Learning physics through play in an augmented reality environment

Abstract The Learning Physics Through Play Project (LPP) engaged 6-8 year old students (n=43) in a series of scientific investigations of Newtonian force and motion including a series of augmented reality activities. We outline the three design principles behind the LPP curriculum: the use of play and participatory modeling, progressive symbolization within rich semiotic ecologies, and cycles of activity. We then present a qualitative case-study analysis of these principles in action as two students develop and demonstrate their understanding of net forces in two dimensions using the LPP microworld. Then, we summarize Pre/Posttest results which show that these young students were able to develop a conceptual understanding of force, net force, friction and two-dimensional motion after participating in the LPP curriculum which leveraged their prior experiences and ability to engage in embodied play as a form of scientific modeling.

Keywords Science education * Augmented reality * Embodied cognition

Introduction

Early elementary science instruction has not kept pace with the developmental literature on young students' cognitive competencies that can be used as building blocks for understanding science concepts (NRC, 2007; Metz, 1995). In fact, young children can, under the right circumstances, learn more complicated ideas than we currently ask of them in early elementary science education. One argument against 'ambitious' science instruction[1] is that aspects of classical experimental design such as controlling variables and separating hypotheses from evidence have proven difficult for young children (Klahr, 2000; Schauble, 1996; Siegler & Liebert, 1975). However, alternative studies have shown that asking students to produce and evaluate models of the real world to help them generate predictions can make it possible for them to effectively participate in the process of scientific knowledge production and learn the content being studied (Lehrer & Schauble, 2006). Modeling—in the case of the Learning Physics through Play project (LPP)[2], hybrid modeling that leverages both computer simulations and physical embodiment to describe Newtonian force and motion—is a critical part of the scientific inquiry process and can help students coordinate theory with evidence (Schwarz & White, 2005). However, while modeling is within reach of early elementary students, they still do not progress very far without carefully scaffolded collaborative experiences (Lehrer & Schauble, 2000). Therefore, our approach to modeling (and curriculum design) is both collaborative and collective, relying upon productive interaction to complement students' existing competencies. We see our simulations and activities as the sparks and anchors for modeling conversations. Students make observations in an environment that is structured by both the teacher and our designed tools, which materially represent their emerging understandings. The models students create are then shared, critiqued and refined within the classroom community with the goal of producing a shared collective model that can be used to understand and make predictions in new situations and contexts.

In this paper, we describe how first and second grade students (6-8 years) learned about the physics of force and motion through a series of technologically enhanced modeling activities. At the heart of the project was a set of augmented reality and motion-capture technologies that were used to leverage students' existing competencies in pretend play and to transition them to formal and symbolic models of force and motion. Briefly (a fuller description is provided below), cameras filmed the area at the front of the classroom. The video feed was passed through object recognition software that recognized and tracked (e.g., the position and orientation) a predefined set of geometric patterns. Students held or wore these patterns as they moved about the room. A projection of the LPP simulation software was displayed on an interactive whiteboard. The simulation software showed the video feed of the students moving around the room. The simulation software also displayed an image of the object that the students were play-acting (e.g. a ball) superimposed by the computer software over their image in

---

[1] We have adapted the term 'ambitious math instruction' from Lampert, M., Beasley, H., Ghousseini, H., Kazemi, E., & Franke, M. (2010, 129-141). which was used to refer to instruction that simultaneously targets conceptual understanding, procedural fluency and productive dispositions towards the domain.

[2] Note that in previous presentations, this project was referred to as the Semiotic Pivots and Activity Spaces for Elementary Science (SPASES) Project NSF Award # DRL-0733218.

the video feed. The superimposed objects would move around the projection in real-time as the students themselves also moved around the room.

In this paper we will first describe the technologies and activities of the LPP project and the design principles that guided us. Second, we present a case study that illustrates how students engaged with the augmented reality activities of the curriculum and illustrates the design principles in action. This is followed by a quantitative analysis of student learning using pre and post assessments. Finally, we discuss some unexpected elements of our findings, the study's general implications for teaching and learning young students using augmented reality, and the theoretical issues raised by this study that may warrant future study by the CSCL community.

Theoretical framework and design principles

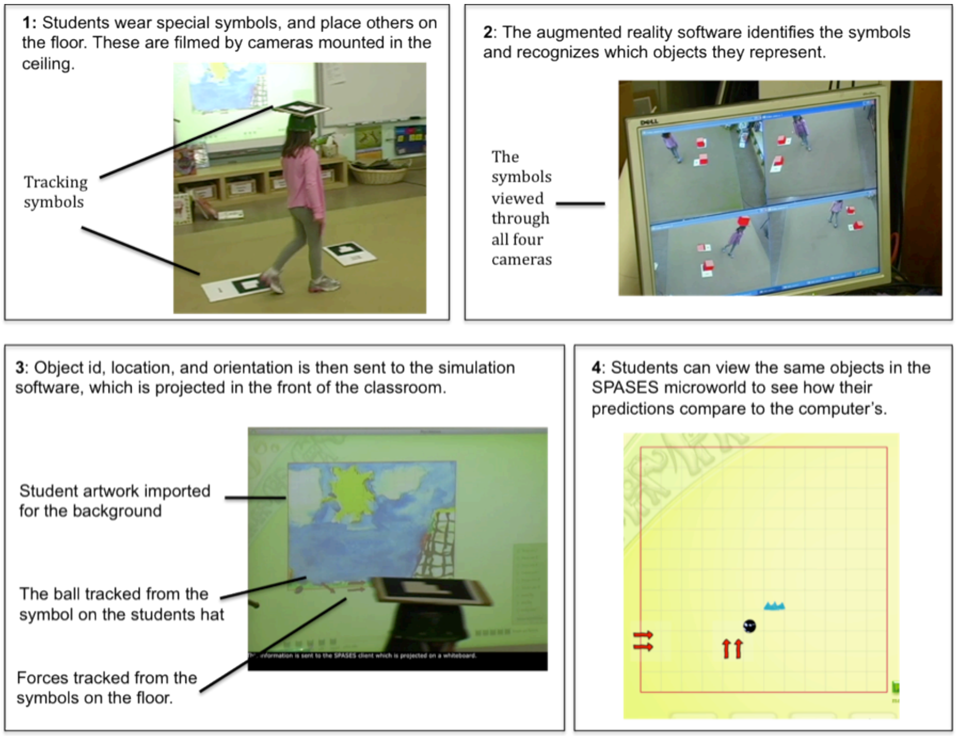
Young children and the concepts of force and motion

Physics is often cited as a privileged domain, where young children have a rich set of experiences to draw upon long before they enter school (Chen, Siegler, & Daehler, 2000; Bransford, Brown, & Cocking, 2000). In infancy, children develop an intuitive notion of objects, including their permanence and their properties. By preschool these intuitions have developed into a sophisticated sense of mechanical causality and understanding of the links between unseen causes and observable results (Bullock, Gelman, & Baillargeon, 1982; Yoachim & Meltzoff, 2003, October). Additionally, pre-school children can distinguish between distance, speed, and time when observing objects in motion (Acredolo, Adams, & Schmid, 1984; Matsuda, 2001). Even so, some concepts of force and motion are difficult for young students to grasp and these conceptual difficulties often persist well into college (e.g., White, 1993). Given the rich set of intuitions that young children have about force and motion, the prominence and import of force and motion in the K-12 curriculum and beyond, and the existing research into students' conceptual intuitions and the interventions that have successfully helped students develop normative understandings, we chose force and motion an ideal test bed to develop and study a new computer-supported, collaborative modeling approach to early elementary science instruction.

