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Learning physics through play in an augmented reality environment

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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 two design principles behind the LPP curriculum: 1) the use of socio-dramatic, embodied play in the form of participatory modeling to support inquiry; and 2) progressive symbolization within rich semiotic ecologies to help students construct meaning. We then present pre- and post-test results to show that young students were able to develop a conceptual understanding of force, net force, friction and two-dimensional motion after participating in the LPP curriculum. Finally, we present two case studies that illustrate the design principles in action. Taken together the cases show some of the strengths and challenges associated with using augmented reality, embodied play, and a student invented semiotic ecology for scientific inquiry.

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). Young children can, under the right circumstances, learn more complicated ideas than we currently ask of them in early elementary science education. With support, early elementary students can engage in productive inquiry, collect and analyze data, produce models, and learn complex concepts. However, 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

[1]We have adapted the term 'ambitious math instruction' from (Lampert et al. 2010) which was used to refer to instruction that simultaneously targets conceptual understanding, procedural fluency and productive dispositions towards the domain.

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difficult for young children (Klahr 2000; Schauble 1996; Siegler and Liebert 1975). Fortunately, there are many alternatives to controlled experimentation that provide opportunities for students to develop a conceptual understanding of complex ideas. One of the most promising for young children is scientific modeling. 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 and Schauble 2006).

However, while modeling is within reach of early elementary students, they still do not progress very far without carefully scaffolded collaborative experiences (Lehrer and Schauble 2000). 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. Augmented reality refers to technology that displays computer-generated information such as images, sound, and video on top of a view of the real world.

In this paper we will first describe the vision-based augmented reality activities of the Learning Physics through Play project (LPP)[2], and the design principles that guided us. Second, we present a quantitative analysis of student learning using pre and post assessments. These findings indicate that the combination of the LPP environment and other classroom activities made it possible for students as young as first grade to meaningfully engage with Newtonian physics. Finally, we present two contrasting case studies that illustrate how students engaged with the augmented reality activities in the curriculum and show how the two design principles work in concert. Our goal in presenting these analyses is to demonstrate the utility of play as a form of scientific modeling, illustrating how it might be effectively augmented to support a productive learning experience when coupled with traditional classroom activities. We close with a discussion of the study's implications for teaching and learning with 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

Our approach to scientific modeling (and curriculum design) is both collaborative and collective, relying upon productive interaction to complement students' existing competencies. To support these kinds of activities in LPP we designed a hybrid modeling environment that employed a computer simulation with an interface based on physical embodiment (in some ways similar to recent game console interfaces such as the Xbox Kinect). Our overarching intent for our activities was for them to be the sparks and anchors for modeling conversations. That is, we want students to make observations in an environment that is structured by both the teacher and our designed tools. The tools are intentionally made to be adaptable so that students can represent their own emerging understandings, no matter how accurate or inaccurate they may be. 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.

[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.

Thus, the technologies are designed to support collaboration as well as the collective activity of the classroom as a community.

Description of the LPP environment and technology

There were two key components to the LPP system: 1) an augmented reality system that uses computer vision to record and display the students' physical actions and locations, and 2) software that translates this motion into a physics engine and generates a response based on the sensing data. The LPP system uses commercially available, open source forms of motion tracking and pattern recognition technologies (Kato, 2006) 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 is instantly imported into the new LPP computer microworld that allows students to model their understanding of force and motion and compare their predictions to simulated results.

To illustrate how the LPP technologies supported successful modeling, we describe one example activity in which the teacher asked the students 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[3], 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 force symbols (arrows), 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 teacher invited the students to continue debating Susie's embodied prediction. The teacher began by soliciting student observations about 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 ask Susie-as-the-ball to walk 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 surprise that their predictions did not match the computer simulation. In the ensuing discussion, students made explicit some of their implicit

[3] All names are pseudonyms.

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 to transform their intuitions and begin 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 to make a prediction. The technology translated the students' physical motion during play into a augmented-reality, computer animation and combined the students' motion with symbolic elements that marked important points in the embodied prediction. 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, et al. 2005) and explore these physics concepts.

Young children and the concepts of force and motion

The reason we chose to create an augmented-reality modeling environment to teach Newtonian force and motion was because we saw a fit between children's development, learning theory, and the affordances of the new technologies. 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 (Bransford, et al. 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, et al. 1982; Yoachim and Meltzoff 2003, October). Additionally, pre-school children can distinguish between distance, speed, and time when observing objects in motion (Acredolo, et al. 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 1993a, b). 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 as an ideal test bed to develop and study a new computer-supported, collaborative modeling approach to early elementary science instruction.

We designed the LPP curriculum to focus on four 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. 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. These topics correspond to some of the key conceptual stumbling blocks to understanding force and motion (Lehrer and Schauble 1998).

Prior research teaching force and motion with technology

There is a relatively long history in the learning sciences of using computer simulations to teach physics. We build on this history, but extend it in three important ways. First, we work with younger children than previous studies. Second, we design our curriculum around play and modeling rather than inquiry. Third, we design to promote the development of the classroom community as a collective, not just the development of individuals.

One of the foundational studies of how to teach force and motion, conducted by diSessa 1988, 1993), was based on the premise that students don't enter school as a blank slate. Rather, they have a number of intuitions about how objects move, and how forces such as gravity or a kick can influence that movement. Many of these intuitions are, from a normative standpoint, "incorrect". However, it is important to avoid labeling these intuitions "misconceptions" because this implies that they have no utility. Rather, as diSessa and colleagues suggest (diSessa 1988, 1993; Smith, et al. 1994), students develop these intuitions through observations of the world around them. One explanation of how student intuitions are activated and changed suggests that intuitions consist of many phenomenological primitives, or p-prims, which are abstractions of one's experiences with the physical world (diSessa 1993). Recent research lends some support to this model of concepts as piecemeal and partial as opposed to coherent theory-like concepts (Clark, et al. 2011).

Regardless of their exact form, research has consistently shown that these early intuitions are persistent, and not simply resolved through rational consideration of their inaccuracy—such efforts often lead to the continued mis-application of those p-prims at some other point in time (Smith et al. 1994). Rather, it is important to help make students' intuitions visible for reflection, and then offer additional experiences and opportunities for students to build new intuitions that combine, integrate and nuance those prior intuitions (Minstrell and Stimpson 1995; Smith et al. 1994).

Here is where computer simulations have played an important role in physics instruction. They have provided students with opportunities to test their intuitions and explore the phenomena in a simplified and idealized context (e.g. a microworld), allowing students to focus on a limited set of factors and experiment with these factors in isolation in order to better understand the core mechanisms. For example, in the ThinkerTools environment middle school students can experiment with the influence of an impulse force upon an objects' motion without having to simultaneously consider gravity, friction, and wind-resistance (White 1993a, b). This allows them to "see" for the first time that objects in motion really do stay in motion until another force acts on them. Thus they can begin to see how their intuitions about the mechanisms of force and motion were in fact derived from observations where multiple factors were influencing the ball but attributed to one incorrect mechanism such as an impetus theory.

To help students to experiment and analyze force and motion within the microworld the simulations are often seeded with a number of tools and visualizations. For example, White's (1993b) Thinkertools microworld include a tool which helps students to see that one can decompose a diagonal force into it's horizontal and vertical components in order to predict the resulting motion it will impart upon an object. For tools such as this to be effective, however, they need to represent information in a manner that students find both approachable and intuitive, which allows them to gain insight into the system being modeled. White (1993a, b) has suggested that an intermediate level of abstraction is ideal—one which lends itself to consideration of the physical phenomena being studied, and yet also provided opportunities for moving beyond the specific details of a single situation to more general explanatory principles. However, these tools and visualizations have to be made into meaningful representations (Greeno & Hall, 1997; Suthers & Medina, 2010) and young children still need to be given ways to explicitly connect the intermediate level abstractions to the concrete phenomena being studied. It is important to note here that we are not suggesting that young children are *limited* to concrete reasoning, but that like all novices, their initial exploration of phenomena benefits from being tied to concrete, observable experiences (Metz 1997).

