Live Physiological Sensing and Visualization Ecosystems: An Activity Theory Analysis

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Figure 1. In this paper, we present a four-day deployment study of *LPSV* tools in a formal classroom environment where **(a)** children brainstorm questions, test hypotheses with a model-based tool called **(b)** *BodyVis* and with an analytic-based tool called **(c)** *SharedPhys*, and **(d)** present their experiment results.

ABSTRACT

Wearable sensing poses new opportunities to enhance personal connections to learning and authentic scientific inquiry experiences. In our work, we leverage the body and physical action as an engaging platform for learning through *live physiological sensing* and *visualization* (LPSV). Prior research suggests the potential of this approach, but was limited to single-session evaluations in informal environments. In this paper, we examine LPSV tools in a classroom environment during a four-day deployment. To highlight the complex interconnections between space, teachers, curriculum, and tool use, we analyze our data through the lens of *Activity Theory*. Our findings show the importance of integrating model-based representations for supporting exploration and analytic representations for scaffolding scientific inquiry. Activity Theory highlights leveraging life-relevant connections available within a physical *space* and considering policies and norms related to learners' physical *bodies*.

Author Keywords

Scientific inquiry, SBL, LPSV, wearables for learning

ACM Classification Keywords

H.5.m. Information interfaces and presentation (*e.g.,* HCI)

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INTRODUCTION

With the emergence of cheap and reliable wearable activity trackers, there has been renewed interest in the role of sensors for learning and education [4,26,27,29]. Indeed, wearable sensing capabilities pose new opportunities to significantly enhance personal connections to learning and authentic scientific inquiry experiences (*i.e.,* asking questions, collecting and analyzing data, making claims) [7]. For example, trackers that learners wear on their wrists or clothes can seamlessly collect data about one's physical activity (*e.g.,* steps taken) and vitals (*e.g.,* heart rate) throughout the day that can be analyzed later on mobile or desktop devices [4,28]. These new capabilities also significantly increase learners' opportunities to apply scientific inquiry to their daily life experiences—to *scientize* everyday life [8,9].

We are particularly interested in leveraging the body and physical action as a platform for learning through *live physiological sensing and visualization* (LPSV) [22,42]. LPSV tools sense and visualize learners' physiological functioning (*e.g.,* heart rate, breathing rate) in real-time, projecting analytic (*i.e.,* graph-based) and model-based representations of the data. For example, *BodyVis* [44] and *SharedPhys* [22] are two LPSV tools that visualize wearers' live body-data on an electronic textile (e-textile) shirt and a large-screen display respectively (Figure 1).

While research on applying wearable sensing to educational technology is still in its infancy, it builds on a long history of prior research on *sensor-based learning* (SBL) (e.g., [19,31,53,55]). These studies have shown the effectiveness of real-time analytic data (*e.g.,* real-time graphs of changes in one's motion) (e.g., [41,53]) and model-based representations [13,31] for supporting authentic scientific inquiry and understanding of complex scientific phenomena. While SBL researchers point to the need to consider aspects of the learning context of SBL tools (*e.g.,* teacher preparation, tool maintenance and management, curriculum) [23,53,56], many SBL studies have been limited to lab-based or shorter-term assessments of learning and often focus on a narrow set of components of the ecosystem. Recent work with new wearable sensing technologies (*e.g.,* fitness trackers) has begun to look at learners' experiences with wearable sensing devices over time and across contexts [6,30]. These studies also point to the importance of understanding the complex contexts in which learners are engaged (*e.g.,* norms and practices of the school day). However, to our knowledge, such rich contextual influences on SBL experiences have yet to be the focus of analysis in SBL studies.

In this paper, we present a multi-day evaluation of how children can engage in life-relevant scientific inquiry with the two aforementioned LPSV tools: BodyVis (Figure 1b), a model-based LPSV tool, and SharedPhys (Figure 1c), an analytic approach to LPSVs [22,42]. To guide our analysis, we use *Activity Theory* (AT) [12,38,39], which places an emphasis on the interaction between people, artifacts, and social groups. The research questions for this study are:

- How does the LPSV ecosystem influence learners' scientific inquiry and life-relevant connections to scientific inquiry?
- How does AT allow us to better understand the roles of facilitation, collaboration, norms, and artifacts in LPSV environments?

We show the importance of integrating model-based representations for supporting exploration and analytic representations for scaffolding scientific inquiry. Using AT also highlights the importance of leveraging life-relevant connections available within physical *spaces* and considering policies and norms related to learners' physical *bodies.* We also highlight the importance of co-design with children and teachers of both technology and activities.

In summary, our contributions include (1) implications for the design and deployment of LPSV systems and supports in formal classrooms for helping learners connect science to their personal interests, and (2) an analysis of LPSV environments using AT and a characterization of how AT provides value in analyzing sensor-based learning systems.

BACKGROUND

We build on three bodies of research. First, our work is situated within SBL research, leveraging new SBL approaches. Second, our learning goals are based on science education research focused on helping learners develop scientizing dispositions and practices. Third, we draw upon AT to understand the rich context of LPSV environments. We cover each below.

Approaches to Sensor Based Learning

Microcomputer-Based Laboratories (MBLs). Research on MBLs shows the potential of leveraging *analytic representations* to support children's scientific inquiry learning. MBLs [53,54] (also called probeware) use sensors to capture data in the real-world (*e.g.,* light, temperature, motion) and display it graphically (*i.e., analytic representations*) in real-time to help learners reason and develop claims about the data being collected. Researchers found MBLs to be effective for learning STEM concepts (*e.g.,* physics [1,33,36,37,53], chemistry, math [56,59]). However, researchers found that MBLs have even greater potential for supporting learners' inquiry skills more generally [23,37,53,55]. Like MBLs, we leverage the design of LPSV tools to promote children's inquiry learning with analytic representations. However, we draw upon wireless sensing capabilities to enable a broader range of activity (*e.g.,* across physical space) and data collection (*e.g.,* breathing rate) in LPSV environments.