LPP focused on 4 broad force and motion concepts. First we targeted the concept of force including: the causal relationship between force and motion; the difference between force and speed; the fact that once a force ended, the speed of an effected object continued (i.e. inertia); and that impulse forces were an interaction between objects but not the objects themselves. These topics correspond to some of the key conceptual stumbling blocks to understanding force and motion (Lehrer & Schauble, 1998). Second, we focused on quantifying the relationship between force and speed, and in particular the application of multiple forces to an object (i.e., net force). Third, students investigated friction as a force. Fourth, the curriculum focused on net forces in two dimensions.

Description of the LPP environment and technology

There were two key components to the LPP system: 1) an augmented reality system that used computer vision to record and display the students' physical actions and locations, and 2) software that translated this motion into a physics engine and generated a response based on the sensing data. The LPP system used commercially available, open source forms of motion tracking and pattern recognition technologies (Kato, 2007) to create an inexpensive alternative to virtual reality within the physical classroom (a 12’ x 12’ carpet at the front of the classroom). Motion tracked by the system could be instantly imported into the new LPP computer microworld that allowed students to model their understanding of force and motion and compare their predictions to simulated results.



1: Students wear special symbols, and place others on the floor. These are filmed by cameras mounted in the ceiling.

2: The augmented reality software identifies the symbols and recognizes which objects they represent.

3: Object id, location, and orientation is then sent to the simulation software, which is projected in the front of the classroom.

4: Students can view the same objects in the SPASES microworld to see how their predictions compare to the computer’s.

Figure 1: The progression from physical objects and motion to a physics microworld in LPP

To illustrate how the LPP technologies supported successful modeling, we describe one example activity in which students were asked to predict how a series of forces would influence the motion of a ball. The students were split into two teams. The first team decided which forces to initially apply to a ball. The second team then chose the forces necessary to stop the ball on a given spot. The target concept was net force, addressing a common intuition that the ball would go in the direction of the last force. We expected that students holding this intuition would predict that when given a force in one direction and a smaller force in the opposite direction, the ball would reverse direction rather than slow down.

Susie, a student chosen to “play” the role of the ball, made her prediction by walking across the rug wearing the symbol for a ball on a hat. We call this type of public performance an embodied prediction. As she walked, she responded to the forces she encountered (i.e., cardboard symbols placed on the floor that represented forces) by speeding up. The system tracked her movement in real time. While the students saw Susie move across the rug, they could also see a ball projected in the LPP microworld moving across the whiteboard, mimicking her movement in the physical classroom. As Susie-as-the-ball passed arrow symbols, her peers also became involved, vocally expressing whether they agreed with her prediction. Did she speed up and slow down in the right places? By the correct amount? Thus, the embodied prediction generated public comment and discussion.

After Susie finished, the students were invited to continue debating her embodied prediction. They began by discussing how many forces were in each location and what their impact would be on the ball. Some students expressed common intuitions while others shared more idiosyncratic ideas. The students then had the chance to compare Susie's embodied prediction with a simulation built into the microworld that mirrored the choices they had made with the physical objects. Since the cards representing forces had already been laid on the floor as part of their activity, and because the system recognized these patterns as forces that operate in particular ways in the physics engine, all that the students had to do to test their predictions was reposition Susie-as-the-ball back to the beginning and press a button to run the simulation. Now the physics engine took over Susie's ball and displayed what would happen for that same scenario in a Newtonian world using the same space and representational system as the children's pretend play. Ultimately, the students all expressed surprised that their predictions did not match the computer simulation. In the ensuing discussion, students made explicit some of their implicit thinking. This discussion provided a key building block for a series of activities that then led to the majority of the students in the group transforming their intuitions and beginning to reason in a normative manner about how forces contribute to an object's motion. To summarize, the students started the activity using pretend play skills, but by the end of the lesson they were engaging in a discussion about modeling and concepts of net force. Through this game-like experience, LPP made it possible for 6-8 year-old students to interrogate their own understanding (Rosebery, Warren, Ogonowski, & Ballenger, 2005) and explore these physics concepts.

We now turn to the broader theoretical framework that guided our design.

Design Principle #1: Play and participatory modeling

For young students in particular, it is important to develop modeling abilities by starting with what they can already do. This is a fundamental premise of constructivism—that students' existing schemata are modified, added to, and reorganized, but not abandoned during the learning process (Smith, diSessa, & Roschelle, 1994). An understanding of modeling begins with symbolism, as models stand for something else and often use collections of symbols to do so. Importantly for the LPP project, as early as pre-school, children are able to distinguish toys, pictures, and video images as representations of real objects, and can use representations successfully to reason about the world (DeLoache & Burns, 1994).

In addition to nascent symbolism, young students have another important competency at their disposal for symbolic representation—one that is not traditionally thought of as a building block for science, but which we believe can be effectively marshaled to that end—this competency is play. Play, particularly embodied, socio-dramatic play where children use their bodies and movements to enact a scene or situation, is an activity that young children are competent at and familiar with from an early age, and which is closely tied to the development of symbolic representation (Nicolopoulou, 1993; Piaget, 1952). In fact, play has been described as the leading activity of childhood responsible for pushing development during the pre-school years (Griffin & Cole, 1984).

The defining feature of pretend play is not that it is fun (although it often is). Rather, its defining feature is the combination of an imaginary situation with a set of rules (Vygotsky, 1978). Play can be seen as a continuum with pretend play on one end, where the imaginary situation is rich and explicit but rules tend to be understated and implicit, and games on the other end, where rules are explicit and the imaginary situation is thinner or more symbolic (Vygotsky, 1978). However, in all forms of play, students are able to engage with quite complicated rule sets. For example, when "playing house," children typically control their behavior based on a set of rules about what fathers do, what mothers do, and what babies do. It is this focus on a set of rules that makes play relevant to science, as scientific phenomena are often described as a set of rules or laws—for example, Newton's three laws of force and motion.

The rules in pretend play are also what make play a valuable part of the learning process and a type of informal inquiry (Youngquist & Pataray-Ching, 2004). In play, children often attempt to govern their behavior by following a set of rules that they do not yet fully understand. Additionally, through play, the rules that govern a situation become visible and often explicit for children (Rosenberg, 1987). Understanding the rules that govern the world is one of the central aspects of scientific modeling. For this reason, researchers have argued that play is an early form of simulation (Bruner, 1986).

To incorporate play into the LPP curriculum, we engaged students in developing and refining participatory models (Author, 2009). Participatory models are embodied, dramatic skits where the students enact a key principle of the system being studied, and leverage their body motion and position as a resource for displaying their understanding. Participatory modeling builds upon the kind of productive collective engagement that has been seen in participatory simulations (Colella, 2000) while shifting the focus to make rules more explicit and reflective for the participants. By identifying these play activities as participatory modeling, we are highlighting the fact that students were explicitly and intentionally presenting, through embodied enactment, their model of how the ball would move.

To facilitate productive modeling throughout the curriculum, LPP began with a first-person experience—an important building block for young students' scientific understanding—where one student pretended to be the ball and used his/her own physical motion to predict and represent the motion of the ball. It has been shown that when learning difficult science concepts, students benefit from examining the system from multiple perspectives, particularly in computationally supported environments where the technology can help students take perspectives beyond their own perceptual capabilities (Noble, Nemirovsky, Wright, & Tierney, 2001; Rosebery et al., 2005) Like traditional computer simulations, LPP offers the outside observer's perspective as well, where one can look down from above and observe forces, friction and motion, running experiments and measuring the phenomena (see Figure 1). However, given the age of our students, LPP began with a first-person experience and then transitioned to an abstracted third person perspective.

Design Principle #2: Progressive symbolization within rich semiotic ecologies

An additional intersection between play and scientific activity is the role of symbolism. In play, the child can choose which features of the situation are relevant and meaningful and which features can be ignored. This is exactly what children have difficulty with when engaging in formal scientific investigations. Young students frequently insist on fidelity, especially visual fidelity, requiring that the model and representation look the same (e.g., water is blue, leaves are green, etc.). For example, a child who pretends a blue cloth is a lake that her toy boat must cross has somewhat rigidly used the similarity in color to assign a symbolic meaning to the cloth. At the same time, she has flexibly chosen to ignore other aspects of the cloth, such as its square shape and lack of wetness, and by not assigning them significance, has made them semiotically invisible. Thus, in play students are able to fluently use symbolism and abstraction in ways that remain difficult for them in other contexts such as formal investigations.