One solution has been to bring in additional resources to help make the tools provided by the environment meaningful. For example, Nemirovsky, et al. (1998) used sensors to track physical objects for the students themselves and presented their motion as a canonical distance-time graph. Students used an iterative process of moving tracked objects and discussing the resulting graph to learn how graphs could be a way to represent force and motion and become a tool for conceptual change. The study showed that the graphs were not meaningful at first—when students simply examined graphs of motion, they encountered the usual difficulties interpreting them. However, when students' physical motions were tracked by a computer sensor that displayed their distance from the monitor, they were able to use their own physical motions to think with, experiment with, and ultimately refer back to. Of particular interest was the way in which this enabled what Nemirovsky et al. (1998) refer to as *fusion*; the ability to talk about referents and the symbols which reference them simultaneously in one consistent space using talk, gesture, and representations without distinguishing between them. This semiotic fusion has also been observed in the work of professional scientists (Hall, et al. 2002; Ochs, et al. 1996). Across these prior studies, semiotic fusion is seen as a productive resource that helped make otherwise opaque representations concrete and meaningful.

A second solution to this dilemma has been to engage students in creating their own representational forms while providing a context that helps them move towards appropriating representations that are at an intermediate level of abstraction. As an activity, inventing representations provides two key benefits. First, by creating their own representational tools, students have the opportunity to more thoroughly explore, recognize, and ultimately appropriate the need filled by the representational form (diSessa, et al. 1991; Enyedy 2005; Lehrer, et al. 2000). In other words, this process will increase the likelihood that students effectively use the invented representation. Second, the act of creating a representation of a phenomena provides students with additional opportunities to notice many of the key features of the phenomena being studied (Lehrer et al. 2000). In other words, through the process of creating and refining a representation that depicts the motion of an object under the influence of various forces, students come to learn more about the phenomena itself. Furthermore, these representational activities may provide a locus for collective or whole-class discussions in which students engage in critique and debate as they refine their representations and by extension their collective understanding (Cobb 2002; Cobb, et al. 2001; Enyedy 2005). In fact, a setting such as this that supports intermediate levels of abstraction and rich debate may be crucial in helping a group of students converge upon and then individually appropriate a shared understanding of a phenomena by voicing, elaborating, and critiquing each other's perspectives as they strive for intersubjectivity about the content being studied (Roschelle 1992).

Our LPP project builds on the extant literature by using computer simulations to help make students' existing intuitions public and available for inspection. We attempt to solve the dilemma of how to provide meaningful representational tools available to the students by synthesizing the two approaches outlined above. We created an environment that allows students to make abstractions concrete by using their own embodied understandings as a resource and we created an environment that allowed the students to author their own representational system to be used in the microworld. We found that children's pretend play provided us a developmentally appropriate umbrella to unite the disparate ideas. Below, we elaborate on how play and invented representations guided our design.

Design principle #1: Socio-dramatic, embodied play in the form of participatory modeling to support inquiry

Young children have an 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 and 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. In play, children often attempt to govern their behavior by following a set of rules that they do not yet fully understand. Thus, in play children externalize their intuitions making them visible for reflection and/or comment by others. For young children play presents an alternative to the traditional ways of eliciting intuitions through verbal or written explanations and/or predictions (diSessa 1993). Additionally, an oddity of children's socio-dramatic play is that children often spend more time articulating and negotiating the rules of a play situation than they spend actually in character "playing" their parts (Cooper, 2009). Because of this constant negotiation and reflection on their play activity, in terms of what they did, why they did it, and what happened as a result, the rules that govern a situation become visible and explicit for children. In this way, children use play to come to a deeper understanding of the rules governing the real world through a type of informal inquiry and simulation (Youngquist and Pataray-Ching 2004).

It has been shown that when learning difficult science concepts, students benefit from examining the system from multiple perspectives and this is a strength of many computer simulations. However, in computer simulations that help students take perspectives beyond their own perceptual capabilities, for young children these new experiences need to be coordinated and integrated with their lived experience (Noble, et al. 2001; Rosebery et al., 2005). Thus, for young children play presents an alternative modeling tool to the microworld computer simulation approach (e.g., White 1993a, b). One that, through new technologies such as vision-based augmented reality, can semiotically fuse (Nemirovsky, et al. 1998) the observer's perspective of more "traditional" computer simulations with the agent's perspective inherent in play activity.

To incorporate play into the LPP curriculum, the teacher engaged students in developing and refining participatory models (Danish 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), but shifts the focus of student activity from trying to produce some desired result (and the affect that accompanies this type of activity) to explicitly having students making and evaluating rules that underlie the simulation.

To facilitate productive modeling, LPP has students first engage in first-person play, where for example, one student pretended to be the ball and used his/her own physical motion to predict and represent the motion of the ball. Like traditional computer simulations, LPP offers the outside observer's perspective, where one can look down from above and observe forces, friction and motion, running experiments and measuring the phenomena (see Fig. 1). However, given the age of our students, LPP began students' investigations 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.

Building directly on the prior work of diSessa (1993) in physics and more generally on the work of Lehrer and Schauble (2002) in scientific modeling, we attempted to side-step the

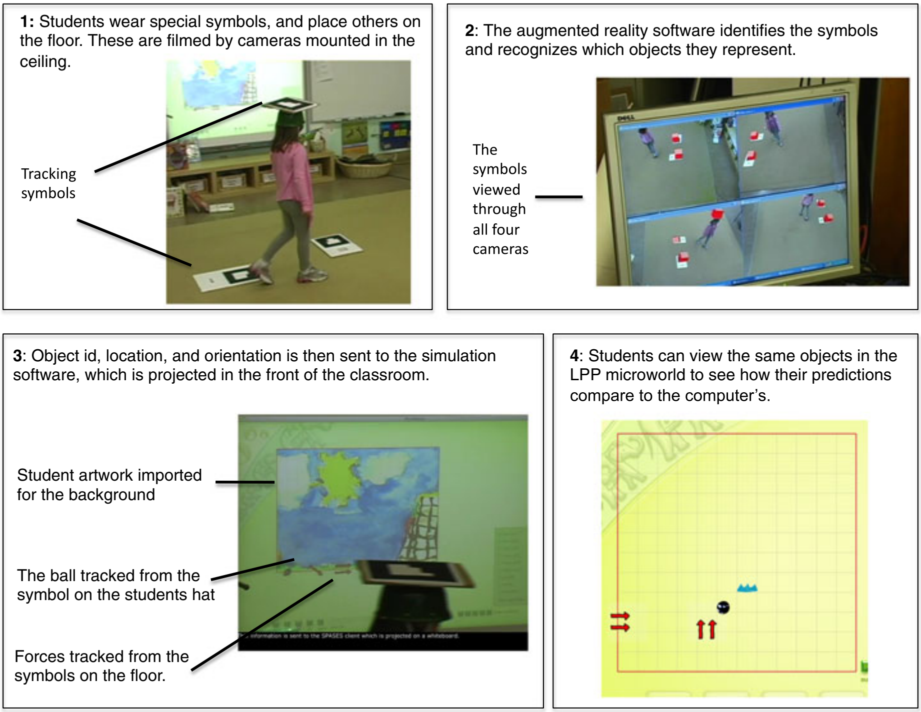


Fig. 1 The progression from physical objects and motion to a physics microworld in LPP

dilemma of needing to learn new formal inscription systems (such as vector diagrams, time distance graphs, etc.,) prior to learning the science content by having the students invent and iteratively refine their own representations of force and motion. 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 (Enyedy 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 (Enyedy 2005). To support students in these practices, many of the activities in the LPP curriculum involved the teacher working with the students to create, critique, and refine symbols for concepts such as force and friction. For example, we initially allowed the students to specify their own symbols, which resulted in many context-specific drawings of a foot kicking or a hand pushing. Then, the students' 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 students quickly discovered the limitations of their initial drawings, such as the challenge of comparing the size of a force when using an image of a foot, and progressed towards arrows as a solution that satisfied the constraints they found in their own 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.