Mixed-Reality and Model-based Representations. Mixed-reality systems create hybrid realities by merging physical and virtual worlds. For this work, we focus on specific mixed-reality systems that leverage whole-body sensing to promote embodied learning experiences. Researchers have used mixed-reality systems to provide *model-based representations* of phenomena (*e.g.,* asteroid movement in space, bonding of chemical elements) [19,31,32]. Using sensors to detect learners' movements, these mixed-reality systems enable learners to become immersed in models of scientific phenomena, using physical movement to explore visual representations. For example, in a room-sized simulation called Meteor [31], learners become asteroids in space, launching their bodies to model asteroids projecting through space. The simulation shows the resulting trajectory in real-time on wall-sized displays. Similarly, our LPSV tools use mixed-reality to provide unique, digitally mediated views of the human body that are responsive to physical action. Moreover, *BodyVis* uses a model-based representation by visualizing real-time body data overlaid on e-textile organ models.

Wearables. With the rise of cheap, reliable, and wireless wearable sensors, researchers have developed commensurate interest in using an MBL approach to support learning and analysis around fitness data, often via analytic representations of data. For example, researchers have studied children's use of fitness trackers and subsequent visualizations to conduct mathematical analyses on their own fitness data [30]. Others have connected fitness tracker data to video games, which use learners' fitness data to unlock new capabilities in the game [6]. Designed specifically to promote children's fitness learning, the goal of these *exergaming* approaches is to help children make better health decisions.

We too leverage wearables with LPSV tools. However, LPSV tools also incorporate e-textiles (*i.e.,* cloth or woven fabric with embedded electronics) to provide model-based visualizations in addition to analytic visualizations. We are inspired by prior work on e-textiles for learning, which has focused primarily on learning circuitry (*e.g.,* [20,45]) and computer science [5,21,50,51] whereas our focus is on body learning and scientific inquiry. Additionally, LPSV approaches incorporate the MBL approach of providing *real-time* visualizations of data sensed with wearables.

Scientizing in LPSV Environments

Our research focuses on understanding how LPSV environments using analytic and model-based representations can be designed to promote novel STEM learning experiences for children. We define scientific inquiry as a set of investigative practices that includes formulating (testable) questions, collecting data, analyzing results, making evidence-based claims, and sharing results [7,49]. Our approach builds on *Next Generation Science Standards* (NGSS) in the US that foreground these science inquiry practices for K-12 grade levels [40]. With few exceptions (*e.g.,* [41,59]), most SBL approaches target learners who are in grades 6-12 or at undergraduate levels. We focus on elementary age learners (ages 5-10) and specifically seek to understand the inquiry practices of *both* early- and upper- elementary aged learners with LPSV tools. Within the NGSS framework, educators and curriculum developers design scientific inquiry experiences that target skills that are specific to each grade level but also cascade from one grade to the next (*e.g.,* posing a simple question based on observations in first grade; evaluating questions that can be investigated and predicting possible outcomes in sixth grade). Consequently, gaining insight into how LPSV ecosystems can support the various scientific inquiry experiences that learners have within and across grade levels is a key design goal.

Studies of MBLs, mixed-reality systems, and wearables have suggested that these SBL systems hold potential not only to promote inquiry and conceptual learning, but also to connect to learners' interests, goals, and dispositions about science [23,30,32]. Designs that create and reinforce personal connections to science serve to address the STEM achievement gap experienced by many groups of underrepresented learners (*e.g.,* African Americans, Hispanics, women) [17]. Our work focuses on implementing LPSV designs that help learners scientize their daily life experiences and recognize science opportunities in everyday situations [8,9], which, in turn, can help them identify as science-minded citizens and members of professional scientific communities. Such experiences are powerful for learners because they are instrumental for helping them connect science and inquiry to their own curiosities, passions, and pursuits even as they face challenges and difficulties [9].

Understanding LPSV Ecosystems with Activity Theory

Throughout its history, researchers have pointed to the importance of deeply understanding the environments in which SBL tools are situated (*e.g.,* [15,35,38]). However, typically, SBL analyses have focused on lab-based and pre-post-test studies of learning (*e.g.,* [10,33,57]). A few studies have focused on curriculum, learners' interactions with SBL tools, and learners' interactions with one another in the environment [11,34,47]. However, these studies often do not leverage analyses that emphasize how the broader context of activities, facilitation, and environmental factors influence learning.

This call to more deeply understand the rich physical, material, and social contexts that technologies are situated within has been issued broadly to HCI researchers [15,18,38,39]. Nardi and others [3,38] have specifically advocated for using AT to understand the ecosystems into which technologies are integrated, and how technology can be designed to fit within these broader contexts of activity and interaction. AT [12,38] is a framework for understanding activity systems and patterns as people interact with mediating (technical and non-technical) artifacts in social systems of rules and norms. Using AT as a framework for understanding interactions with technology allows researchers to characterize aspects of the activity system that arise as people interact within them [3].