Our goal was for students to transform their everyday semiotic competency into a fundamental skill of scientific modeling, and for this to happen children needed opportunities to progressively refine their symbols, adapting them to the problems they were trying to solve (Author, 2005; Lehrer & Schauble, 2002). Giving them such opportunities allows the students to create increasingly robust symbols, and to develop shared norms about the importance of the symbols to their local activity (Author, 2005). To support students in these practices, many of the activities in the LPP curriculum asked the students to create, critique, and refine symbols for concepts such as force and friction. For example, we had students draw pictures of pushing and kicking as initial symbols for forces. Then, their artwork was imported into and used within the LPP environment in order to provide a consistent set of symbols across activities. As the students encountered new contexts, ran into difficulty with their symbol, or developed a deeper understanding of what force meant to them, students were free to develop new symbols for force to be used by the system and their peers in their subsequent activity.

The process of progressive symbolization is also intended to lead the students to weave together a rich semiotic ecology (Goodwin, 2000) where different semiotic resources such as gesture, talk, and pictures are laminated one on top of the other to create a deeper conceptual understanding of both the abstract symbols and of the concept itself. Students seldom used the symbols in isolation. They were gestured over, used in conjunction with everyday talk, or with the new specialized vocabulary of physics they were learning. Therefore, an additional element of this design principle was to support students in fluidly navigating between these semiotic fields, choosing the one that made the most sense at the time but keeping that choice in relation to other ways that the concept was represented.

Design Principle #3: Cycles of activities

Similar to other curricula that incorporate a microworld, we also wanted to provide the students with opportunities to explore the physical phenomena directly and then to reflect upon the relationship between their physical observations and the often-idealized simulations and models that they worked with. Furthermore, we assumed that students' pathway through these activities would not always follow the same conceptual progression—they would likely have different intuitions and comfort with the content. Therefore, our goal was to develop cycles of activity that supported the students in collaboratively exploring the relationship between the physical world and their models, supported them in reflecting upon this relationship, and allowed them to participate in a manner consistent with their current level of comfort with the content and the representational system being used. We aimed to create an environment where students were encouraged to articulate their understanding with whatever resources they found intuitive whether it be gesture, talk, or symbols. Thus, even when students were expected to enact a prediction, they could complement that enactment by using talk, pointing, and other semiotic resources as they saw fit.

We illustrate this by considering the cycles of activities related to using the LPP microworld. Students often began by creating an embodied prediction in response to a prompt (e.g., given these forces, where will the ball roll?). Typically, after making their embodied predictions, the students seamlessly transitioned into a physics microworld to compare their embodied predictions to what would actually happen in a perfect Newtonian world. Students positioned objects within LPP using either the shared interactive whiteboard, or the augmented reality objects, allowing differential entry points in the real or virtual world. Like prior effective microworlds (c.f., White, 1993), LPP allowed students to see and manipulate a situation in ways impossible in the real world (e.g., turning off friction). Asking students to place objects on the whiteboard or in the physical classroom had the added benefit of creating public and open tools for discussion (Author, 2007; Hutchins, 1993). This openness, also an important feature of LPP, allowed students to interrogate their peer's choices or propose alternative predictions for what they thought would happen. In this way students could collectively reflect on their comparisons of the real world and the model, as well as construct meaning around the symbols in the system.

In addition to their interactions with LPP, students also engaged in non-computer-mediated experiences and investigations in the real world, as well as play-acting without technology, or technology without pretend play and tracking. This range of activities was intended to connect student understandings at multiple levels of abstraction—from actual balls they could touch to symbols about motion devoid of any reference to the objects doing the moving.

Methods

Participants

The LPP curriculum was successfully implemented in two multi-age classrooms with students aged 6-8 years (x=7.1 years) at the UCLA Lab School (n=43). The students were roughly even in terms of first and second grade students (twenty two 1st graders & twenty one 2nd graders) and in terms of gender (21 boys & 22 girls). The ethnicity of the children roughly mirrors the ethnicity of the state of California (although Latinos are under-represented in our sample); 53% Caucasian, 22% African American, 14% Latino and 11% Asian.

The curriculum lasted 15 weeks (2/18/09 through 6/8/09) and consisted of 26 one to two hour sessions. The average length of a lesson was 90 minutes. Four major topics were covered; force and speed (5 lessons), net force in one dimension (11 lessons), friction (4 lessons), and two-dimensional motion (7 lessons). In addition to the augmented reality activities the lessons also involved hands-on investigations, physical modeling activities, and discussion.

Procedures

Students were individually interviewed before and after the unit with a protocol based in part on a modified version of the Force Concept Inventory (Hestenes, Wells, & Swackhamer, 1992). To document learning processes and how the curriculum was enacted by the teachers, we videotaped two case study groups (students were organized into small groups of 8-9 students) and all whole-class activities.

The pre- and posttest interviews were transcribed and coded for degree of conceptual understanding. Reliability for each item was determined by calculating the Intra-class Correlation Coefficients (ICC) for each item. Five of the 34 items were dropped because of low inter-rater reliability. An additional ten items were dropped due to a high proportion of missing answers. These missing answers were due in part to student attendance, but also due to variability in the way that various members of the research team administered the interview, and the difficulty in parsing the continuous transcript into discrete answers. As a result, the final pretest and posttest scales were comprised of nineteen items. Reliability analyses were conducted on the pretest and posttest items to examine whether the data had a unidimensional structure. The Cronbach's alpha for the pretest scale was .46. The Cronbach's alpha for the posttest scale was .35. Two explanations may account for the low alpha values: (a) sample characteristics and (b) multidimensional test items. With respect to the sample characteristics, the sample size was small; with a larger sample, reliability is expected to be higher. Also, the items were intended to capture a range of cognitive demands across multiple concepts. The low alpha value may also simply reflect the intentional multidimensional facets of the test items.

Given this study was a within-subject, pretest-posttest design, test-retest reliability was analyzed in order to determine that the test items are sensitive to change (Guttman, 1945). A Pearson correlation coefficient was computed to examine the correlation between the pretest and posttest scores. Results indicate that the scores were significantly correlated, $r(41) = .28$, $p < .04$.

Results

Play, modeling, and learning in a LPP augmented reality activity

As noted above, the LPP curriculum was motivated by three key design principles: 1) the use of play and participatory modeling, 2) the inclusion of progressive symbolization, and 3) and cycles of activities. In examining the video record, we found that the fluid integration of these three principles was crucial to the success of the LPP curriculum; the principles did not work in isolation and it would be counter productive to attempt to disentangle the role of each principle in supporting student learning separately. Instead, we examine the principles and attempt to explicate how their synthesis played a role in helping students to develop the rich conceptual understanding that is evident in the pre- and post- test results. In this section, then,, we present a brief case study of students' progression through several representative activities in order to highlight each of the principles as they emerge, rather than in the order we initially enumerated them.

The activities we present come late in the curriculum when students are investigating motion in two-dimensions (i.e., perpendicular forces applied to an object). We selected this topic for illustration in part because it was the most challenging unit in our curriculum, and also one of our more successful units. Figure 2 depicts one of the contexts students were asked to make predictions about, a "large"[3] horizontal force of 3 units (point A) that is applied to a ball that was originally set in motion by a "medium" vertical force of 2 units (point B). Students were asked to predict the path of a ball that was initially placed at point A, coinciding with the initial vertical force that would be applied once the simulation was begun.

---

[3] Large and medium are labels that the students chose to apply to those different forces.