Implementing our design principles

The two principles outlined above guided our design process. We also attempted to make choices about features of the LPP software and activities in a manner that was consistent with both the prior literature, and students' developmental strengths. However, our aim here is not to definitively or empirically prove that these design principles were the main contributors to student learning. The augmented reality LPP software was just one of many types of experiences that together made up the unit. These experiences included investigations in the real world, play-acting without technology, technology enhanced participatory modeling, and more traditional computer simulations. Providing a 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. However, it makes disentangling the unique contribution of the software impossible given our design. Our aim with the pilot project was to establish a proof of concept that augmented reality when combined with other activities could leverage young students competence with socio-dramatic play and help them learn a complex set of concepts normally reserved for much older students. In future work we intend to employ other experimental designs, including control groups, to investigate systematically some of the aspects of the design we speculate about here.

The teacher's role in LPP

We have not yet mentioned the critical role that the teacher played in shaping students' engagement with the tools and activities that we designed. While teacher participation is crucial to all classroom curriculum implementations, we believe that the conceptual and technical complexity of the LPP project made this a particularly important issue to address early in our design work. Additionally, our design conceptualizes learning as a collective activity, with the teacher holding a privileged role within the classroom community. Therefore, to ensure that our LPP designs would integrate effectively with the target classroom environment, we worked closely with a collaborating classroom teacher during both the design and implementation of the project. Before the project, the teacher advised on the topic area and collaborated on the design of the curriculum, providing expertise in what was accessible and appropriate for the age group. During the project, the teacher participated in weekly planning meetings, was aware of project goals and the rationale for the use of technology, and played a central role in interpreting and reflecting on student progress during the project and incorporating this into ongoing lesson development.

The teacher supported design principle 1: play and participatory modeling by prompting students to engage at a deep level through framing all activities in a search for meaning and understanding. Before beginning activities, the teacher elicited students' predictions and followed up with questions such as "how do you know?" setting a consistent expectation to explain one's thinking. During the activity, the teacher paused at appropriate moments to elicit students' observations, discuss emerging results and adjust course as necessary to take advantage of the group's questions and interests.

The teacher also provided support for design principle 2: progressive symbolization by coaching students as they created their representations and supporting discussion about how to most effectively symbolize the target concepts of speed, force, motion, and friction. When introducing activities, the teacher frequently used demonstration materials such as artists' representations of force and speed to illustrate potential techniques and prompt ideas. During small group work, the teacher coached students through mini conferences in which she helped students articulate their thinking, made suggestions about representational considerations such as communicating ideas clearly, or technical considerations such as using bold lines and color to help make concepts readable. The teacher also provided supportive materials such as picture books about force and speed. In small groups, the teacher asked students to discuss their representations with neighbors, and facilitated small group discussion about different representations in order to help students further refine their representations. In the whole group, the teacher supported students in sharing their work with the class, and highlighted student questions that brought up relevant direction for the entire group, such as "how do you show direction with your symbol for force?" The teacher also led the group toward consensus around which symbol would be used in subsequent inquiry by both strategically choosing the representations to be considered and structuring discussion so students considered the options with an eye to the function of representation.

Methods

Participants

The LPP curriculum was successfully implemented in two multi-age classrooms with students aged 6–8 years (=7.1 years) at the UCLA Lab School (n=43). The students were roughly even in terms of first and second grade students (22 first graders and 21 second graders) and in terms of gender (21 boys and 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.

Procedures

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 min. Four major topics were covered; force and speed (five lessons), net force in one dimension (11 lessons), friction (four lessons), and two-dimensional motion (seven lessons). In addition to the augmented reality activities the lessons also involved hands-on investigations, physical modeling activities, and discussion. 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.

Assessment measures

Given this age group's limitations expressing their ideas in writing, students were individually interviewed before and after the unit using an assessment protocol that was developed specifically for this project. The assessments included two types of items. The first set of items used open-ended prompts that measured *declarative understanding* by having students provide their definition of terminology (e.g., *force* and *friction*). The second set of items used scenario-based prompts as the context for measuring *conceptual understanding* and *problem solving*.

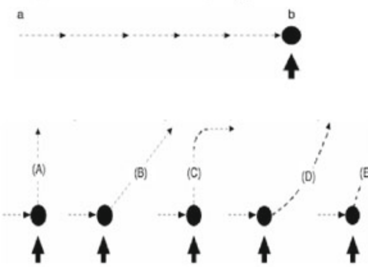
In our scenarios students were presented with objects (e.g., soccer balls, volleyballs, basketballs, and girls on skateboards), traveling across one or more surfaces (e.g., a wood floor, grassy lawn, and an ice skating rink), and asked to reason through different situations (e.g., racing, or a sequence of different surfaces and/or forces). To align the interview with how we expected students to learn through play, we provided students with simple paper manipulatives (e.g., cutouts of the objects and surfaces) that they could manipulate to express their ideas. They were also given a variety of tools to measure distance and time, (e.g., rulers, stopwatches, measuring tape).

Conceptual understanding For each scenario, students were asked to (a) identify where the forces are, (b) describe qualitative and quantitative differences in applied forces on various surfaces, contexts, objects, and scenarios, and (c) make predictions about the resulting speed or direction of applied forces. Students were also asked to provide justifications or rationales for each of their responses to the questions. For example:

> **Q**: And why does it [the ball] slow down the most [on the grass]?
> **A**: Because they [the grass blades] are sticking up the ball has to pass on and then bump into them and make them go down.

We also modified two Force Concept Inventory items (Hestenes, et al. 1992) as measures of conceptual understanding. In the original item, students were asked to make a prediction (e.g., the direction of a puck when given an additional force and identify the trajectory of a cannonball fired out of a cannon). For the FCI items used (FCI Items 8–10 and FCI Item 12), we made linguistic modifications to make it more developmentally appropriate for our age range. Primarily this meant including a more concrete context, simplifying the vocabulary, and removing some clauses that added to the linguistic complexity (See Table 1 for an example of the modifications to an FCI item).

Table 1 Sample modified Force Concept Inventory question

Prompt Image: 	**Original Prompt:** The figure depicts a hockey puck sliding with constant speed *vo* in a straight line from point "a" to point "b" on a frictionless horizontal surface. Forces exerted by the air are negligible. You are looking down on the puck. When the puck reaches point "b," it receives a swift horizontal kick in the direction of the heavy print arrow. Had the puck been at rest at point "b," then the kick would have set the puck in horizontal motion with a speed *vk* in the direction of the kick. **Modified Prompt:** You are watching your two friends play on the air hockey table. You are looking down at the puck. See, that's the top of the puck. One of your friend hits the puck here [Point to "a"] and it starts moving in a straight line to here [Point to "b."] The puck is still moving fast and your other friend hits it this way, in the direction of the arrow

Problem solving Finally, students were given a set of items requiring that they manipulate elements in the scenario to accomplish a given goal. For example, students were asked to apply the right amount of forces in the appropriate directions to make objects "speed up," "slow down," or "stop."