In this study, we use AT to understand how the components of LPSV ecosystems come together to influence learners' scientizing. Our analysis enables us to understand how learners interact within LPSV ecosystems and how the infrastructure of facilitation, activities, technology (*i.e.,* LPSV tools) and non-technical artifacts (*e.g.,* charts, experiment guides) can be designed to support scientizing interactions in LPSV environments. In summary, our work builds on prior SBL, and more specifically, LPSV, research and advances it by conducting a multi-session field study of LPSV environments across multiple age groups of learners, leveraging iterative, participatory design with teachers and children of activities and LPSV technology. We use AT as a framework for understanding the emergent interactions within the environment, particularly as they relate to learners' scientizing experiences.

EVALUATING LPSV TOOLS IN THE CLASSROOM

To examine how LPSV tools and the surrounding socio-technical infrastructure impact learners' scientific inquiry and connections to everyday life, we conducted a multi-day study in three elementary-school classrooms. We describe our LPSV tools, our study method, and findings, which are analyzed through the lens of AT.

For more than three years, we have iteratively co-designed [14] the two LPSV tools used in this study, BodyVis and SharedPhys, as well as the associated learning activities with an intergenerational design team (children ages 7-11 and adults) and elementary school teachers. We have conducted eight participatory design sessions, from brainstorming and early prototyping of design ideas to feedback on working prototypes of both the tools and the learning activities. Insights from this process have guided tool design and learning activities. For example, with BodyVis, child designers emphasized dynamics, interactivity, and reactivity to the human form and function and with SharedPhys

Figure 2. BodyVis shows internal layers of the human body along with physiological phenomena of the wearer. Shown above: **(a)** the heart vibrates and lights up according to the wearer's heart rate, **(b)** the lungs visualize the breathing rate with lights, **(c)** the stomach shows how food is processed, **(d)** the intestines illuminate the digestion pathway.

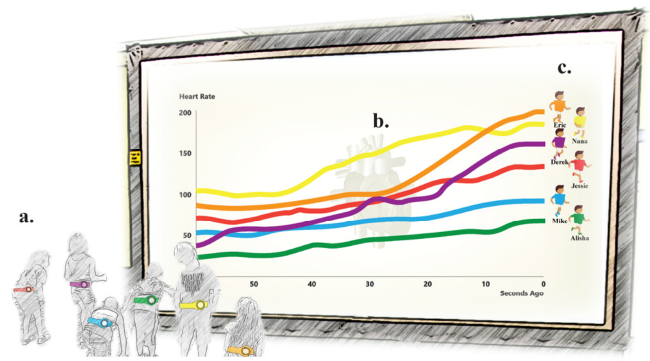

Figure 3. SharedPhys transforms **(a)** six wearers' sensed physiological data into **(b)** a graph in real-time. **(c)** Personalized avatars run fast or slow according to the user's heart rate.

physical movement, live physiological data, and social/temporal comparisons. Both BodyVis and SharedPhys use a wearable chest strap sensor (the *Zephyr BioHarness 3* [60]) that measures heart rate, breathing rate, and movement and wirelessly communicates this data in real-time.

BodyVis: Model-based Representations. BodyVis, (Figure 2) visualizes physiological phenomena (*e.g.,* heart and breathing rate) on wearable e-textile fabric anatomy [39]. Users can dynamically detach and reattach organs (*i.e.,* heart, lungs, liver, a portion of the stomach) to view the multiple layers of the human body. If organs are returned to the proper place, they immediately function again. Digestion is simulated via animated LEDs and an animated video of stomach activity, which is displayed on an embedded, modified smartphone screen.

SharedPhys: Analytic Representations. SharedPhys (Figure 3) is a mixed-reality tool in which multiple learners' heart and breathing rates are sensed and visualized in real-time on a large display [17]. While SharedPhys has multiple visualizations, in this study we used only one: *Moving Graphs*, which is a line graph visualization of heart rate data over the last 60 seconds. Up to six learners can use the system simultaneously (lines are color-coded and labeled per user). This analytic representation enables learners to investigate how their physiology changes with physical activity and supports the development of STEM skills including graph literacy, quantitative comparison, and basic statistics.

LPSV Learning Activities. We designed LPSV activities based on science education research [2,9] that suggests beginning with semi-structured experiences to help learners develop inquiry skills and progressing towards more choice-based projects that allow learners to incorporate their own personal interests and curiosities. This work continues our commitment to understanding the user's point of view through participatory design approaches [14] to designing LPSV tools and activities. Prior to conducting the study, we held two meetings with the three teachers whose classes would be participating in our study to plan the specifics of each day. Teachers provided feedback and ideas on the outline of the session plans.

Daily activities were the same across all classes:

- **Day 1:** learners discussed questions they had about the body and engaged in free-form exploration of BodyVis and SharedPhys with a scavenger hunt.
- **Day 2:** learners again discussed questions they had about their bodies and brainstormed physical activities that would increase and decrease their heart and breathing rates in small groups with BodyVis. They then tested their hypotheses as a group with SharedPhys.
- **Day 3:** learners continued to pose questions about their bodies and planned scientific investigations of their choosing with BodyVis or SharedPhys.
- **Day 4:** learners presented their choice-based investigations. Researchers led whole group discussions and facilitated group work while teachers supported the activities by facilitating group work and supporting researchers.

METHODS

We analyze the four-day sequence of activities using a broad range of collected data including video observations, pre-and post-assessments, focus groups with learners, and interviews with teachers at the end of the study, and non-technical artifacts in the environment.