When discussing this kind of motion, the students in our data typically focused on four aspects of the motion of the ball in their predictions and observations: 1) the general pattern of motion after the second force (e.g., “diagonal”); 2) the specific path that the ball might take; 3) the transition point where the new force was applied; and 4) the mechanisms of how the different forces influenced the ball. As we will illustrate below in the case study of Sara and David, it appears that both students’ current level of understanding, and the immediate semiotic means that were available to them, influenced the kinds of observations that they made, thus creating a context for reflection upon their ideas.

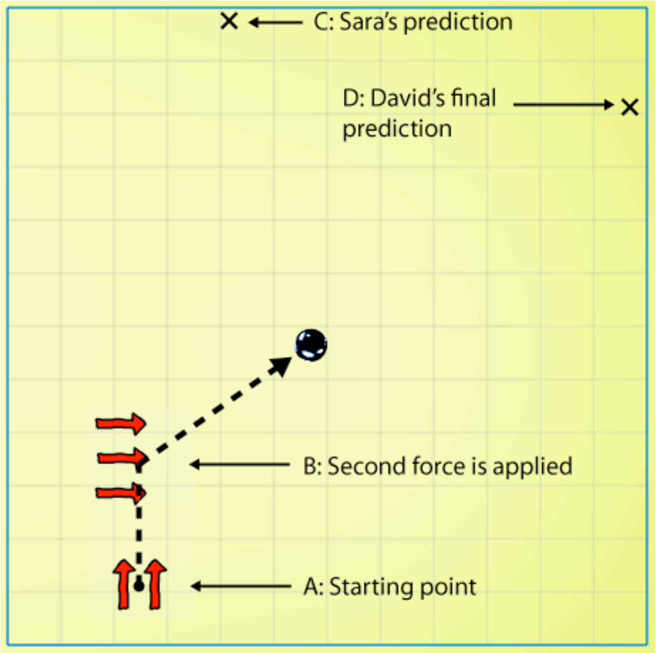


Figure 2: The LPP window depicting 2-dimensional motion. The dashed line depicts the path of the balls motion once the simulation was begun. The ball was initially placed at point A, on top of a vertical force of 2. Once it began moving, the ball encountered the force of 3 at point B, which altered it’s trajectory.

Case study of Sara and David

To ground our analysis of students’ exploration of two-dimensional motion, we focus on the events that led up to and followed the key play and participatory modeling activity that students engaged in as part of this unit. We focus on this activity in part because it is a clear example of our first design principle in action, and in part because we see it as a key turning point in students’ learning trajectory. The activity, in which students used the LPP environment to model their predictions through embodied play, took place on the 27th day of the intervention, and the 3rd day since we had begun discussing 2-dimensional motion resulting from perpendicular forces. For this activity, the teacher asked the students to place the LPP cards on the floor that coincided with the force of 2 and 3 as illustrated in figure 4. Then, the teacher asked the students to predict the path of the ball once the simulation began by acting out their prediction.

We focus our analysis for this paper on two students, Sara and David, members of the 8 person focal group. These two students were chosen because in the previous 2 days of activities, they had demonstrated a number of non-normative conceptions about this situation, but in the activity we describe, they seemed to make some intellectual progress towards understanding how perpendicular forces of different sizes determine the velocity of the ball.

Sara and David's initial predictions

Before we discuss the breakthroughs that Sara and David appeared to have made on the 3rd day of 2-dimensional motion, let us first briefly recap their intuitions from the first two days and demonstrate the second and third design principle in action. The first day consisted of a number of hands-on experiments with soccer balls. The goal of these experiments was to expose and challenge students' conception that the second of two kicks, delivered at right angles to each other, would completely determine the motion of the ball. Furthermore, we wanted to help the students to ground their predictions in the kinds of embodied experiences that they typically had on the playground with kicking balls. Thus, the students were asked to kick[4] soccer balls after predicting the path that the balls would take. The students were then led through multiple rounds of discussion and experimentation in which they described the potential path of the soccer ball and then attempted to direct it by kicking it once it was already in motion.

After this day of physical experiments with the soccer balls, both focal students appeared to accept that equal sized horizontal and vertical forces would produce a diagonal motion. However, neither student had a robust concept that would extend this observation to new situations where the forces varied in relative size. When presented with such a situation, both of our focal students reverted back to their initial idea of the ball going in the direction last hit (which in this case was also the larger of the two forces). For example, when the teacher sets up a small horizontal force and a large vertical force using the LPP simulation software on the whiteboard and asked Sara, "Now what is going to happen? From what we know so far, what is going to happen?", David interrupted and blurted out "it goes straight up" and traces a path in the air in front of his body. This interruption is important not only because it reveals David's current understanding, but also because it shows how students consistently took advantage of the familiar semiotic resource of gesture to illustrate their current understanding, moving fluidly between the symbol system of the projected simulation and their own non-eidetic gestures (they were not simply pointing at the simulation) to illustrate the point being discussed. This form of embodied illustration of horizontal and vertical directions continued to play a role in how students presented their ideas, and was ultimately reified in their written symbolic presentations of the same ideas. (Design Principle #2: Progressive symbolization within rich semiotic ecologies).

A split second later and overlapping with David, Sara, who had been nominated by the teacher to formally share her idea, expressed the same idea but also explicitly referred to the speed that the ball was traveling at different points in time—information that was only implicitly conveyed through gesture by David. As she explained her idea she also gestured, although she gestured over the diagram drawn on the whiteboard rather than in reference to her own body. Sara then said: "When it goes slow [traces a horizontal line over the whiteboard from the first force to the second force] When it goes like this, then when it hits this part it will go up [traces a vertical line up from the second force drawn on the whiteboard]".

---

[4] Actually they were asked to poke the soccer ball with a stick to better simulate an impulse force and to provide better control over the direction of the force. We use the term kick here to map the experiment back to an everyday context that may be more familiar to the reader.

The slight differences between these two predictions in terms of the information included (e.g., speed) highlight the fact that this approach allows students to represent the information that they consider most relevant at the time, which may also have revealed elements of their current understanding.

These predictions also illustrate the necessity of including cycles of activity in our design (Design Principle #3: Cycles of activity). While these early activities were crucial in helping students begin to explore their understanding of perpendicular forces, both students' ideas still seemed to be in flux and quite contingent on the surface features of the context rather than the rules of physics. Of particular import, they both demonstrated the common intuition that the resulting motion was in the direction of the most recent force rather than a combination of the new force and the current motion.

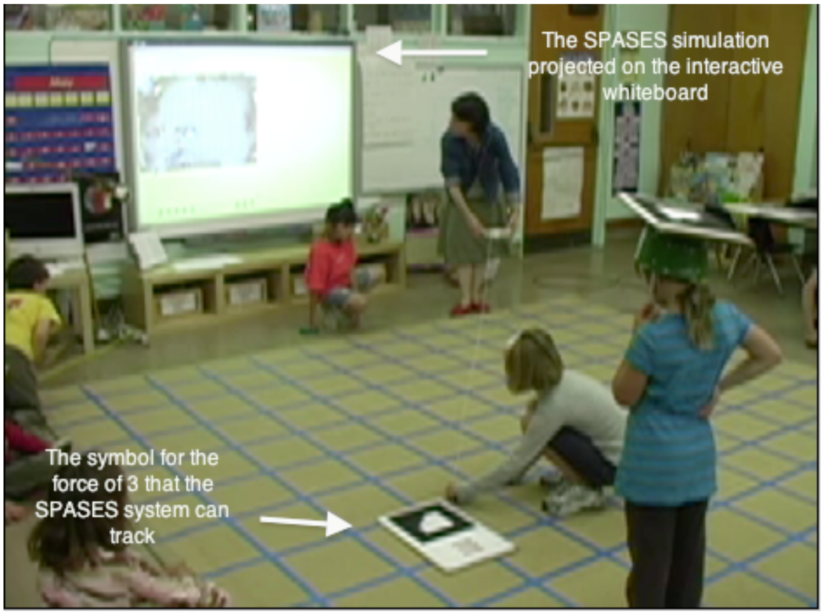


Figure 3: The classroom layout depicting the physical objects that coincide with the simulation in Figure 2.