The pre- and posttest interviews were transcribed and coded for degree of conceptual understanding. Inter-rater reliability for each item was determined by calculating the Intraclass Correlation Coefficients (ICC) for each item. Choosing the appropriate ICC model is determined by the nature of the data and what is examined to be reliable (McGraw & Wong, 1996). We employed a two-way, mixed-effect model to examine the absolute agreement of measurements across the raters. Five of the 31 items were dropped because of low inter-rater reliability. The inter-rater ICCs for the 26 remaining items ranged from .84 to 1.00.

An additional ten items were dropped due to a high proportion of missing answers. These missing answers were due to the inherent difficulty in treating an open-ended interview as if it were a standardized assessment. Variability in the phrasing or order of questions as interviewers responded to students led to difficulty in parsing a continuous transcript into a standardized set of discrete answers. Thus while the answers had acceptable inter-coder reliability, we did not think they provided us an accurate method to compare one student's thinking and learning to another's. As a result, the final pre-test and post-test scales were comprised of 19 items spread over the four instructional objectives; with seven questions for speed, six questions for friction, four questions for net force, and two questions for two-dimensional motion.

Results

The pre- and post-text gains

Before presenting the case studies, we first present the student learning outcomes based on the pre- and post-test scores. The lack of a control group makes it impossible to argue that the observable learning gains can *only* be attributed to our two design principles. However, that is not our goal. Rather, we intend the pre- and post-test performances to situate the case-study analysis within the larger story where young children are clearly learning—a context where many of the students progressed from demonstrating many non-normative views about basic physics, to a context where many of the students were able to offer accurate predictions and descriptions on a number of measures. The qualitative analyses will be used to make our case for potential mechanisms for learning that are tied to our technical innovations.

Descriptive statistics were obtained on performance on the pre-test and post-test items. For the 43 students, the average pre-test score was 5.42 (SD=1.38) out of a possible of 16 points. The average posttest score was 8.54 (SD=2.17). First, correlational analyses examined the relation between grade level, age at the start of the study, gender, pre-test and post-test scores. Results indicate there is no correlation between any of the demographic variables and the assessment scores (see Table 2).

A paired-samples t-test was conducted to compare pre-test scores and post-test scores. Post-test scores were significantly higher than the pre-test scores, $t(42)=9.11$, $p<.001$. The effect size of the gain was large, $d=1.99$, indicating that the pre-test to post-test change was close to two standard deviations. To better understand the magnitude of the changes between pre-test and post-test, a Wilcoxon signed rank test was computed. Results indicated that 39 (91 %) of the students showed a pre to post-test gain ($Z=5.29$, $p<.001$), with 36 (84 %) of the students increasing performance greater than one standard deviation. In sum, students demonstrated significant improvement on all of the key measures.

To examine differences in content understanding on these four specific topics, force and speed, friction, net forces, and two-dimensional motion, we have analyzed four exemplary questions. Given that this was the first time the assessment protocol was being used, 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, that requires fewer assumptions about the distribution of the data.

For the topic of force and speed, we analyzed responses to a scenario that asked students to determine who would win the race when one skateboarder was given an additional force. The highest value was given to answers that quantified the number of extra forces that applied and also indicated that speed increases (e.g.,"Because a thing goes faster when you push and she gets one more push."). Partial credit was given to answers that just quantified the number of extra forces with no explicit reference to speed (e.g., "Because she got two pushes.") or refers to the additional force without mentioning quantity (e.g., "Because you push right here."). The sign test indicated that 18 (42 %) of the students received significantly higher scores on the post-test than on the pre-test, $Z=2.09$, $p=.04$.

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

Table 2 Pearson correlations between background variables and test scores

	Pre-test	Post-test	Age at start	Grade	Gender
Pre-test	1.00	0.26	0.16	0.16	−0.09
Significance		0.09	0.32	0.31	0.57
Post-test		1.00	0.14	0.26	0.15
Significance			0.39	0.10	0.33

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 16 (37 %) of the students received significantly higher scores on this question during the posttest than on the pre-test, $Z=2.38$, $p=0.02$.

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 10 (23 %) of the students received significantly higher scores on this question during the post-test than on the pre-test, $Z=2.71$, $p=0.007$.

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 Table 1). The sign test indicated that 29 (67 %) of the students received higher scores on the post-test than on the pre-test, $Z=4.85$, $p<.001$.

Summary of quantitative findings

Taken together, these findings suggest that many of the students made significant progress in learning the content as measured by the pre- and post-test. In particular, we were pleased to see that a number of students had begun to accurately make the accurate prediction regarding two-dimensional motion given the difficulty of this question. As noted above, without a control group it is not possible to definitively suggest that these learning outcomes can solely be contributed to the designed curricula or to our two design principles. However, we believe that the lack of regular opportunities to discuss concepts such as force and motion implies that it is likely the curricula can be credited for these gains. Furthermore, we were able to see in many cases how students presented non-normative views when engaged in LPP activities, and then slowly confronted and eventually changed those views. To illustrate some of the mechanisms through which we believe the LPP curricula was able to help students appropriate the content, we now present two detailed case studies.

Qualitative case analysis

As noted above, the LPP curriculum was motivated by two key design principles: 1) the use of socio-dramatic, embodied play in the form of participatory modeling to support inquiry; and 2) progressive symbolization within rich semiotic ecologies to help students construct and integrate meaning. To illustrate the role that LPP played in supporting both participatory modeling and symbolization, we will present two case studies from within the larger curriculum. Taken together the cases illustrate some of the variability in the way that the augmented reality activities were used by students, which may in turn have contributed to the variability in learning outcomes as measured by the pre-post assessment analysis. It is worth noting here that both cases demonstrate how the two principles worked in tandem. We do not attempt (nor do we think it would be productive to try) to disentangle the role of each principle in supporting student learning separately. Instead, we examine the principles in action and attempt to explicate how their synthesis played a role in helping students to develop the conceptual understanding that is evident in the pre- and post-test results as well as explain some of the limits of those findings.

Case 1: Learning friction with LPP

In this first case study, we argue that the embodied aspect of socio-dramatic play and participatory modeling is a powerful resource for learning—sometimes leading the students toward valuable insights, but sometimes leading the students down the “wrong” conceptual path. As we will illustrate below, the embodied aspect affords students with the opportunity to use their bodies to reason with, and as a resource for representing or sharing their understanding. At the same time, the framing as play, is crucial in how students approach the situation, immersing themselves in their perception of the phenomenon being studied in order to explore the inherent rules and articulate them for discussion. The case will also highlight the strengths and challenges of progressive symbolization by illustrating the students’ use and ongoing refinement of a symbol system designed to help them reason about forces and friction. We suggest that this symbol system offers some of the students a powerful tool for reasoning about the phenomena, while also necessitating revisions to the symbols as new ideas reflect flaws in the current symbols. In highlighting the affordances of both embodiment and symbolization we will illustrate the potential of augmented reality systems such as LPP for supporting an exploration of the rules underlying phenomena. In describing the potential pit-falls, our goal is to highlight the importance of both the curricula and teacher in carefully navigating around the multiple opportunities provided by the LPP system.

In this activity the students were using the LPP system to learn about friction in a game they called the “mailroom game”. Earlier in the year the students had visited the post office and saw a machine that fascinated them. The machine processed letters by running them along a belt and through various mechanisms that sorted, bundled, and stamped the letters. We tried to capitalize on this interest by working with the teacher to design a game to learn about friction where an object (nominally the envelope represented by a ball[4] on the screen) was propelled along a two-dimensional path (i.e. to represent the belt) by impulse forces. As the envelope moved it encountered additional forces and frictions of various sizes to represent why it might slow down or speed up as it encountered different parts of the machine. All of the surfaces represented were also surfaces that the students could physically experiment with in the classroom environment. Figure 2 shows the layout of the game board for the activity. The envelope/ball first encounters a force of two going to the right. Next, it encounters a force of one in the same direction. It then encounters a blank square (no friction & no force), a linoleum floor (low amount of friction), another blank square (no friction or force), a carpet (medium friction) and a welcome mat (high friction).

