and education for mixed-reality learning environments. *Advances in Human-Computer Interaction*. 2008, (2008), 1–20.

[5] Blum, T., Kleeberger, V., Bichlmeier, C. and Navab, N. 2012. mirracle: An augmented reality magic mirror system for anatomy education. *2012 IEEE Virtual Reality (VR)* (Mar. 2012), 115–116.

[6] Boeije, H. 2002. A Purposeful Approach to the Constant Comparative Method in the Analysis of Qualitative Interviews. *Quality and Quantity*. 36, 4 (2002), 391–409.

[7] Bonafide, C.P., Brady, P.W., Keren, R.C., H., P., Marsolo, K. and Daymont, C. 2013. Development of heart and respiratory rate percentile curves for hospitalized children. *Pediatrics*. 4, 131 (2013), 1150–1157.

[8] Bonsignore, E., Hansen, D., Kraus, K., Ahn, J., Visconti, A., Fraistat, A. and Druin, A. 2012. Alternate Reality Games: platforms for collaborative learning. *Proceedings of the 10th International Conference of the Learning Sciences (ICLS)* (2012), 251–258.

[9] Carini, R.M., Kuh, G.D. and Klein, S.P. 2006. Student engagement and student learning: Testing the linkages. *Research in Higher Education*. 47, 1 (2006), 1–32.

[10] Chi, M.T.H. 1997. Quantifying Qualitative Analyses of Verbal Data: A Practical Guide. *Journal of the Learning Sciences*. 6, 3 (Jul. 1997), 271–315.

[11] Colella, V. 2000. Participatory Simulations: Building Collaborative Understanding Through Immersive Dynamic Modeling. *Journal of the Learning Sciences*. 9, 4 (Oct. 2000), 471–500.

[12] Danish, J.A., Enyedy, N., Saleh, A., Lee, C. and Andrade, A. 2015. Science Through Technology Enhanced Play: Designing to Support Reflection Through Play and Embodiment. *Proceedings of the 11th International Conference on Computer Supported Collaborative Learning (CSCL2015)* (2015), 332–339.

[13] Deniz, H. and Dulger, M.F. 2012. Supporting Fourth Graders' Ability to Interpret Graphs Through Real-Time Graphing Technology: A Preliminary Study. *Journal of Science Education and Technology*. 21, 6 (Dec. 2012), 652–660.

[14] Dourish, P. 2001. *Where the Action Is: The Foundations of Embodied Interaction*. The MIT Press.

[15] Enyedy, N., Danish, J.A., Delacruz, G. and Kumar, M. 2012. Learning physics through play in an augmented reality environment. *International Journal of Computer-Supported Collaborative Learning*. 7, 3 (Jul. 2012), 347–378.

[16] Ganong, W.F. and Barrett, K.E. 2005. *Review of medical physiology*. New York: McGraw-Hill Medical.

[17] Garcia-Barros, S., Martínez-Losada, C. and Garrido, M. 2011. What do Children Aged Four to Seven Know about the Digestive System and the Respiratory System of the Human Being and of Other Animals? *International Journal of Science Education*. 33, 15 (Oct. 2011), 2095–2122.

[18] Gardner, C.M., Clegg, T.L., Williams, O.J. and Kolodner, J.L. 2006. Messy Learning Environments: Busy Hands and Less Engaged Minds. *Proceedings of the 7th International Conference on Learning Sciences* (2006), 926–927.

[19] Gulinson, S. and Harrison, J. 1996. Control of resting ventilation rate in grasshoppers. *The Journal of experimental biology*. 199, 2 (1996), 379–389.

[20] Hailstone, J. and Kilding, A.E. 2011. Reliability and Validity of the Zephyr™ BioHarness™ to Measure Respiratory Responses to Exercise. *Measurement in Physical Education and Exercise Science*. 15, 4 (Oct. 2011), 293–300.

[21] Hamza-Lup, F.G., Santhanam, A.P., Imielinska, C., Meeks, S.L. and Rolland, J.P. 2007. Distributed Augmented Reality With 3-D Lung Dynamics—A Planning Tool Concept. *IEEE Transactions on Information Technology in Biomedicine*. 11, 1 (Jan. 2007), 40–46.