Day 3, Step 1: Preliminary predictions

The small group work on day 3 again began with the teacher positioning the small vertical and large horizontal force (see figures 2 and 3) and asking the students to articulate their predictions. Sara first made her prediction by tracing her finger along the simulation window that was projected on the smart board. She moved her finger from point A (where the initial vertical force was) to point B (where the ball encountered the larger horizontal force) and then up to point C (a point along the edge of the simulation window that lies on a diagonal from point B). This was a diagonal path, but at an incorrect angle. Further this was a departure from her predictions on the previous day in that it was no longer is consistent with her rule that the ball would go in the direction of the last push when the forces were of unequal size. This was further evidence that her concept was either unstable, very contextual, or in the process of evolving. These kinds of shifts also reinforced the design choice of cycling through multiple activities in which students continued to express and explore their understanding, with each activity providing new opportunities for the students to challenge their initial non-normative conception.

Sara appeared to pause briefly at point B, when her gesture encountered the second force, however it was unclear whether she had done so. Furthermore, she did not explain her thinking in any detail. This prediction, therefore, appeared to sit between the two descriptions of motion that we listed above (claiming a vague diagonal and claiming a specific path). Sara's prediction appeared specific in that it identified a concrete spot on the board, and yet also vague in that Sara did not appear to count or otherwise identify the specific location in a systematic manner.

This tension appears to have been necessitated by the current environment. Having to make a prediction in the physical space as opposed to only verbally forced the students to be specific—perhaps more specific than their current thinking allowed for. This was the reason behind our supporting such intuitive and yet vague symbolic choices early in the inquiry process. We then challenged the students to be more specific through multiple cycles of inquiry and symbolization as they refined both the specificity of their prediction and the concomitant method for representing those predictions (Design Principle #2: Progressive symbolization within rich semiotic ecologies).

In fact, Sara repeated her gesture 3 times because the teacher was addressing another student the first two times, and Sara's prediction shifted to a new location each time, further suggesting that she was not systematically selecting the slope of the line or the endpoint. As we will see below, however, by forcing her to commit to an endpoint, the LPP activity may have presented an opportunity to help her realize that there was in fact a more systematic approach that she might have used.

The teacher, Ms. Craig, then retrieved some string for Sara to mark her prediction on the rug. The string was intended to make the prediction at the same scale as the embodied prediction tracked with the LPP technology, so that the comparison between the embodied prediction and the simulation would be easy to see. Once the string was placed, without being asked, Sara adopted the kind of playful, embodied modeling stance that was supported throughout the curriculum (design Principle #1 play and participatory modeling). Sara began by standing up, positioning herself along the trajectory of the ball, and walking in short exaggerated steps to the second force. She then paused, marking this point as a key transition, and then quickly walked along the path of the string to the endpoint. Most importantly, however, this walk along the string clearly reiterated her prediction of how the ball would move, with the exaggerated pause at the second force highlighting the importance of that transition moment anew. This kind of walking the path to demonstrate the motion of the ball was something that the students did quite frequently to articulate their prediction of the balls motion, and their understanding of the key transition points. Furthermore, the exaggerated nature of Sara's initial steps were a trope that the students frequently adopted to illustrate the fact that the ball progressed at a consistent speed that was determined by the initial force.

Superficially, Sara's placement of the string and her walk along it appeared to simply reiterate the prediction that she made along the whiteboard. However, we argue that this does considerably more in that it created a shared public symbol of her prediction to be contrasted with David's prediction in the next few moments. Furthermore, her walk along the line allowed Sara to express her belief about the motion of the ball, something that we will see her repeat slightly later. The importance of this walk for Sara's explanation is further established a few minutes later when she articulated the difference between her prediction and the final path of the ball by re-walking the space rather than simply gesturing over it.

Ms. Craig then asked David to make his prediction. David immediately began to model the motion of the ball by taking on the role of the ball and walking to just below point B (see figure 3), the second force, and positioning himself next to it. He then stepped back and points down in the direction of point A (the initial force). He took a short step forward while sliding his pointing finger forward so that it traced an imaginary line between point A and B. He then stopped at point B where the second force was applied and raised his arm, pointing into the distance towards the corner. The teacher reiterated his gesture by saying, “You think it will go more over there, toward the corner?”, and David nodded while shifting his gesturing hand towards the corner. In this simple sequence, we see how David first leveraged play-acting as a form of modeling to articulate the element of his prediction that he was most confident in, and then shifted to gesture to articulate the less-sure element of his prediction—the resulting path of the ball (Design Principle #1: Play and participatory modeling).

If one re-enacts David’s embodied prediction, one can begin to see why this form of modeling may lead to different patterns of reasoning and insight than modeling from an objective, third person perspective. As one takes two steps from point A to B, one’s orientation automatically preserves the direction of the first force. Contrast this with Sara’s prediction over the whiteboard where her gesture preserved on the location of the ball, or to her string-prediction where her body was to the side of and at an angle to the position and orientation of the ball. This difference played out as David traced an arc from his current position facing the predicted path with his arm. While not conclusive here, it may be that this allows one to map the size of the second force to the size of the arm swing to better predict the angle. Further, the use of the arm-swing to model how large a turn the ball will take may make it less likely for a student to conclude that the ball will go in the direction of the last hit. In this case the direction of the last hit is a ninety-degree turn which is the maximum amount one can swing one’s arm without turning your body. It may be that the embodiment gives a physical sense of the extreme nature of this change that is not conveyed in symbolic models.

Alternately, it may be that David was not predicting a precise path with his arm swing, but rather used it only to depict a general direction (Design Principle #2: Progressive symbolization within rich semiotic ecologies). This hypothesis is consistent with the fact that David first pointed to a spot where he believed the ball would roll, then while running off the prediction veered off to a slightly different spot on the carpet. In this case, it may be that the walking the path phase of the embodied prediction was an important learning opportunity for David. During the walk, he was focused on the endpoint of his motion so that he had the second point in his line and could place the yarn as his final prediction. This focus on an endpoint may have provided him with an opportunity to reflect upon his modeling as he created it—refining the meaning he assigned to his arm wave gesture. Once David finished his walk, he sat in the spot and declared that that is the destination of the ball.

Regardless of the precision that participatory model may or may not have provided to David, what was important was that this type of embodied prediction brought different resources to bear than he used at the white board, and led to different ways of thinking and different conclusions. In this case, David had taken up the role of the ball, and modeled the rules of two-dimensional motion as he understood them through play-acting. Then, one of the researchers asked David to clarify why he thought the resulting motion would be so much further toward the corner than Sara’s prediction. David turned around and once again used embodiment to reason and explain his thinking. He gestured back toward the string that marked his prediction, and traced the path of a ball as he narrated the different forces upon it. In his explanation, David highlighted the relative importance of the large force.

This was an important moment because David was now articulating aspects of his reasoning that were not publicly available prior to this moment, and that were not clear in his earlier prediction. Furthermore, his explanation depended on the fact that the balls and string were already placed. It was not clear that anyone other than the research assistant observed this prediction. However, there were many other occasions in our data where students ere able to layer semiotic systems in this manner to clearly articulate their prediction. They often began with a physical representation (the string) and a gesture to mark the progression of balls and forces (in David's case, pointing along the line) and then laminated this with a discussion of the mechanism behind his choices. While the precise order varied across examples, we believe that part of the success of this kind of layered explanation stemmed from the fact that it allowed the students to focus on one aspect of their prediction at a time—describing the motion, or the mechanism, but not both at once. Of course, one goal of the project as that the students' explanations could fluidly incorporate both at the same time. However, at these early stages where students are were the process of making sense of their ideas, we believe that being able to layer their explanations in this manner helped them to do so more fluidly. Certainly, David's explanation of the mechanism was not made visible in his initial prediction, and so from a pragmatic standpoint, this kind of sequential re-explanation through different semiotic fields was a key part of the process in helping us as observers to make sense of what David might have understand about the physics concepts underlying his prediction. More importantly, these opportunities also made student' reasoning visible to the teachers who could then respond or adjust accordingly.