Students were asked to walk along a life sized game board and pretend to be the ball/envelope using their bodies to predict how fast the ball/envelope would be at any point. The LPP system tracked their movement and displayed an overhead video feed on the white-board. Students could also see the artwork and symbols (e.g. the arrows) they had designed in a previous lesson to represent different size forces. It is important to note, inline with Design Principle 2, that these symbols were not chosen arbitrarily. Rather, they were designed through multiple activities as students struggled with how to both represent and

[4] The initial implementation of LPP allowed for all artwork to be substituted except for the ball. Students were, however, able to imagine the ball as a letter and referred to it as such throughout this activity. To avoid this challenge, however, future iterations will support a replacement of all visual elements in the system.

Fig. 2 The LPP Representation of the mailroom game and symbolized forces

quantify different size forces. This is, however, an ongoing process. As we will see below, some students have not fully appropriated the quantitative implications of this symbol. Furthermore, the students have not yet invented a symbol for friction. Therefore, in the current case study, the system displayed icons that depicted the real surfaces placed on the game board. That is, if a real welcome mat was on the real-life game board then the system showed a picture of a welcome mat. Since the students had collectively decided to symbolize small, medium and large forces by the 1, 2 or 3 arrows, when forces were placed on the floor the corresponding symbol was visible "floating above" the floor on the video image (see Figs. 3 and 4).

The first student to make a prediction was Marissa. She correctly predicts that her speed will increase as she encounters the second force. However, when she walks to the linoleum square (intended to depict a low friction tile), she says that because she is moving fast when she gets to it she will slip and her speed will increase—an idea that was common in our pre-tests when we asked the students about low friction surfaces such as ice. The researcher leading the activity asks if others agree and a boy named Scott disagrees and predicts that she will slow down slightly. A debate ensues. When asked what she thinks will happen when she reaches the welcome mat (a high friction tile), Marissa predicts that this surface will slow her down and perhaps make her come to a stop. Scott's prediction in this case, perhaps because of his overreliance on the simulation as a formal system and his assumption that friction is like other forces, is that the welcome mat will in fact reverse the direction of the ball/envelope that is traveling at a speed of two tiles per turn.

When the simulation is finally run and Scott is proven right in the first case (that the ball/envelope slows down slightly) but Marissa's prediction is correct in the second case (that the ball/envelope rolls to a stop but does not reverse direction), the teacher organizes a post-mortem discussion to explore why this might be. As part of this discussion she moves the students to consider that friction may be a different type of force than the impulse forces the

Fig. 3 The real-world view of the mailroom game

Fig. 4 The LPP view of the mail-room game

students have been working with to date, and suggests that as a result the students may need a separate symbol set to describe friction. This exchange is presented in the excerpt below.

1	Researcher 1:	[Marissa draw a card a force card] 2! Okay so she got a force of 2.
2	Researcher 2:	(inaudible) Then she lands on 1.
3	Researcher 1:	Right, okay. Now what? So what speed are you going?
4	Marissa:	1
5	Researcher 1:	Well what did you start with?
6	Marissa:	2, 3.
7	Researcher 1:	So you're going 2 and then you're going 3
…		(Approximately 1 min)
8	Researcher 1:	[to Marissa as she walks the board] What happens now?
9	Marissa:	I slip?
10	Researcher 1:	Ah, okay, so we have a good, we have an interesting situation
11	Marissa:	I'm slipping! [Marissa acts out "slipping" kicking her leg up and throwing her hands out]
12	Researcher 1:	Marissa is going speed 3, and then she landed on, the linoleum, so she says she might slip, so what's that going to do to your speed?
13	Marissa:	Make it faster.
14	Researcher 1:	Interesting, okay … does everyone agree that if she lands on the linoleum it'll make her go faster?
15	Group:	Yes
…		
19	Marissa:	Because, because if there's a 3, and I'm going very fast, I would land on this and I would slide [physically pretends to slide on the board), because it's slippery.
20	Researcher 1:	Okay, so that's going to make your speed go faster?

In this first exchange we see that with a little prompting Marissa understands the arithmetic of how an impulse force affects a ball already in motion and can correctly calculate the speed of the ball (line 6). However, when making an embodied prediction about friction, she creates a special case for low friction surfaces. While other rough surfaces slow you down, she predicts that smooth surfaces will speed you up. Thus she has made her thinking visible through embodied play but is also drawing on her embodied experience with slippery surfaces to reason through the situation (Design Principle #1). More interestingly it seems that the physical embodiment and pretend play is, at least initially, working against the goals of the curriculum. In line 9 Marissa is very tentative and phrases her answer as a question, but as Marissa physically pretends to slip (lines 11 & 19), she evokes memories of what it felt like to slip and fall and states her incorrect prediction more confidently. It seems likely she is focusing on the speed of her feet, which from her perspective appear to move faster than the rest of her body and then is generalizing this to the overall motion of her whole body relative to the floor. Here the first person perspective of pretend play leads students down a potentially problematic conceptual path, highlighting the need to help them understand the difference between their personal experiences with slipping and a general rule for friction. Fortunately, the public nature of the shared augmented reality display provides opportunities for public comment and alternative hypotheses that can promote productive debate. Below we see Scott's alternate prediction.

1	Scott:	No, she's going to slow down when she's sliding.
2	Researcher 1:	Why do you think so Scott?
3	Scott:	Because it's a surface that's not providing any new—like for example it's like the mail machine, things are moving…
4	Researcher 1:	Ok
5	Scott:	But when she gets to that surface, nothing's moving
6	Researcher 1:	Nothing's moving her … and then why would she slow down rather than just continuing?
7	Scott:	Because when she's slowing down (demonstrates slowing down while walking) she hits this (on linoleum) there's no force on it, but there's a … (inaudible)
8	Researcher 1:	Okay, so we have two different opinions.

While the majority of students seem to agree with Marissa that she will speed up when encounters the slippery linoleum surface, not all do. Scott articulates his disagreement in line 1, grounding his explanation in his observation of the real mail machine. Scott does not contest the fact that Marissa (as the envelope) will continue to slide (line 1), but does assert that she will be slowing down. When asked why he explains that to speed up you need a new force (line 3) given by something that is moving (line 5). Note that while Scott's reasoning adopts a third-person observer's perspective (in contrast to Marissa who reason's from her first person experience), in expressing his prediction he also uses his body and illustrates by walking the path and slowing down to depict his prediction (line 7).

A few minutes later the students are asked to make predictions about the effect of a high friction surface on the motion of the ball/envelope. From the perspective of who produces the normative answer, Marissa and Scott's roles are now reversed with Marissa offering a more normative prediction.

1	Researcher 1:	Okay? What's going to happen now?
2	Marissa:	I'm going to stop?
3	Researcher 1:	You're going to stop? Okay.
4	Marissa:	Because this is a very rough friction and .. it's rougher than this one, because this one's very smooth (walking back to linoleum) and then, this one is very rough and it, and it sticks up more than that one.
5	Researcher 1:	Ok
6	Marissa:	And it can stop me because when I try to slide (slides feet back and forth on the mat), I can't slide on it, and .. it's the most powerfullest because it's very prickily and spiky
7	Researcher 1:	okay, okay
8	Marissa:	And those, and those, they're sticking up (does gesture with hands) like this, so I have to try to push them over (pushes one hand down with other)
9	Researcher 1:	Okay so part of the stopping is having to try to push those big things sticking up?