Data Collection

Our study was conducted at a public elementary school in the Washington DC metro area (68% Black/African American, 23% Hispanic/Latino, 3% Asian, 2% Caucasian, 3.5% Mixed Race; 65.6% free and reduced-priced meals). We conducted four, one-hour sessions per class, for a total of twelve sessions across three classrooms. 75 public school children participated in the LPSV sessions across grade levels (though only 62 returned consent forms to participate in our study; we report on data only from these 62). This included 25 first graders (24 with consent), 21 second graders (17 with consent), and 29 fourth graders (21 with consent), for a total of 27 females, 24 males, and 11 undisclosed consented participants. The three teachers of the classes were all female.

In each session, we collected video data of learners' experiences and interactions, as well as artifacts created by learners during the sessions (*e.g.,* their notes and investigation plans). We also conducted pre- and post-assessments at the beginning of Day 1 and the end of Day 4, respectively of children's learning, interest-based, and personally meaningful experiences with LPSV tools. Additionally, on Days 1-3, learners completed shorter daily assessments focused on the same topics. At the end of Day 4, we conducted focus group interviews with the children in each class (a total of 43) who consented to be in our study (in groups of three to five children) and interviews with teachers after the study implementation. Because of the limited number of second graders who returned consent forms, we only conducted one focus group with five of the consented participants. Finally, two researchers took detailed daily post-observation field notes.

Data Analysis

To answer our research questions, we specifically focused our analysis on video observations, interview data, and post/daily assessment responses. We then triangulated across data types using the AT model to generate broader themes, also triangulating with other data types (*e.g.,* paper-based artifacts used in the classroom).

Video Data. We used four video cameras to record various angles of each classroom. When learners worked in small groups, we arranged cameras to record each group. Researchers selected one video angle from each day (that did not focus on non-consented learners) to observe interactions in the classrooms. Two researchers coded video data for types of interactions with the tools, motivations, and influences of those interactions (*e.g.,* questions learners had about their bodies), life-relevant experiences, and scientific inquiry experiences.

One researcher derived an initial codebook based on our research questions and our study protocol. Two researchers then met to discuss the codebook before each researcher coded Day 1 videos for each class. Coders used structural coding [52] to structure data according to social and material aspects of the environment and ways learners were interacting within the environment. Additionally, researchers recorded vignettes and occurrences of life-relevant experiences and scientific inquiry in a separate document. Following the first round, coders met to discuss disagreements, new codes, and to clarify code definitions. For the remaining videos, coders randomly selected and independently coded video angles for one group each day of every class (a total of nine videos). The coders then met to jointly discuss, synthesize, and summarize major themes and findings across all videos.

Pre-Post-Daily Assessments. The pre-, daily, and post-activity assessments contained two high-level, open-ended questions and Likert scale questions. We focused our analysis on the open-ended questions as they were more informative of contextual influences on learners' experiences. For each question, a single researcher developed an initial codebook that contained a set of common factors found in the data. Then, two researchers coded sample data (15% of the total) and finalized the codebook through discussion. Two researchers independently coded the entire dataset. We verified the inter-rater-reliability (IRR) of coding with Krippendorff's Alpha [16,24] and resolved all disagreements through discussion. To assess engagement, we collected participants' answers to "*Why did you have fun in the activity?*" (α=0.96). To assess what children thought they learned, we coded answers to the question, "*What did you learn today?*" (α=0.97). Finally, we grouped the Likert scale questions (*e.g.,* "*Learning about my body and body organs is fun*" "*I think it is important to understand how my body works*") by day and grade to evaluate daily activities, and quantitatively analyzed overall scores and their change over time.

Focus Groups and Interviews. We conducted focus groups with children and interviews with teachers to examine and compare design suggestions for BodyVis and SharedPhys, the learning activities, the classroom ecosystem, the engagement of the learners, and (for teachers only) their experiences with scaffolding and preparation. To code this data, three researchers did an initial round of coding, using structural coding [52] to group data by topic (*e.g.,* design suggestions for BodyVis, collaboration, *etc.*). After discussing the initial codebook, researchers did a second round of focused coding [52] to identify themes in the data. To establish IRR, an additional coder coded themes in each category. The two coders then reviewed any disagreements, and integrated their codes into a major set of themes for that category in an initial axial coding round [52]. The lead coder then reviewed the axial codes for redundancy.

Activity Theory Application. To integrate themes across data types and link to aspects of the ecosystem, we performed a final, meta-matrix, axial coding round [35]. Here, we grouped major themes by categories and connections specified by AT [12] (Figure 4): *Subject*, *Artifacts*, *Rules*, *Community*, *Division of Labor*, *Object*, and *Outcome*. Our *Subject* is the learner. LPSV tools and non-technical artifacts (*e.g.,* food used in investigations, scaffolding charts) are the *Artifacts*. The *Rules* that governed the classroom participation are the norms, conventions, and guidelines for regulating activity in the system. *Community* refers to the social context in which learners collaborate with one another or with researchers and teachers. *Division of Labor* refers to the division of actors in the system (*e.g.,* learners, teachers, research facilitators). In our case, this includes ways learners divvied tasks among themselves but also ways facilitators and teachers played different roles and fulfilled different responsibilities in the system. We then triangulated broader themes with additional data from artifacts and post-observation field notes.

FINDINGS

We present the themes we found as they relate to learners' scientific inquiry and life-relevant connections to inquiry. For each theme, we discuss how the outcomes are influenced by aspects of the AT framework. We then point to design implications based on the themes.