Step 2: Running the simulation

When Ms. Craig then began the projected computer simulation, the students responded almost immediately. They cheered quite loudly, and appeared to immediately recognize the mismatch between the two predictions that were visible in the physical space, and the equivalent motion in the projected simulation. This was made clearer when Sara said that both predictions were wrong, and then walked the space to illustrate the actual path of the ball relative to David's prediction. From this, we gathered both that the students had no problem transitioning from the projected simulation to the physical space, and also that they could then refine their predictions in the physical space. This was particularly interesting because the student whose job it was to enact the ball had not taken the opportunity to enact the predictions prior to this demonstration. In a sense, Sara and David had usurped this role with their own predictions, and Sara then took on the role of depicting the actual motion of the ball based on the simulation within the physical space so that it could be more easily reconciled with the earlier embodied predictions. As Sara walked her prediction, David also appeared to realize that the end-point of his prediction was accurate, and the path was simply somewhat off because he had placed the beginning of the string at the edge of the force instead of the middle of it. He quickly moved to adjust this.

It is important to note that Sara appeared to take her mistaken prediction in stride. This as perhaps a happy by-product from the association of science with play (Design Principle #1: Play and participatory modeling). Bateson (1976) asserted that an important aspect of play is one's orientation towards the activity, pointing out that a playful punch is not interpreted in the same way as a real punch would. Likewise, in this case Sara seems to have had an orientation toward her own activity and prediction that made the lesson a safe place to share one's ideas and even be wrong. In fact, she as rather quick to help clarify what the final motion was. From this we infer again that while she may have been committed to the diagonal motion of the ball, she was not committed to the specific path that she had specified—it was a guess. In terms of her learning trajectory, this suggests that she may have understood the outcome of combining two perpendicular forces only in a qualitiative way (i.e., that it produced a diagonal) without yet being at the point where she was could calculate the vector.

Step 3: Describing the simulation

As noted above, Sara and David used similar semiotic means to make their predictions, and then to comment upon the simulation that had recently been completed. Specifically, Sara walked across the grid near the string marking David's prediction, and David simply adjusted the position of the string from his prediction to reflect the actual path of the ball. While it is valuable that the students can use similar techniques to describe the completed simulation as they had used to make their initial predictions, there is no reason to believe that they have reached a deeper level of understanding based upon these clarifications. We turn briefly to another student from this group, Lisa, to highlight the collaborative discussion that arose from participatory modeling as students transitioned to more traditional and abstract models.

Ms. Craig had asked Lisa to explain the motion of the ball in a subsequent experiment where a horizontal force of 2 was applied to a ball that begun its motion due to a vertical force of 3. Some of the students were surprised at the steepness of the angle of the balls motion. Lisa explained that it was caused by the force of three followed by the force of two, and illustrated this with her fingers. One of the students didn't hear the prediction, and so Ms. Craig asked Lisa to repeat her prediction as can be seen in Excerpt 1 (we present the repetition because it is slightly clearer, although the content of the two predictions appears to be identical).

Excerpt 1:

1 Lisa: There was 3 and then there was 2.
2 Ms. Craig: Three going which direction?
3 Lisa: Three going up. [She gestures with three fingers, moving her hand upwards in the vertical plane. See figure 5.]
4 Lisa: Two going to the left. To the right [gestures in front of her body, but it is hidden from the camera]
5 Ms. Craig: To the right [nodding].
6 Lisa: And then, took away 2. And you still have one going up. [She now gestures with one finger moving upwards]

Figure 4: Lisa shows the force of 3 using her fingers as she gestures upwards

Lisa used finger gestures in two dimensions to illustrate the different forces. She used 3 fingers pointing upwards to represent the vertical force of 3, and then appears to have used 2 fingers pointing to the right to represent the horizontal force. This kind of gesture was incredibly powerful in that it set the stage for laminating arithmetic symbols onto the other semiotic means to produce a precise, quantitative method to combine to forces and predict the path of the ball. In fact, Lisa did exactly that in line 6 when she says, “You still have one going up”. While this description appears to erroneously suggest that the ball would simply move slowly in the vertical plane, we don’t believe this is what she meant. Instead, we believe she was attempting to describe how skewed the line was from the prototype of a diagonal (i.e., a 45 degree angle). Recall she had just observed the physics engine produce the correct path, so we can assume she knew that it didn’t not in fact go straight up. We believe she was using a method of cancelling and then adjusting the angle from 45 degree based on what is left over. If this as true, Lisa appears to have been using her fingers to represent an elementary form of vector arithmetic to calculate the path of the ball in response to perpendicular forces. Unfortunately, this insight is not made explicit or entirely clear to the other students through this discussion.

Nevertheless, a number of students were seen to use this kind of gesture throughout the curriculum, and the teacher also modeled this gesture to help reinforce it. This gesture was particularly powerful because it allowed the students to quantify their predictions, and to maintain a visual record of the different forces all encapsulated in one gesture. This embodiment of two forces and their relative sizes appears, therefore, to have been a key aspect of how a number of the students were able to transition from the qualitative prediction that a ball would move diagonally when it encountered a force perpendicular to its current motion, to a more quantitative description of what that diagonal path would look like (Design Principle #2: Progressive symbolization).

Step 4: The final poster

When we examine the students’ final projects for this unit, we see further evidence of their understanding of 2 dimensional force and motion. We also see evidence of the concurrent progress that they had made in thinking about how to symbolize this understanding (Design Principles 2 and 3, illustrating the inter-connected relationship between the two). At the end of the unit, each group was asked to prepare a poster summarizing their understanding of one of the “big ideas” they had studied. The case study group was one of two groups that made their posters on perpendicular forces. This provided us with one final piece of evidence in our efforts to track the students' conceptual development.

Each poster had several required parts. One of these required parts was to articulate a rule that described how the motion of an object behaved in these circumstances. The case study group articulated two rules on their poster (they are transcribed verbatim including the spelling errors of the children).

> Our rules:
>
> If you have a horizontil a then a vertical force the ball will go on a diagonal and the speed will increase.
>
> The forces compermis. Vertcle and horezontol bump in to each other then it will be dieagenle

There are two things of note in these rules. First, the students' first rule was a qualitative rule that described both the direction and the increase in speed of the ball. The inclusion of speed is important because it avoids a common new intuition that children develop when they first move away from the intuition that the ball always goes in the direction of the last hit. White (1993) found that students often erroneously think that the ball traveling in a diagonals line will travel slower because the interaction of the two forces takes up energy. Our students correctly identified that the speed of the ball increases with the second force. More importantly, this can traced back to the embodied gestures and walking within the LPP environment, where the students displayed this belief even though they did not articulate it verbally.

Also of note is that the second rule has a nascent mechanism for why the ball goes diagonally, namely, that the forces "compromise" and that the two forces "bump into each other". Although, these mechanisms for two-dimensional motion are not entirely accurate, the speculation and thinking is a step in the right direction and is impressive given the age of the children involved.

The pre- and post-text gains

Having described the type of collaborative learning taking place in the augmented reality activities, we know turn to a more systematic and quantitative look at learning outcomes for the entire curriculum. Descriptive statistics were obtained on performance on the pretest and posttest items. For the 43 students, the average pretest score was 4.99 (*SD* = 1.59) out of a possible of nineteen points. The average posttest score was 7.66 (*SD* = 1.7). First, correlational analyses examined the relation between grade level, age at the start of the study, gender, pretest and posttest scores. Results indicate there is no correlation between any of the demographic variables and the assessment scores (see Table 1).