[22] Harcourt Inc. 2007. *Harcourt Health and Fitness: Grade 4*. Harcourt School Publishers.

[23] Inside the brains of Xbox One Kinect (Kinect v2): *https://youtu.be/ziXflemQr3A?t=1m47s*. Accessed:

2015-03-01.

[24] Ioannidou, A., Repenning, A., Webb, D., Keyser, D., Luhn, L. and Daetwyler, C. 2010. Mr. Vetro: A Collective Simulation for teaching health science. *International Journal of Computer-Supported Collaborative Learning*. 5, 2 (Mar. 2010), 141–166.

[25] Jacob, J. and Pescatore, T. 2013. *Avian Respiratory System*.

[26] Johnson-Glenberg, M.C., Birchfield, D.A., Tolentino, L. and Koziupa, T. 2014. Collaborative embodied learning in mixed reality motion-capture environments: Two science studies. *Journal of Educational Psychology*. 106, 1 (2014), 86–104.

[27] Kim, J.-H., Roberge, R., Powell B., J., Shafer B., A. and Jon Williams, W. 2013. Measurement Accuracy of Heart Rate and Respiratory Rate during Graded Exercise and Sustained Exercise in the Heat Using the Zephyr BioHarnessTM. *International Journal of Sports Medicine*. 34, 06 (2013), 497–501.

[28] Klemmer, S.R., Hartmann, B. and Takayama, L. 2006. How bodies matter: five themes for interaction design. *Proceedings of the 6th ACM conference on Designing Interactive systems - DIS ’06* (New York, New York, USA, Jun. 2006), 140–149.

[29] Kreitmayer, S., Rogers, Y., Laney, R. and Peake, S. 2012. From Participatory to Contributory Simulations: Changing the Game in the Classroom. *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI ’12* (New York, New York, USA, May 2012), 49–58.

[30] Landry, P., Minsky, J., Castañer, M., Camerino, O., Rodriguez-Arregui, R., Ormo, E. and Pares, N. 2013. Design Strategy to Stimulate a Diversity of Motor Skills for an Exergame Addressed to Children. *Proceedings of the 12th International Conference on Interaction Design and Children* (New York, NY, USA, 2013), 84–91.

[31] Laura Malinverni, N.P. 2014. Learning of Abstract Concepts through Full-Body Interaction: A Systematic Review. *Journal of Educational Technology & Society*. 17, 4 (2014), 100–116.

[32] Lee, V.R. 2014. Combining High-Speed Cameras and Stop-Motion Animation Software to Support Students’ Modeling of Human Body Movement. *Journal of Science Education and Technology*. 24, 2-3 (Oct. 2014), 178–191.

[33] Lee, V.R. 2014. Introduction: Technology Meets Body, Body Meets Technology. *Learning technologies and the body: integration and implementation in formal and informal learning environments*. V.R. Lee, ed. 1–20.

[34] Lee, V.R. 2015. *Learning Technologies and the Body: Integration and Implementation In Formal and Informal Learning Environments*. Taylor and Francis.

[35] Lee, V.R. 2013. The Quantified Self (QS) movement and some emerging opportunities for the educational technology field. *Educational Technology*. 53, 6 (2013), 39–42.

[36] Lee, V.R. and Drake, J. 2013. Quantified Recess: Design of an Activity for Elementary Students Involving Analyses of Their Own Movement Data. *Proceedings of the 12th International Conference on Interaction Design and Children* (New York, NY, USA, 2013), 273–276.

[37] Lee, V.R., Drake, J.R., Cain, R. and Thayne, J. 2015. Opportunistic Uses of the Traditional School Day Through Student Examination of Fitbit Activity Tracker Data. *Proceedings of the 14th International Conference on Interaction Design and Children* (New York, NY, USA, 2015), 209–218.

[38] Lee, V.R. and DuMont, M. 2010. An Exploration into How Physical Activity Data-Recording Devices Could be Used in Computer-Supported Data Investigations. *International Journal of Computers for Mathematical Learning*. 15, 3 (Dec. 2010), 167–189.