In this example, Marissa predicts that the high friction surface will slow the ball/envelope down. As before she evokes a mechanism to explain why, in this case the mechanism is the need to push down the “prickly and spiky” parts of the surface while sliding past them. Similar to her first prediction she physically acts out the prediction first rubbing her foot across the rough mat (line 7) and then second using gestures to zoom in on her mechanism. Like her first prediction, her answer is still rooted in her embodied experience and is expressed with her body as much as her words (line 9). However, her explanation here does not overtly contradict her first prediction and she is left with two separate cases for how friction works. Slowing down on rough surfaces but speeding up on smooth ones. This kind of reasoning is inline with a knowledge in pieces account of conceptual understanding, highlighting how multiple lived experiences can contribute to a potentially contradictory set of descriptions (Smith, et al. 1994). Fortunately, the embodied nature of the LPP environment and curricula make it possible to help students express these multiple conceptions so that they may begin to reconcile them. Once again, Scott disagrees with Marissa’s prediction, and the researcher asks him to articulate this below:

1	Researcher 2:	Scott has a different idea about what’s going to happen when she hits the
2	Scott:	It says that her old speed is 1,
3	Teacher:	Yeah it was 1
4	Scott:	Well then I think she should, and then minus 3, she could go back 2 spaces
5	Teacher:	So it’s a different theory, whether she’s going to stop, a lot of people think she’s going to stop. Scott thinks she’s going to be pushed in the other direction

Of particular interest to us is that Scott’s disagreement is couched in terms of the arithmetic of forces. By responding in this way, he appears to be appropriating the idea of reasoning about force and motion as a formal system symbolized through the addition and subtraction of finite forces represented by arrows—the symbols the students created. This leads him to make a non-normative prediction for the case where a slow moving object encounters a high friction surface. Doing the math (line 4) leads him to predict that the object will reverse direction rather than just come to a stop. What is of note across this case is that, for both students, relying exclusively on either embodiment (as Marissa does) or on a formal model (as Scott does) leads to prediction that is correct for some contexts but incorrect in others. It is the aim of the project to provide the tools and situations to productively fuse or blend these two ways of reasoning.

Progressive symbolization (Design Principle #2) is one of the main avenues that we hoped to use to promote this conceptual integration. After watching the simulation engine perform the scenario, the teacher identifies the need to refine their symbol system to differentiate between impulse forces and the force of friction. Thus the teacher is highlighting the progressive aspect of progressive symbolization by reminding students that the symbol system they invent is always open for revision (design principle #2).

1	Researcher 2:	Okay, so let’s see what happens. (Researcher 1 runs the scenario.)
2	Teacher:	There it goes, are you seeing? Are you watching it? Slowed down just like we thought, now what’s going to happen? ....
3	Audrey:	Oh it stopped!
4	Teacher:	It stopped!
5	Students:	(quietly) yes!
6	Teacher:	So it did meet one of our predictions. But here’s my question, why did it stop, why didn’t the ball go in the other direction Marissa?

7	Marissa:	Because I think that since it rolled over that (carpet) it was slow, and then it, if, if 2 of , if it slowed down on that one and that's an even stronger friction I think it would stop because
8	Teacher:	Yeah so it's super strong friction so why doesn't it go in the other direction though? Claire? Why didn't Marissa get pushed the other way, why didn't the ball go the other way? From that friction?
9	Claire:	Because it's all friction, it can't go back
10	Teacher:	But here's, I think the confusion, now that I think about it, is probably from the way that we're annotating friction. Cause we're annotating with backwards force, you know, like we're using the same arrows that we use for force in the other direction

This first case has shown that embodied play can be a resource for reasoning, the articulation of student predictions, and the construction of informal models that we have termed participatory models. Embodiment, however, is no silver bullet. Students still tended to create special cases rather than an integrated concept of friction and embodiment had the potential to mislead students at the same time it helped them think through potential mechanisms of friction. Likewise, the case demonstrated the challenges associated with treating force and motion in a formal way abstracted from one's personal experience. Progressive symbolization was intended to help integrate student understandings in way that was meaningful to them, but given the pre-post results where only 37 % of the students had a significant gain in this subscale, it is clear we were not entirely successful for this topic. In the second case we will attempt to further explore the potential of progressive symbolization that is built on a foundation of participatory models. In doing so we will highlight some of the different ways the LPP system was used by the students and the consequences of this variation. In this second case we also present an example where all of the elements of the LPP curricula appear to work together, resulting in a productive integration of ideas. We then illustrate briefly the fact that these successful integrations appear to be relatively common at the end of the implementation.

Case 2: Embodying two-dimensional motion

The activities of our second case 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 5 depicts one of the contexts students were asked to make predictions about, a "large"[5] 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. 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 (Figure 6, 7 and 8).

The participatory modeling activity that students engaged in as part of this unit 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

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

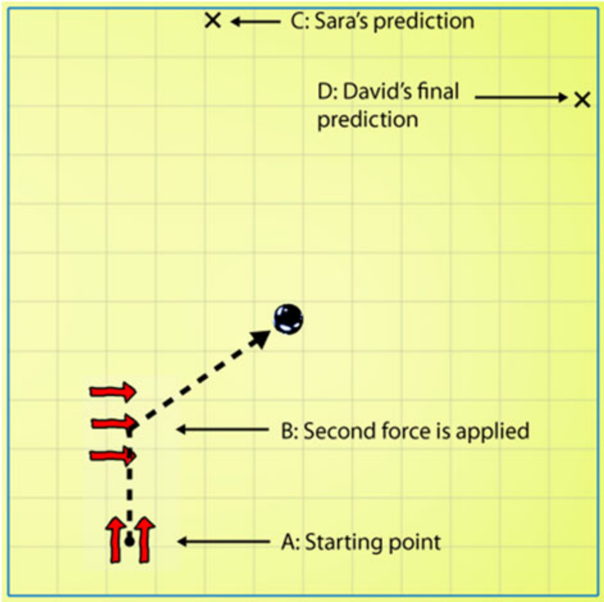


Fig. 5 The LPP window depicting 2-dimensional motion. The dashed line depicts the path of the balls motion once the simulation was begun. The ball was initially placed at point A, on top of a vertical force of 2. Once it began moving, the ball encountered the force of 3 at point B, which altered its trajectory

illustrated in Fig. 5. 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 case on two students, Sara and David, members of the 8 person focal group that was observed during this session. 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 intellectual progress that Sara and David make using the LPP environment, let us first briefly recap their intuitions from the first 2 days of the unit. The first day consisted of a hands-on experiment with a soccer ball. The goal of this experiment was to expose and challenge students' conception that the second of two forces, delivered at right angle to the first, 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. The students were asked to poke[6] a soccer ball and then poke it again once it was in motion. The students were then led through multiple trials that varied the size of the two pokes.

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

[6] They were asked to poke the soccer ball with a stick, rather than kick it, to better simulate an impulse force and to provide better control over the direction of the force.

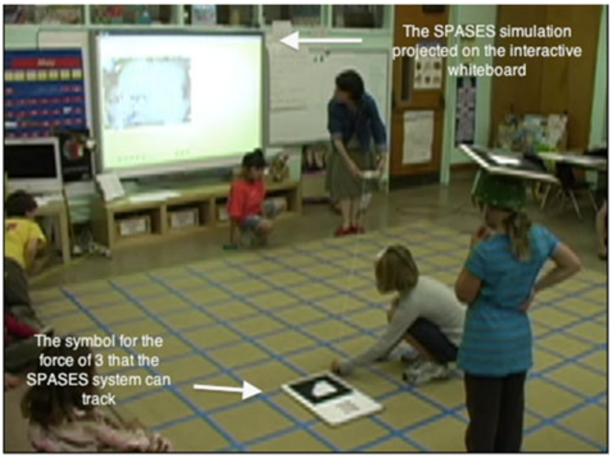
hit (which in this case was also the larger of the two forces). For example, when the teacher sets up a small horizontal force and a large vertical force using the LPP simulation software on the whiteboard and asked Sara, “Now what is going to happen? From what we know so far, what is going to happen?”, David interrupted and blurted out “it goes straight up” and traces a path in the air in front of his body. Thus, much like the first case where Marissa invented two separate cases for friction, the students here created two cases for orthogonal forces: one case for when the forces were of equal size and one case when the two forces were not the same magnitude. 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 an underlying set of physics rules that they were attempting to apply to the situation. 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.