Table 1. Pearson correlations between background variables and test scores

	Pretest	Posttest	Age at start	Grade	Gender
Pretest	1.00	.28*	0.11	0.16	-0.09
		0.04	0.23	0.16	0.29
Posttest	.28**	1.00	0.09	0.23	0.20
Pearson correlation	0.04		0.28	0.07	0.11

A paired-samples t-test was conducted to compare pretest scores and posttest scores. Posttest scores were significantly higher than the pretest scores, t(42)= 9.26, p < .001. The effect size of the gain was large, *d* = 1.64, indicating that the pretest-posttest change was greater than one standard deviation. To better understand the magnitude of the changes between pretest and posttest, a Wilcoxon signed rank test was computed. Results indicated that (88%) of the students showed a pre-to-posttest gain (Z = 4.88, p < .001), with 32 (74.4%) of the students increasing performance greater than one standard deviation. In sum, students demonstrated significant improvement on all of the key measures.

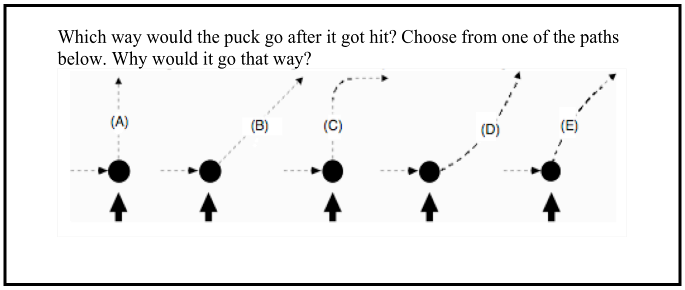
Scales were formed for our four content objectives: force and speed, friction, net forces, and two-dimensional motion. However, due to the small number of items per scale, the reliability of each scale was extremely low. Therefore, in order to examine differences in content understanding on these four specific topics, we have analyzed four exemplary questions. A Wilcoxon signed rank test was computed to examine changes in scores on each of these items. The Wilcoxon signed rank sum test is a non-parametric version of a paired sample t-test, which we chose to use because it requires fewer assumptions about the distribution of the data.

For the topic of force and speed, we analyzed the question that asked students "What is a force?" The highest value was given to answers that reflect the understanding that either force makes something go proportionately faster or slower, or that forces change the speed of an object. Partial credit was given to answers that describe forces as a verb (e.g., it makes something move) or as a noun (i.e, provides an example of a force). The sign test indicated that 24 (56%) of the students received higher scores on the posttest than on the pretest, Z = 3.34, p < .001.

For the topic of friction, we analyzed responses to a scenario that asked students to explain why a moving soccer ball slows down when rolling on a grassy surface. The highest value was given to students who described the resulting action and the mechanism of the friction (e.g., "Because those things sticking out of it, it will hold them back, it will try to push the ball back and stop."). Partial credit was given to answers that either described the surface quality of the grass (e.g., "So that's why it slows on the grass, because it's a little bumpy.") or connected the change in speed to friction or the grass (e.g., "Because it's really high friction right here, that's where it stops."). The sign test indicated that 15 (35%) of the students received higher scores on this question during the posttest than on the pretest, although the results were approaching significance, p = .08.

For the topic of net forces, we analyzed responses to the questions "What size force would you give to stop a ball that got the large size force? Why would you do that?" The highest value was given to responses that provided the correct amount of force (i.e., the same amount of force) and explained that an equal number of forces must be applied in order to stop an object (e.g., "Because same force of speed hitting each other would probably just stop." Partial credit was given to students who simply provided the solution but no explanation. The sign test indicated that 12 (28%) of the students received higher scores on this question during the posttest than on the pretest, although the results were not significant, p = .24.

For the topic of two-dimensional motion, we analyzed the response to the modified FCI item that asked students to predict the path of a puck that received another hit (see Figure 5). The sign test indicated that 29 (67%) of the students received higher scores on the posttest than on the pretest, Z = 4.67, p < .001.



Which way would the puck go after it got hit? Choose from one of the paths below. Why would it go that way?

Figure 5: modified FCI question about 2-D motion

Discussion

The qualitative case study of David and Sara illustrates the potential for building upon students' existing competencies using play and play-acting as a form of embodied modeling within the science classroom. The transition from play to modeling is not, however, spontaneous, nor is it a straightforward progression. Rather, students were exploring complex ideas first through play, iteratively refining their explanations and models through the cycles of activities. However, as an exploratory project, many questions remain regarding the exact path that students' conceptual understanding took as they engaged in generating these models and the extent to which these different modes of collaboration contributed to their learning.

To complement these findings, the pre- and posttest results indicate that, with the support of the LPP technology and curriculum, the students were able to engage with the force and motion concepts despite their youth. In addition, we were pleased to see that neither gender nor age were correlated to posttest performance. We were initially concerned that the LPP environment might appeal more to and therefore provide a greater benefit for boys. The environment overlaps with many of the stereotypical interests and styles of boys'—it involves a mechanical topic, involves physical activity, and heavily depends on computer simulations and gaming. Nevertheless, from our videotapes we saw that girls were just as deeply engaged during the activities as boys and contributed substantially, if not to a greater extent, during the whole-class and small group discussions.

We were particularly surprised by two of our findings. While our overall results were encouraging, the sub-topic results showed some unevenness in student learning. We had relatively small gains in students' ability to quantify the relationship between speed and distance and their understanding of force. In contrast, we had relatively large gains in students understanding of two-dimensional motion, a topic that has proven difficult for much older students.

With regards to the relatively disappointing gains in the area of friction, much of the students' difficulty can be traced back to two factors. First, students came in with more experience with friction both in and out of the classroom, and thus scored higher on the pretest on these items. Second, students' intuitions conflicted with our use of ice as a low friction environment. As stated above in our third design principle, we were committed to having some sort of physical and familiar environment for students to be able to explore. Given this commitment, we had relatively few inexpensive options of familiar non-friction/low friction environments—air hockey tables and ice. Neither was ideal in that both introduced new mechanisms (an upward force and lubrication respectively). We choose ice on the assessment (and oiled surfaces as an alternate to ice in the activities) because the net balance between gravity and the upward air pressure in the hockey table seemed to necessitate a discussion of gravity—a topic that was not covered by our curriculum. Perhaps because our dramatic play activities were kinesthetic in nature, we found that a large number of students were bringing in their memories of falling on ice, including the sensation of their legs speeding up as they fell. As a result, students inferred that in no/low friction environments, objects sped up rather than maintained their inertia. This interpretation of their past experience interacted with our activities in unanticipated ways, contributing to our weaker results on this topic.

The results for two-dimensional motion, however, surprised us for the opposite reason. Given how entrenched the intuition is that an object will travel in the direction of its last hit, and the difficulty that older students have shown on this FCI assessment item, we had modest expectations for this topic in our curriculum. While the majority of our students at the time of the posttest were limited to a qualitative sense of the direction and speed of the new vector, we were encouraged that our results were similar to the results obtained by White's (1993) seventh grade students after the Thinker Tools software and curriculum. Based on our preliminary analysis of the video records, we attribute the students' success in this area to the additional semiotic resources the students had in the augmented reality environment. Further, the ways in which embodied action was annotated and formalized helped to create what others have called semiotic fusion (Nemirovsky, 2003), liminal spaces (Ochs, Gonzales, & Jacoby, 1996) and conceptual blends (Fauconnier & Turner, 1998). In our case, embodied actions laminated with symbol systems invented by the students were used as a key resource to ground abstract aspects of the students' models of force and motion. This line of reasoning warrants future study, as it is at the heart of the question of why the LPP environment worked and would help determine what might generalize from this study to other studies and other computer-mediated environments.