[39] Lee, V.R. and Thomas, J.M. 2011. Integrating physical activity data technologies into elementary school classrooms. *Educational Technology Research and Development*. 59, 6 (Aug. 2011), 865–884.

[40] Lindgren, R. and Johnson-Glenberg, M. 2013. Emboldened by Embodiment: Six Precepts for Research on Embodied Learning and Mixed Reality. *Educational Researcher*. 42, 8 (Nov. 2013), 445–452.

[41] Lindwall, O. and Ivarsson, J. 2004. What makes the subject matter matter? Contrasting probeware with Graphs & Tracks. *Renderings & reasoning: Studying artifacts in human knowing*. J. Ivarsson, ed. Universitatis Gothoburgensis. 115–143.

[42] Lui, M., Kuhn, A.C., Acosta, A., Quintana, C. and Slotta, J.D. 2014. Supporting Learners in Collecting and Exploring Data from Immersive Simulations in Collective Inquiry. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2014), 2103–2112.

[43] Meng, M., Fallavollita, P., Blum, T., Eck, U., Sandor, C., Weidert, S., Waschke, J. and Navab, N. 2013. Kinect for interactive AR anatomy learning. *2013 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (Oct. 2013), 277–278.

[44] Miles, M.B., Huberman, A.M. and Saldaña, J. 2013.

Qualitative Data Analysis: A Methods Sourcebook. Sage Publications, Inc.

[45] Milgram, P. and Kishino, F. 1994. A Taxonomy of Mixed Reality Visual Displays. *IEICE TRANSACTIONS on Information and Systems*. The Institute of Electronics, Information and Communication Engineers.

[46] Miller, R.E. and Fowler, M.E. 2014. *Fowler's Zoo and Wild Animal Medicine, Volume 8*. Elsevier Health Sciences.

[47] Moher, T., Uphoff, B., Bhatt, D., Silva, B.L. and Malcom, P. 2008. WallCology: Designing interaction affordances for learner engagement in authentic science inquiry. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (2008), 163–172.

[48] Monkman, H. and Kushniruk, A.W. 2015. A see through future: augmented reality and health information systems. *Studies in health technology and informatics*. 208, (Jan. 2015), 281–5.

[49] My Incredible Body - Guide to Learn About the Human Body for Children - Educational Science App with Anatomy for Kids: *https://itunes.apple.com/us/app/my-incredible-body-guide-to/id853953105*. Accessed: 2015-08-05.

[50] Myers, M.J. and Burgess, A.B. 2003. Inquiry-based Laboratory Course Improves Students' Ability to Design Experiments and Interpret Data. *AJP: Advances in Physiology Education*. 27, 1 (Mar. 2003), 26–33.

[51] National Research Council 2012. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. The National Academies Press.

[52] Next generation science standards: 2012. .

[53] Nicolaou, C.T., Nicolaidou, I., Zacharia, Z. and Constantinou, C.P. 2007. Enhancing Fourth Graders' Ability to Interpret Graphical Representations Through the Use of Microcomputer-Based Labs Implemented Within an Inquiry-Based Activity Sequence. *Journal of Computers in Mathematics and Science Teaching*. 26, 1 (2007), 75–99.

[54] Norooz, L. and Froehlich, J. 2013. Exploring early designs for teaching anatomy and physiology to children using wearable e-textiles. *Proceedings of the 12th International Conference on Interaction Design and Children (IDC '13)* (New York, New York, USA, Jun. 2013), 577–580.

[55] Norooz, L., Mauriello, M.L., Jorgensen, A., McNally, B. and Froehlich, J.E. 2015. BodyVis: A New Approach to Body Learning Through Wearable Sensing and Visualization. *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (2015), 1025–1034.

[56] Pecher, D. and Zwaan, R.A. 2005. *Grounding Cognition: The Role of Perception and Action in Memory, Language, and Thinking*. Cambridge University Press.

[57] Poh, M.-Z., McDuff, D.J. and Picard, R.W. 2010. Non-contact, automated cardiac pulse measurements using video imaging and blind source separation. *Opt. Express*. 18, 10 (May 2010), 10762–10774.