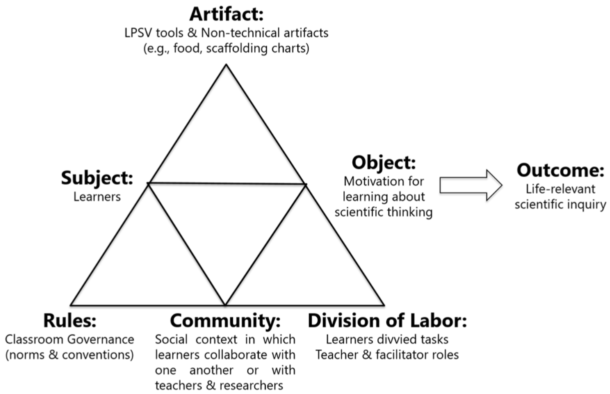

Figure 4. The Activity Theory framework that guided our analysis.

Scientific Inquiry

Differences Between Grade Levels

We observed that there were differences between first and second graders' inquiry focus and that of fourth graders that influenced how learners used the BodyVis and SharedPhys artifacts. Younger learners tended to focus on exploring the BodyVis shirt itself, especially removing and re-attaching the organs and activating the digestive simulation. Fourth graders, on the other hand, tested more of their own actions and activities, and engaged in more complex inquiry discussions with both tools. In all three grade levels, learners' questions raised complex inquiry procedure considerations (*e.g.,* about bias, external influences on results). For example, with SharedPhys, learners frequently focused on competition—trying to get the highest heart rate, which sometimes interfered with their scientific investigations as learners compromised the planned procedure to make their heart rates higher. While it was challenging to get the first and second graders to engage in discussion about these biases, the fourth graders made observations themselves when experimental procedures were not followed correctly.

First and second graders asked inquiry questions and designed investigations that raised complex inquiry considerations, but were often not able to explore the complexity of their procedures and results. For example, a first-grade group investigated how different forces (pushing, pulling, lifting, kicking, and running) affected their heart rate. During their test in the whole group with SharedPhys, one wearer exerted effort beyond the task he was assigned (running while pushing his chair) and another exerted less effort (lifting her chair once and holding it in the air). Though facilitators raised these issues with learners, the limited time made it challenging to discuss them fully and it was unclear whether learners understood these complexities as their discussions in post-assessment and focus groups emphasized simplistic understandings of their results. For example, a member of the group studying the effects of forces/movements said she learned, "*When you use force, when you push, pull, run, or you kick, or sometimes when you skip, your heart rate goes fast.*" While the learner understood generally that her heart rate increased with the exercises, she did not discuss the nuances of the differences nor what may have caused those differences.

In contrast, fourth graders' inquiry questions raised similar complexities, but learners themselves often observed the biases. For example, one group testing the differences in heart rate between different sports discussed how they exerted more or less effort in their procedure because of their skill in the sport and how the variance in their skill level may have impacted their resulting heart rates.

Influence of Community and Artifacts. All learners faced tensions between life-relevant aspects (*e.g.,* competition). However, differences in inquiry development facilitated different interactions with LPSV tools (*i.e.,* artifacts) in different grades (*i.e.,* communities). While fourth graders were especially attuned to scientific inquiry aspects of their experience, first and second graders were particularly engaged with the model-based representation of BodyVis. For example, in daily assessments, many fourth graders' (62%, 13/21) responses to questions about their enjoyment of the activity related to scientific inquiry aspects of the activity, while fewer first graders (25%, 6/24) and second graders' (24%, 4/17) responses related to scientific inquiry. Similarly, in focus groups with learners, as learners reflected on what they learned, first and second graders were more specific about organs and organ function (*e.g.,* "*That [food] goes to your stomach. How it goes into the small intestines.*") whereas fourth graders were more detailed about scientific inquiry processes (*e.g.,* "*[SharedPhys] could track how your heart rate was high and the average of all, everyone*"). Thus, fourth grade learners may have been better prepared to engage in scientific inquiry, while first and second graders were more attuned to exploring the model-based visualization. These differences between grades influenced learners' interaction with BodyVis and SharedPhys as younger learners tended to spend more time interacting with BodyVis' model-based representations, while fourth graders focused on SharedPhys' analytic representations for supporting their inquiry.

Role of Facilitators and Teachers

Teachers and facilitators played important roles in scaffolding learners' scientific inquiry, especially as learners planned their investigations. Learners needed help developing testable questions, selecting which question to pursue as group members discussed their ideas, and then planning procedures for their experiments. As learners carried out their tests, they continuously needed to be reminded to slow down between activities so that they could start the next experiment with their resting heart rates. Facilitators needed to help the first and second graders remember to record their results and decipher what to record as they were often not sure about the specific heart rates displayed on the SharedPhys graph.

Teachers also reported being disappointed in their students' post-assessment responses regarding what they learned.

They observed that their students learned about the relationship between their heart rate and exercise as well as the relationship between eating and digestion, and scientific inquiry skills. For example, they mentioned: understanding what a testable question is, designing and carrying out investigations, general ideas about reading a graph. However, in their observations of learners' responses as they handed in their daily assessments, teachers noticed that their students did not report many of these learning aspects themselves. In fact, across all daily assessments 7.5% of responses (13 out of 172) to what they learned were left blank and in 15.6% of responses (27 out of 172) learners said they did not learn anything.

Influence of Division of Labor and Artifacts. Teachers reflected on the roles that they and the researcher facilitators played in the environment (*i.e.,* division of labor) and ways the tools (*i.e.,* artifacts) and facilitation could be designed to better support learners. To help teachers scaffold inquiry, they suggested that SharedPhys show the numerical heart rates on the visualization and that users should be able to pause the real-time visualization for reflection and analysis. Both children and teachers suggested that SharedPhys include bar graphs to help younger learners compare and understand values. In terms of teachers' roles with the artifacts, they suggested that clear learning objectives be given and discussed before and after each session so that learners could more readily observe the scientific inquiry skills they were developing. Teachers themselves also desired more specific connections to content. While they suggested more direct instruction be incorporated into activities with LPSV tools, the fourth-grade teacher also suggested incorporating opportunities for learners to do their own research related to their investigations.