Step 1: Preliminary predictions Sara first made her prediction by tracing her finger along the simulation window that was projected on the smart board. She predicted a diagonal path, but at an incorrect angle—a departure from her predictions on the previous day in that she did not predict it would go in the direction of the last push when the forces were of unequal size. We take this as evidence that her concept was either unstable, very contextual, or in the process of evolving. 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. In fact, Sara repeated her gestural trace of the ball’s path three 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. 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 record 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 (Fig. 6), without being asked, Sara adopted the kind of playful, embodied modeling stance that was supported throughout the curriculum and that we saw in Marissa’s interactions of the first case (Design Principle #1). 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. 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, like her dramatic pause, was a visual trope that the students frequently adopted during play to illustrate (symbolize) the fact that the ball progressed at a consistent speed that was determined by the initial force (e.g., high steps indicated a fast speed).

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 inscription of her prediction to be contrasted

Fig. 6 The classroom layout depicting the physical objects that coincide with the simulation in Fig. 5



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 without having to fully articulate her reasoning. The LPP environment was designed with the intention of frequently requiring students to make a prediction in the physical space as opposed to only verbally. This forced students such as Sara to be specific—perhaps more specific than the student's current thinking allowed for. 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).

Ms. Craig then asked David to make his prediction. Unlike Marissa in the first case who used embodied action to evoke a physical memory, David seems to use his embodied action to work out what he thinks will happen. David begins to model the motion of the ball by taking on the role of the ball and walking to just below point B (see Fig. 7), 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 and then runs his predicted path, sitting down on the spot of the edge of the carpet where he think the ball will go.

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 physical orientation automatically preserves the directional component of the ball's inertia. Contrast this with Sara's prediction over the whiteboard where her gesture preserved only the location 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 representations (such as the FCI item used in our assessment).

Fig. 7 David's gestural prediction

We believe that part of the success of this kind of explanation that laminated physical action onto the heavily structured and augmented physical environment 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 necessarily both at once. This kind of flexibility was one of the intentions behind our second design principle in that it allows students to capitalize on those aspects of the rich semiotic ecology that are most meaningful to their current reasoning and / or prediction.

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 gather 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 the 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 walks her prediction, David appears to realize that the slope of his prediction was accurate but displaced because he had placed the string at the edge of the force instead of originating from the middle of it as the simulation did. He says, "It didn't go exactly on my line, it went like this" and then walked the correct path.

It is important to note that Sara appears to take her mistaken prediction in stride. This is perhaps a happy by-product from the association of science with play (Design Principle #1). 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 embodied prediction that made participatory modeling a safe place to share one's ideas and even if wrong.

Step 3: Integration through progressive symbolization Thus far, in the second case we have concentrated on our first design principle—how participatory modeling served as a resource for thinking and making that thinking visible to others. We have also shown how the students held and articulated a number of, sometimes contradictory, partial models for how force and motion work. In the next section, we attempt to illustrate how our second design principle, progressive symbolization, facilitated students in integrating their multiple ideas into a more coherent conceptual system, centered on their participatory model. To illustrate this process, 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.

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 Fig. 8.]
4	Lisa:	Two going to the left. To the right [gestures in front of her body with her fingers hidden from the camera]
5	Ms. Craig:	To the right [nodding].
6	Lisa:	And then, took away 2 [two fingers from her left hand touch two fingers from her right hand]. And you still have one going up. [She now gestures with one finger moving 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° angle). Recall she had just observed the physics engine produce the correct path, so we can assume she knew that it didn’t in fact go straight up. We believe she was using a method of cancelling and then adjusting the angle from 45° based on what is left over. If this is 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.

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).

Fig. 8 Lisa shows the force of 3 using her fingers as she gestures upwards

Step 4: Evidence of integration via rules in the final poster When we examine the students' final projects for this unit, we see further evidence of their understanding of two-dimensional force and motion. 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. Sara and David's 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. Recall that play, much like Newton's descriptions of motion, are grounded in a set of rules. As such, here we were formally asking the students to express themselves in rules. 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 (1993a, b) found that students often erroneously think that the ball traveling in a diagonal 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, the use of the embodied metaphor of bumping can traced back to the embodied gestures and walking within the LPP environment where forces quite literally did 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.

Discussion

The Learning Physics through Play (LPP) project was founded on the idea that young children could productively use play as an entry point to scientific modeling. Play and modeling are both rule-based activities. Play and modeling are both tied to inquiry. Finally, play and modeling both encourage students to reflect on the rules and how well these rules represent reality. Vision-based augmented reality presents a new type of technology that is particularly well suited to supporting play and the transition to more formal scientific modeling. To facilitate this transition from embodiment to more abstract representations, we embedded participatory modeling in the context of progressive symbolization, where students were responsible for inventing and refining the set of symbols that would help them understand and express Newtonian force and motion. In the remainder of this paper we will briefly summarize some of the key findings of the LPP project, discuss how these findings relate to prior research about children's engagement with force and motion concepts, and suggest some fruitful new directions for how to think about play and symbolism in the design and analysis of CSCL environments.

Pre- and post-test results indicate that, with the support of the LPP technology and curriculum, the students were able to meaningfully engage with the force and motion concepts despite their youth. In addition, we were pleased to see that neither gender nor age was correlated to post-test 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 case studies 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 speculate that two design elements may have supported this balance in interest and success across age and gender lines: 1) playful activities and experiments that were drawn from students own lived experiences, and 2) the ability to generate new artwork. In the first case, socio-dramatic play is considered to be quite universal across gender and these ages, and therefore likely helped to invite the students into the LPP environment. As we noted above, each students engaged in the embodied play in somewhat idiosyncratic ways, tapping into those resources that they found most meaningful (walking, talking, gesturing, etc.). In this way, the shared play experience may have simultaneously provided common ground in a shared model, and individual engagement in terms of how students represented or laminated ideas. Second, by asking students to identify objects in motion, create scenarios (via illustrated backgrounds) and design new games such as the mailroom game, we gave students the opportunity to bring their own interests into the environment regardless of their gender, thus allowing them to connect to the curriculum, particularly in the early stages before we transitioned into a more formal system

Moving beyond the apparent gender equity in our pre- and post-test results, it is important to note that while these pre- and post-test results do indicate an increase in students' understanding of the target concepts, questions still remain regarding the depth of their understanding. Our goal in reporting these results is not to suggest that students' understanding was as robust or deep as what we might expect in high school. Rather, our goal is to suggest that these topics are not completely out of reach for young students. When combined with our qualitative analyses, it is clear that even 6-year-old children can meaningfully explore the target concepts of force and motion, articulating their intuitions and in many cases developing new conceptions that mirror normative explanations.