[58] Price, S. and Rogers, Y. 2004. Let's get physical: The learning benefits of interacting in digitally augmented physical spaces. *Computers & Education*. 43, 1-2 (Aug. 2004), 137–151.

[59] Price, S., Sakr, M. and Jewitt, C. 2015. Exploring Whole-Body Interaction and Design for Museums. *Interacting with Computers*. (Sep. 2015), iwv032.

[60] R., J., Jablon and Wilkinson, M. 2006. Using Engagement Strategies to Facilitate Children's Learning and Success. *YC Young Children*. (2006), 12–16.

[61] Reiss, M.J. et al. 2002. An international study of young peoples' drawings of what is inside themselves. *Journal of Biological Education*. 36, 2 (Mar. 2002), 58–64.

[62] Revelle, G. 2013. Applying developmental theory and research to the creation of educational games. *New directions for child and adolescent development*. 2013, 139 (Jan. 2013), 31–40.

[63] Ross, P.M., Tronson, D.A. and Ritchie, R.J. 2008. Increasing Conceptual Understanding of Glycolysis & the Krebs Cycle Using Role-Play. *The American Biology Teacher*. 70, 3 (Mar. 2008), 163–168.

[64] Royuk, B. and Brooks, D.W. 2003. Cookbook Procedures in MBL Physics Exercises. *Journal of Scienzwace Education and Technology*. 12, 3 (Sep. 2003), 317–324.

[65] Russell, D.W., Lucas, K.B. and McRobbie, C.J. 2004. Role of the microcomputer-based laboratory display in supporting the construction of new understandings in thermal physics. *Journal of Research in Science Teaching*. 41, 2 (Feb. 2004), 165–185.

[66] Saarelainen, M., Laaksonen, A. and Hirvonen, P.E. 2007. Students' initial knowledge of electric and magnetic fields—more profound explanations and reasoning models for undesired conceptions. *European Journal of Physics*. 28, 1 (Jan. 2007), 51–60.

[67] Saldaña, J. 2012. *The Coding Manual for Qualitative Researchers*. SAGE Publications Ltd.

[68] Singh, V. 2010. The Electron Runaround: Understanding Electric Circuit Basics Through a Classroom Activity. *The Physics Teacher*. 48, 5 (Apr. 2010), 309.

[69] Snibbe, S.S. and Raffle, H.S. 2009. Social Immersive Media: Pursuing Best Practices for Multi-user Interactive Camera/Projector Exhibits. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2009), 1447–1456.

[70] Stage Goal 23: Understand human body systems and factors that influence growth and development: *http://www.isbe.net/ils/pdh/pdf/goal23.pdf*. Accessed: 2015-05-01.

[71] Struck, W. and Yerrick, R. 2009. The Effect of Data Acquisition-Probeware and Digital Video Analysis on Accurate Graphical Representation of Kinetics in a High School Physics Class. *Journal of Science Education and Technology*. 19, 2 (Oct. 2009), 199–211.

[72] The Human Body: *https://itunes.apple.com/us/app/the-human-body-by-tinybop/id682046579*. Accessed: 2015-08-04.

[73] Tinker, R. 2000. *History of Probeware*.

[74] Tzaneva, V. and Perry, S.F. 2010. The control of breathing in goldfish (Carassius auratus) experiencing thermally induced gill remodelling. *The Journal of experimental biology*. 213, 21 (2010), 3666–3675.

[75] Vessey, J.A., Braithwaite, K.B. and Widemann, M. 1990. Teaching Children About Their Internal Bodies. *Pediatric Nursing*. 16, 1 (1990), 29–33.

[76] Zephyr BioHarness 3: Model BH3: 2014. *http://www.zephyranywhere.com/products/bioharness-3/*.

[77] Zucker, A.A., Tinker, R., Staudt, C., Mansfield, A. and Metcalf, S. 2007. Learning Science in Grades 3–8 Using Probeware and Computers: Findings from the TEEMSS II Project. *Journal of Science Education and Technology*. 17, 1 (Nov. 2007), 42–48.