Physical Set up of Classroom and Classroom Norms

Differences in the setup of the physical space and rules around how learners could move about the space influenced learners' scientific inquiry with SharedPhys and BodyVis. The first and second grade rooms had more open space where learners often sat on the floor (Figure 5a and 5b). The fourth-grade classroom (Figure 5c), however, had many more desks and very little open space. We observed that learners often struggled to see while at their desks in this classroom (*i.e.,* craning their necks and attempting to kneel on their chairs to see the screen). In the first- and second-grade classes, we placed SharedPhys in the middle of the open space (Figure 5a), making it easier for learners to see the screens at their desks. This also facilitated purposeful collaboration across groups with BodyVis. For example, in post-observation field notes, a researcher noted that learners could move around between groups to make comparisons between shirts or observe other groups' interactions with BodyVis. Although we tried to create more open space in the fourth-grade class by moving desks closer to the exterior of the room, there was still limited room for free space to allow learners to move about and better explore the tools. Additionally, across all three grades, teachers often required structure around how learners moved about in the space, further limiting learners' abilities to interact with BodyVis and SharedPhys.

Figure 5. Different physical setups of classrooms affect learners' collaborative inquiry. **(a)** First grade and **(b)** second grade have more open space, while **(c)** fourth grade space is limited.

Influence of Space, Rules, and Artifacts. The classroom use of both BodyVis and SharedPhys (*i.e.,* artifacts) was facilitated or constrained by use of the space and rules and norms around how learners could use the space. Specifically, open space was helpful to allow learners to explore the tools, move about for inquiry around physical activity, and analysis (*i.e.,* being able to clearly see the screens). Additionally, rules and norms teachers held for classroom management could limit learners' visibility and access to LPSV tools. For example, although learners did have more freedom to move due to space in the second-grade class, the teacher indicated in her interview that she would have preferred more structure in terms of learners' use of space: *"…rather than everyone standing in the back watching, specific seats. You're going to sit in your normal seat on the rug unless you're wearing a [BioHarness]*."

Life-Relevant Connections to Inquiry

Personal and Social Connections to LPSV Tools

Learners' interest in the technical artifact, particularly for BodyVis, was shown in their daily assessment responses and design ideas. In daily assessments, when asked why the activities were fun and for their favorite part of the activities, the following themes emerged from learners' responses: seeing invisible parts of the body (*e.g.,* "*that I got to see the digestion*"), the wearable experience (*e.g.,* "*because I got to wear the sensor*", "*because I can touch it and see it"*), social sharing or competition ("*when we got to use the belts [BioHarness] because it was like a race to see who can go the fastest"*), scientific inquiry (*e.g.,* "*because I got to learn and exercise and test my heart rate*"), physical activity ("*To see people do works out because I saw there hear go faster and faster*"), and presenting their own ideas with posters ("*I had fun because we got to share our poster*"). Most fourth graders (71%, 15/21) listed physical activity responses for the fun factor, whereas most first and second graders (67%, 16/24 and 83%, 15/17 respectively) listed the wearable experience as a fun factor.

Learners' interest in the wearable experience of BodyVis was also evident in the design ideas they had for the shirt. Across all grade levels, learners wanted to expand the visualizations of BodyVis to explore more organs and systems (*e.g.,* brain, veins, bones, muscles, vocal chords). Learners' design ideas along with their daily assessments provide further evidence of the engagement we observed with the LPSV tools.

Influence of Community, Subject, & LPSV Artifacts. Learners' interests and connections with LPSV tools were both personal (*i.e.,* subject) and social (*i.e.,* community). Learners life-relevant connections were more personally-oriented with BodyVis rather than SharedPhys as they wanted to explore their interests in body organs with the shirt. Life-relevant connections with SharedPhys were more socially-oriented as learners enjoyed competing with one another and engaging in group investigations.

Leveraging the Environment for Life-relevant Connections.
We observed that learners leveraged aspects of the environment to make their own life-relevant connections to inquiry and body learning. As they planned investigations, they drew upon artifacts present in the classroom (*e.g.,* food, chairs), community aspects (*e.g.,* one learner wanted to investigate the difference between children's heart rate and a pregnant woman as their teacher was pregnant), and popular culture (*e.g.,* dances like NFL quarterback Cam Newton's "dab", videos and television shows popular among the class). In one example, a fourth-grade group wanted to investigate the effects of singing or dancing on their heart rate. When no one in their group felt comfortable singing in front of the class, they decided to focus on dancing. They selected the "Carlton" dance, popular from the television show *The Fresh Prince of Bel-Air*, which involves swinging arm movements and a small amount of bouncing. When it was their group's turn to test their procedure, one group member kept track of time while another played a YouTube clip of the dance on their teacher's iPhone. The room erupted in laughter as the wearers did the Carlton dance to the television episode. Afterwards, the group recorded, "*The Carlton didn't increase the heart rate that much. It [heart rate] only went up a little bit, then the heart rate dropped. Our hypothesis was wrong [not supported]*."