Conclusion

LPP is an important proof of concept project. We aimed to demonstrate that young children can begin their learning trajectory in science off on the right foot—both in terms of the complexity of science content and the type of ambitious science instruction that will lead to generative inquiry skills and a robust scientific epistemology. Pre/Posttest results show that these 6-8 year old students were able to develop a conceptual understanding of speed, force, friction and two-dimensional motion. What we have shown here is that the students are able, with the LPP technology and activities to learn force and motion concepts at an earlier age than thought possible.

In particular, we believe LPP was successful because it leveraged embodied play as an intuitive resource for students to transition into scientific modeling. Further, we suggest that the LPP microworld, cycles of activities, and multiple semiotic means all provided opportunities for the students to work with the teacher to construct and refine a robust conceptual model of force and motion. The LPP microworld was, in many ways, at the center of this process, leveraging augmented reality as a tool to transition between the embodied and symbolic worlds. In future studies it will be valuable to further explore the role of play and embodiment in developing students' modeling skills.

Acknowledgements

This project was supported by a grant from the National Science Foundation (DRL-0733218). This project would also not be possible without the help from members of our team who are not authors on this paper [blinded]. Finally we would like to thank the [blinded], who taught the lessons and lead the students in some remarkable discussions of force and motion.

References

Acredolo, C., Adams, A., & Schmid, J. (1984). On the understanding of the relationships between speed, duration, and distance. *Child Development, 55*, 2151-2159.

Author (2009). *BeeSign: a design experiment to teach kindergarten and first grade students about honeybees from a complex systems perspective.* Paper presented at the annual meeting of the American Educational Research Association.

Author (2005). Inventing mapping: creating cultural forms to solve collective problems. *Cognition and Instruction*, 23 (4), 427-466.

Author (2007). Negotiated representational mediators: How young children decide what to include in their science representations. *Science Education, 91* (1), 1-35.

Bateson, G. (1976). A theory of play and fantasy. In J.S. Bruner, A. Jolly & K. Sylva (Eds.) *Play: Its role in development and evolution* (pp. 119 - 129). New York: Basic Books Inc. Publishers.

Bransford, J. D., Brown, A. L., and Cocking, R. (2000). *How people learn*. Washington, DC: National Academy Press,

Bruner, J. (1986). *Actual minds, possible worlds.* Cambridge, MA: Harvard University Press.

Bullock, M., Gelman, R., & Baillargeon, R. (1982). The development of causal reasoning. In W. J. Friedman (Ed.), *The developmental psychology of time* (pp. 209-254). New York: Academic Press.

Chen, Z., Siegler, R. S. & Daehler, M.W. (2000). Across the great divide: Bridging the gap between understanding of toddlers' and older children's thinking. *Monographs of the Society for Research in Child Development 65* (2), i-viii+1-105.

Colella, V. (2000). Participatory simulations: Building collaborative understanding through immersive dynamic modeling. *Journal of the Learning Sciences, 9* (4), 471-500.

DeLoache, J. S., & Burns, N. M. (1994). Early understanding of the representational function of pictures. *Cognition, 2* (52), 83-110.

Fauconnier, G., & Turner, M. (1998). Conceptual integration networks. *Cognitive Science, 22* (2), 133-187.

Goodwin, C. (2000). Action and embodiment within situated human interaction. J*ournal of Pragmatics, 32*, 1489-1522.

Griffin, P., & Cole, M. (1984). Current activity for the future: The Zo-ped. *New Directions for Child Development, 23*, 45-64.

Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force concept inventory. *The Physics Teacher, 30,* 141-158.

Hutchins, E. (1993). Learning to navigate. In S. Chaiklin & J. Lave (Eds.), *Understanding practice: Perspectives on activity and context* (pp. 35-63). Cambridge: Cambridge University Press.

Kato (2007) ARToolkit (Version 2.72.1) [Software]. Available from http://www.hitl.washington.edu/artoolkit/

Klahr, D. (2000). *Exploring science: The cognition and development of discovery processes.* Cambridge, MA: MIT Press.

Lampert, M., Beasley, H., Ghousseini, H., Kazemi, E., & Franke, M. (2010). Using designed instructional activities to enable novices to manage ambitious mathematics teaching. *Instructional Explanations in the Disciplines,* (in press) 129-141.

Lehrer, R., & Schauble, L. (1998). Reasoning about structure and function: Children's conceptions of gears. *Journal of Research in Science Teaching, 31* (1), 3-25.

Lehrer, R., & Schauble, L. (2000). Inventing data structures for representational purposes: Elementary grade students' classification models. *Mathematical Thinking and Learning, 2,* 49-72.

Lehrer, R., & Schauble, L. (2006). Scientific thinking and science literacy. In R. W. Damon, K. Lerner, A. Renninger & I. E. Sigel (Eds.), *Handbook of child psychology, 6th edition, (vol. 4)* (pp.153-196). Hoboken, NJ: Wiley.

Matsuda, F. (2001). Development of concepts of interrelationships among duration, distance, and speed. *International Journal of Behavioral Development, 25*, 466-480.

Metz, K. E. (1995). Reassessment of Developmental Constraints on Children's Science Instruction. *Review of Educational Research, 65* (2), 93-127.

Nemirovsky, R. (2003). *Three conjectures concerning the relationship between body activity and understanding mathematics.* Paper presented at the PME 27, Honolulu, Hawai-I.

Nicolopoulou, A. (1993). Play, cognitive development, and the social world: Piaget, Vygotsky, and beyond. *Human Development 36* (1), 1-23.

Noble, T., Nemirovsky, R., Wright, T., & Tierney, C. (2001). Experiencing change: The mathematics of change in multiple environments. *Journal for Research in Mathematics Education, 32* (1), 85-108.

NRC (2007). *Taking science to school: Learning and teaching science in grades K-8.* Washington, DC: National Academies Press.

Ochs, E., Gonzales, P., & Jacoby, S. (1996). "When I come down, I'm in a domain state": Grammar and graphic representation in the interpretive activity of physicists. In E. Ochs, E. A. Schegloff & S. Thompson (Eds.), *Interaction and grammar* (pp. 328-369). Cambridge: Cambridge University Press.

Piaget, J. (1952). *Play, dreams and imitation in childhood.* New York, NY: W. W. Norton & Co, Inc.

Rosebery, A., Warren, B., Ogonowski, M. & Ballenger, C. (2005). The generative potential of students' everyday knowledge in learning science. In T. Carpenter and T. Romberg (Eds.), *Understanding matters: Improving student learning in mathematics and science* (pp. 55-80). Mahwah, NJ: Erlbaum.

Rosenberg, H. S. (1987). *Creative drama and imagination.* New York, NY: Holt, Rinehart & Winston.

Schauble, L. (1996). The development of scientific reasoning in knowledge-rich contexts. *Developmental Psychology, 32* (1), 102-119.

Schwarz, C., & White, B. (2005). Meta-modeling knowledge: Developing students' understanding of scientific modeling. *Cognition and Instruction, 23* (2), 165-205.

Siegler, R. S., & Liebert, R. M. (1975). Acquisition of formal scientific reasoning by 10- and 13-year-olds: Designing a factorial experiment. *Developmental Psychology, 11*, 401-412.

Smith, J. P., diSessa, A. A., & Roschelle, J. (1994). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *Journal of the Learning Sciences, 3* (2), 115–163.

Vygotsky, L. S. (1978). *Mind in society : the development of higher psychological processes.* Cambridge: Harvard University Press.

White, B. (1993). Thinker tools: Causal models, conceptual change, and science education. *Cognition and Instruction, 10* (1), 1-100.

Yoachim, C. M., & Meltzoff, A. N. (2003, October). *Cause and effect in the mind of the preschool child.* Paper presented at the biennial meeting of the Cognitive Development Society.

Youngquist, J., & Pataray-Ching, J. (2004). Revisiting "play": Analyzing and articulating acts of inquiry. *Early Childhood Education Journal, 31,* 171-178.