Thus the LPP findings extend the current learning science literature by suggesting a new tool to bridge theories that suggest building on students intuitions (which are formed at an early age in privileged domains such as physics) and practical CSCL tools and environments that have largely limited the study of complex science concepts until much later—typically middle school (e.g. White 1993a, b). Much of the prior work on CSCL design has accepted the assumption that students need to use canonical formalisms (e.g., algebra) as tools to describe complex phenomena such as physics, and as a result design environments for students where these formalisms are believed to be within reach—often delaying complex science topics such as physics until at least middle school. Some prior research has suggested that students can engage in these concepts at slightly younger stages using well-designed simulations or computer programming languages that make it possible to engage the science without the need for advanced mathematics (diSessa 2000; Sherin, et al. 1993). LPP extends this work even further by illustrating how play, as an orientation to activity, might make it possible to engage students at an even earlier age, complementing careful tool design with an orientation that builds upon the affordances of developmentally appropriate activities to support engagement with these complex ideas. Given the increasing interest in developing meaningful multi-year learning progressions (c.f., NRC 2007), this work therefore suggests alternative pathways to meaningful engagement with science concepts at an early age as a possible building block for the design of learning progressions that might similarly leverage students' intuitive notions of the world around them.

To further examine the details of how the students in the LPP environment did engage with physics content, we presented two case studies. These cases were also intended to connect the quantitative results more closely to our design principles and to explore the variation in the way the LPP system was taken up by students across the four topics. Across both cases and all the students within the cases, we observed that students used their bodies and embodied play to articulate their understandings and to make their predictions visible to the rest of the class. Publicly walking off a prediction emerged as a common practice in this classroom, as did elaborating one's motion with other semiotic forms such as narration, exaggerated gestures, or leaving a physical trace of one's movement. Linked to the practice of embodied prediction was the classroom norm that developed for the audience to comment on and critique these predictions. The LPP system played an important role in making these embodied predictions publicly available via projection, repeatable through VCR-like controls, and permanent through graphical traces of one's movement.

The cases also highlighted that participatory modeling brought a new set of resources for students to reason with that were different than traditional classroom activities. In the friction case we saw that participatory modeling led students, for good or ill, to bring in their own lived experiences as a "moving object". Analytically, participatory modeling may have also helped students to zero in on the causal mechanism behind changes in motion, as was the case for Marissa's explanation of why prickliness caused objects to slow down that was explored and articulated through her toes. The second case study elaborated how students embodied resources might be productively blended with other semiotics forms to help students to reason through novel situations in powerful ways. Here we saw how David made use of force symbols, the structure created by the tape and yarn on the carpet, as well as his own physical movement to accurately predict the path of the ball when given orthogonal forces of different magnitudes.

The qualitative findings of LPP add additional nuance to the field's understanding of the value and difficulty of using abstract symbols to teach complex science concepts. White (1993a, b) work with TinkerTools made effective use of an intermediate level of abstraction in designing the symbols to be used in their physics simulations. Intermediate level abstractions were, they argue, ideal in that they allows students to reason about the phenomena without becoming overly bogged down by the concrete situation, which often focused them too narrowly upon the specifics of the lived experience and inhibited abstraction across multiple experiences and scenarios. In contrast, we have shown that it may be possible to productively balance and capitalize upon concrete lived experiences while also engaging students with symbols that hearken back to those very experiences. Rather than initially restrict students to an intermediate level of abstraction, LPP was successful in helping students to begin with embodied representation (e.g., a foot kicking a soccer ball) and then discover for themselves the power of a more abstract representations. Similar to earlier work with re-inventing representations and progressive symbolism (diSessa et al. 1991; Enyedy 2005), this may provide designers with an alternative pathway towards supporting meaningful abstract symbols that allow students to pivot between the abstract and the concrete, and appreciate the value of both.

Further, in both cases we saw that students had a tendency to create a series of special cases rather than one integrated conceptual system to explain and predict motion. To encourage conceptual integration, we embedded our LPP system within a collective framework of progressive symbolization. In the friction case we saw how the progressive aspect of progressive symbolization worked. The need for a symbol for friction arose organically out of the students' confusion at using the same symbol to represent impulse forces and the force of friction. It is the creation of a symbol that allows (and to some degree forces) students to articulate the way in which a symbol, such as friction, interacts with other elements of the model such as speed and force. It may be that this helps students create a system that when applied to different context levels the situational variability helping them reason the same way about them rather than treating them as a series of isolated cases (diSessa 1993).

While it could be argued that any material inscription allows for the unification of multiple observations or instances (Hall et al. 2002), what is different here is that the symbol in this case was invented by the students in the context of their embodied activity. As a result the symbol is likely to index a rich history and set of resources that make the symbol more personally meaningful to the student. Elsewhere, the relationship between first person experience and other semiotic forms in the process of sense making and problem solving has been called semiotic fusion (Nemirovsky 2003), liminal spaces (Ochs et al. 1996) and conceptual blends (Fauconnier and 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.

Finally, we believe the LPP results extend previous work in physics education and CSCL by offering evidence that play can support students' science inquiry activities in meaningful ways. While it is not possible to suggest from our current findings that play was the "cause" of student learning, we have attempted to illustrate that play is clearly an activity that afforded students an opportunity to express, explore, and revise their conceptual understanding. Furthermore, our implementation of play intentionally incorporated play into the learning environment in a manner that is somewhat unique in CSCL designs. Therefore, we believe the preliminary success of the LPP environment suggests several possible future directions for research within CSCL that may tap into play as a form of activity. 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.

Future directions for play in CSCL

We see several ways in which the current LPP findings suggest new avenues for research into the role of play in supporting learning. First, we have attempted to move beyond simplistic accounts that position play as "powerful" or "motivating" and suggest that focusing on a specific theoretical framing for play may afford researchers an opportunity to describe and then observe in more detail how play might support specific forms of learning. In particular, we built upon Vygotsky's (1978) notions of play that highlight the rules that lie at the heart of all play situations. This focus allowed us to more systematically design our LPP environment to support play *intended to make those rules visible*. In future work, we believe it will be important to more thoroughly explore not only the potential for play as a form of inquiry into hidden rules, but other specific theoretical models for how play might support learning. We see this as particularly relevant given the current focus on games to support learning. While play researchers have long spoken of the unique differences between games and socio-dramatic play, the potential for each of these fields to contribute uniquely to learning disciplinary content, particularly in a computer-supported environment is still in the nascent stages.

In the current study, our use of play included the goal of being able to view one's play as a form of model, coupled with new formal symbols. Augmented reality then arose as a fitting complement to this approach. While other technologies may be equally or possibly better suited, our goal in noting this is to suggest that it may be fruitful to begin documenting and exploring the fit between specific forms of play and the technologies that are likely to facilitate this.

Furthermore, fit between instructional goals, theory, and technological affordances is not unidirectional. While existing research has supported that augmented reality is a powerful technology that can enhance inquiry learning (Klopfer, 2008; Yoon, et al. 2011) we believe that using augmented reality to support learning through play in a small scale, local environment is unique, and thus sheds light on the power and new potentials of augmented reality.

As a final note, we would like to suggest that it is important when thinking about Play in CSCL learning environments to consider the fit and function of complementary activities designed to encourage academic learning. In our current design, play was never expected to work on its own. Rather, discussion, debate, and progressive symbolization were all incorporated into our design in an effort to supplement and complement those unique features of play that we found most powerful, while extending them into more academic spaces.

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 has the potential to lead to generative inquiry skills and a robust scientific epistemology. Pre- / Post-test results were encouraging and show that young students are able, with the LPP technology and activities to learn force and motion concepts at an earlier age than thought possible. More generally, we believe this shows that young children need not be limited to memorization of science facts or unstructured explorations just because they cannot design controlled experiments for inquiry. Future work will be needed to further unpack the depth of conceptual understanding that students develop through augmented reality environments and participatory modeling, as well as the role that this type of instruction might play as a building block for subsequent concept learning and for developing students' modeling skills.

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