Influence of Supporting Artifacts, Community, & Division of Labor. We observed that supporting artifacts in the environment (*e.g.,* timers, phones, in other cases jump ropes, food) inspired and supported learners' inquiry investigations. They also drew upon the community for inspiration, leveraging characteristics of teachers and students (*e.g.,* gender, pregnancy, asthma) as well as popular culture (*e.g.,* dances, television shows) to support and inspire their questions. Performance in the community (*e.g.,* playing their favorite sport, singing in front of the class) also influenced group decisions about which questions they would pursue. Teachers played important roles (*i.e.,* division of labor) in helping learners gain access to resources needed to engage in personally meaningful investigations (*e.g.,* use of the teacher's iPhone) and helping them integrate personally meaningful content into their inquiry experiences. We observed that the three teachers had different classroom management approaches, which influenced *how* and *whether* they scaffolded such connections. For example, While the fourth-grade teacher encouraged learners to make these connections and provided the resources, the second-grade teacher was much more structured in her classroom management orientation, which impacted learners' access to personally meaningful resources in the classroom.

Touching & Sensitive Topics
Instituted and Emergent Policies on Touching. As the study progressed, the BodyVis shirts facilitated learners' playfulness and exploration, but researchers and teachers observed the need to institute a policy about touching due to privacy concerns. Adults instructed learners to ask permission of the wearer before touching the shirts. While the first-grade teacher implemented this rule at the beginning of the first session, the second- and fourth-grade teachers realized the need for the policy after observing learners interacting with the shirts.

We also observed emergent norms with respect to touching among learners. In the first-grade class, where children are still developing social collaboration skills [25] learners initially crowded around the wearer and tried to interact at once with the shirt. Slowly, they began to take turns as wearers enforced the rule to ask permission and as others realized their limited ability to interact with the shirt all at once. First graders reflected on this in focus groups when asked about their collaboration (*e.g.,* "*So we all took turns, and we didn't - calling out, and we weren't talking over anybody, and we were being patient and polite*."). In the fourth-grade class, we observed that some wearers were hesitant to allow opposite gender classmates to touch their shirts (*e.g.,* a female wearer allowing other female group members to interact with the shirt but slapping a male observer's hand away as he attempted the same interaction).

Sensitive Topics Arise. In some cases, sensitive topics came up as learners interacted with the shirts and thought of body-related questions and observations. The fourth-grade teacher expressed concern about this prior to the study as she planned to talk with her students about appropriate and inappropriate topics of discussion. She continued to monitor this throughout the four sessions, often curbing conversations that could lead to inappropriately mature discussions. For example, when one fourth grade learner asked "*How babies live inside the womb*" the teacher explained that questions should be focused on things that BodyVis and SharedPhys can help investigate.

In interviews, teachers observed the need for considering BodyVis shirt sizes. One teacher also pointed to challenges larger or more developed second graders had putting on the BioHarness, especially young girls who were starting to wear bras. A fourth-grade learner similarly suggested that more sizes be created for BodyVis shirts. For the study sessions, we created five shirts: one large and four small and adapted the BioHarness chest straps to accommodate different body sizes. Additionally, shirts fully open in the back and re-attach with Velcro to allow for a wider range of sizes. In our analysis of session video, we did not observe problems with fit; however, we carefully planned with teachers before the sessions size requirements for individual students. We did, however observe that some learners who were larger-sized had higher heart rates and were more physically stressed (*e.g.,* sweating, heavy breathing) by physical activity.

Influence of Physical Bodies on Artifacts, Subjects, Norms, & Division of Labor. We observed that issues related to learners' (*i.e.,* subjects) physical bodies brought up sensitive topics and considerations that related to both artifacts, community norms, and facilitator roles (*i.e.,* division of labor). The focus of LPSV activities on the body posed tensions on existing rules in the classroom, as learners broached topics considered inappropriate in class. Additionally, we technically allowed discussions about fitness levels and sizes, but went against norms as these topics could potentially be embarrassing for learners, particularly in whole group settings. For example, as learners were focused on competing with one another using SharedPhys, facilitators raised the question of whether higher heart rates were always a good thing. The topic was not explored further in the conversation, but could have been potentially sensitive for learners who had the highest heart rates. Teachers played important roles helping learners navigate sensitivities (*i.e.,* division of labor), assisting children in putting on the BioHarness, and instituting policies and norms before issues arose. Providing multiple BodyVis shirt sizes helped ease sensitive topics around body size. However, with SharedPhys' representation of heart rate, learners could easily misconstrue the health implications of their data (*i.e.,* preferring to have higher heart rates).

DISCUSSION

Although prior SBL research points to the importance of considering the contexts in which SBL tools are situated (*e.g.,* [31,48,53]), this has often not been the focus of SBL studies. Prior analyses have focused, for example, on the types of learning possible and ways learning develops with SBL tools (*e.g.,* [23,33,41]) and the types of representations and interactions that children need to foster learning (*e.g.,* [31,46,58]). The foci of these analyses are centered around learning goals and outcomes, but they do not fully account for the significant impact of the material and social contexts in which SBL tools are situated. As such, designers are likely to miss key design insights useful for effective use and uptake of SBL systems in specific contexts.

Leveraging AT to guide our analysis enabled us to consider these rich contextual factors. We were also able to identify key influences and tensions common in elementary school classrooms that impact use of LPSV tools. Specifically, we offer two types of design implications: (1) design implications for supporting life-relevant inquiry and (2) implications for integrating LPSV and SBL tools into classrooms.

Designing Artifacts to Support Life-Relevant Inquiry

Looking across the two tools, our findings indicate that, similar to prior studies of LPSV tools [43,44], model-based representations in BodyVis supported exploration and observations. However, we found that when using BodyVis, it was more challenging to observe changes over time or make comparisons. Similar to prior SBL studies (*e.g.,* [23,54]), analytic representations in SharedPhys inspired and scaffolded scientific inquiry skills and processes. With SharedPhys, however, we observed a need for simpler visualizations (*e.g.,* showing just one learner at a time) especially for younger learners. These findings offer particularly useful insights for supporting learners across age ranges.

First, our findings suggest the potential of *iteratively linking model-based and analytic representations to help learners navigate between the two types of representations*. Such linking may be leveraged to support the integration of content understanding and skill development. For example, clicking on a wearer's avatar on SharedPhys might show a digital replica of the BodyVis shirt that responds to learners' interactions with the physical shirt (*e.g.,* removing organs, activating simulations). Similarly, users could click on another link to get back to the Moving Graphs visualization. As learners' curiosity is piqued or as they develop content understanding, they can easily navigate between investigations and analysis. Using simple concrete visualizations can help younger learners slowly progress to more complex analytic representations. We suggest leveraging their interests in wearable explorations to promote their capacity for more complex inquiry.

Second, our findings point to the importance of *considering and leveraging non-technical artifacts in LPSV (and SBL) environments to promote learners' inquiry investigations and life-relevant connections.* While there are aspects of the environment that are difficult to change (*e.g.,* there may not always be a pregnant teacher in the classroom), supporting artifacts (*e.g.,* food, books, toys, timers, speakers) can be more easily incorporated into the environment to inspire, manage, or facilitate investigations. For example, designers might create a kit to come with LPSV tools that includes artifacts for physical activity and life-relevant connections (*e.g.,* balls, jump ropes, food, music) as well as those for new types of inquiry ideas and content connections (*e.g.,* books, brain teasers, pillows).

Integrating LPSV and SBL Tools Into Classrooms

Prior work focused on learning gains with SBL and mixed-reality tools have pointed to the importance of considering contextual aspects of the learning environment (*e.g.,* teacher preparation, curriculum, norms, routines) (*e.g.,* [15,35,38]). Our AT analysis points to specific design implications and contextual considerations for designers when integrating LPSV and SBL tools into classrooms. While these findings are more general guidelines and considerations for LPSV contexts, they should also inform the design of LPSV tools.

First, our findings show the importance of *allowing for incremental integration of new variables and life-relevant components into inquiry experiences for younger learners* to help them focus on aspects relevant to inquiry (*e.g.,* leveraging individual visualizations before moving to multiple-wearer representations that encourage competition). As learners advance in their inquiry skills, as we observed with older learners, personally relevant aspects can be leveraged to help them consider complex inquiry considerations and make increased life-relevant connections.

Second, our findings point to the importance of *helping educators mitigate the range of sensitive discussions, physical activity, and noise levels that may arise in LPSV environments.* Our findings indicate the roles teachers must assume to address sensitive topics and issues that arise in LPSV contexts. Designers should thus consider ways to help educators mitigate and address these roles. For example, designers might consider different sized wearables (with clear, easy-to-see labeling), artifacts that promote quiet experimentation (*e.g.,* the books and brain teasers mentioned previously), and pausing features on real-time visualizations that can ease the challenges teachers face as they try to manage LPSV classrooms and support learning. Similarly, to ease concerns wearers might face with others touching them, designers should consider leveraging digital replicas of wearable e-textiles—perhaps through augmented reality—to allow non-wearers to get closer perspectives of content without making wearers uncomfortable. In cross-gender groups where wearers may feel less comfortable, such designs might facilitate collaboration without encroaching on personal space.

Finally, LPSV designers should *consider health implications in the design of LPSV representations*. While it is important not to highlight individual fitness levels and sensitivities, it is also important that children understand important concepts about their health and physiology as they analyze LPSV data. The use of aggregate data might be helpful for discussing the health implications of data. For example, designers might leverage an entire class's aggregate data to compare with another class's to discuss heart health and physical fitness. Such designs might reduce focus on individual learners but still allow for meaningful discussion around real-time data.

CONCLUSIONS

Our close work with teachers and learners through participatory design, interviews, and focus groups is well-aligned with Nardi's [39] call for multiple data points and incorporating users' voices into technology design. This approach helped generate design implications and policies for navigating contextual inquiries important for effective use of LPSV tools. Our use of AT to analyze LPSV ecosystems also revealed several key tensions for design consideration. First, we show the tensions that exist between how children perceive LPSV tools and how teachers perceive them (*e.g.,* motivating noisy competition *vs.* fostering learning and assessment). Second, our findings show the tensions to consider related to sensitivity and the body (*e.g.,* touching, personal fitness, appropriate and inappropriate conversations). Finally, our use of AT enabled us to see important aspects of the environment that influence how LPSV tools are used (*e.g.,* supporting artifacts, spatial layout of rooms). These insights point to important design considerations for LPSV designers and they raise key issues that should inform design decisions and approaches.

We do not suggest that AT is the only framework that can be used to analyze such rich contextual influences on learning and interaction with SBL tools. Indeed, Nardi [39] and others (*e.g.,* [15]) have advocated for the use of other contextually-based frameworks that can provide similar insights. We do, however, advocate for more of such analyses to uncover the opportunities and tensions inherent in SBL contexts. While learners in our study constructed their own investigations with LPSV tools, our future vision is to support more constructionist learning experiences for children. We are currently developing tools that will enable learners to construct their own BodyVis designs. Additionally, our assessments in this study were limited in that they do not capture children's inquiry learning in a way that naturally fits with their personal practices. We are currently developing ways to create assessments that can better examine learners' inquiry in the context of personally meaningful experiences.

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