Play and Augmented Reality in Learning Physics: The SPASES Project

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Abstract: The Semiotic Pivots and Activity Spaces for Elementary Science (SPASES) Project was implemented as a proof of concept. Our goal was to demonstrate that with the right set of technological supports, young children can start their learning trajectory in science off on the right foot by engaging in rich scientific investigations into complex science topics. The SPASES curriculum was successfully implemented in two multi-age classrooms of 43 students aged 6-8 years at a progressive elementary school in Los Angeles, CA. Pre/Post-test results show that these 6-8 year old students were able to develop a conceptual understanding of force, net force, friction and two-dimensional motion after participating in the SPASES curriculum which leveraged their prior experiences and ability to engage in embodied play as a form of scientific modeling.

Introduction

Early elementary science instruction has not kept pace with the developmental literature on young students' cognitive competencies that can be used as building blocks for understanding science concepts (NRC, 2007; Metz, 1995). In fact, young children can, under the right circumstances, do more and learn more complicated ideas than we currently ask of them in early elementary science education. One argument against 'ambitious' science instruction (1) is that aspects of classical experimental design such as controlling variables and separating hypotheses from evidence have proven difficult for young children (Klahr, 2000; Schauble, 1996; Siegler & Liebert, 1975). However, alternative studies have shown that asking students to produce and evaluate models of the real world to help them generate predictions can make it possible for them to effectively participate in the process of scientific knowledge production and learn the content being studied (Lehrer & Schauble, 2006). Models—and in the case of the SPASES project, hybrid models that leverage both computer simulations and physical embodiment to describe Newtonian force and motion—are a critical part of the scientific inquiry process and can help students coordinate theory with evidence (Schwarz & White, 2005). However, while modeling is within reach of early elementary students, they still do not progress very far without carefully scaffolded experiences (Lehrer & Schauble, 2000).

In this paper we describe how first and second grade students 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 called SPASES (Semiotic Pivots and Activity Spaces for Elementary Science) that were used to leverage students' existing competencies in pretend play and transition them to formal and symbolic models of force and motion. Briefly (a fuller description is provided below), cameras filmed the area at the front of the classroom. The video feed was passed through object recognition software that recognized and tracked (e.g., the position and orientation) a predefined set of geometric patterns. Students held or wore these patterns as they moved about the room. A projection of the SPASES simulations software was displayed on an interactive whiteboard. The simulation software showed the video feed of the students moving around the room. The simulation software also displayed an image of the object that the students were play-acting (e.g. a ball) superimposed by the computer software over their image in the video feed. The superimposed objects would move around the projection in real-time as the students themselves also moved around the room.

Theoretical Framework and Design Principles

Young Children and the Concepts of Force and Motion

Infants develop an intuitive notion of objects, including their permanence and their properties. By preschool these intuitions have developed into a sophisticated sense of mechanical causality and understanding of the links between unseen causes and observable results (Bullock, Gelman, & Baillargeon, 1982; Yoachim & Meltzoff, 2003,). Additionally, pre-school children can distinguish between distance, speed, and time when observing objects in motion (Acredolo, Adams, & Schmid, 1984; Matsuda, 2001). Even so, some concepts of force and motion are difficult for young students to grasp and these core but challenging concepts were the target of our instructional intervention.

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

Description of the SPASES Environment and Technology

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

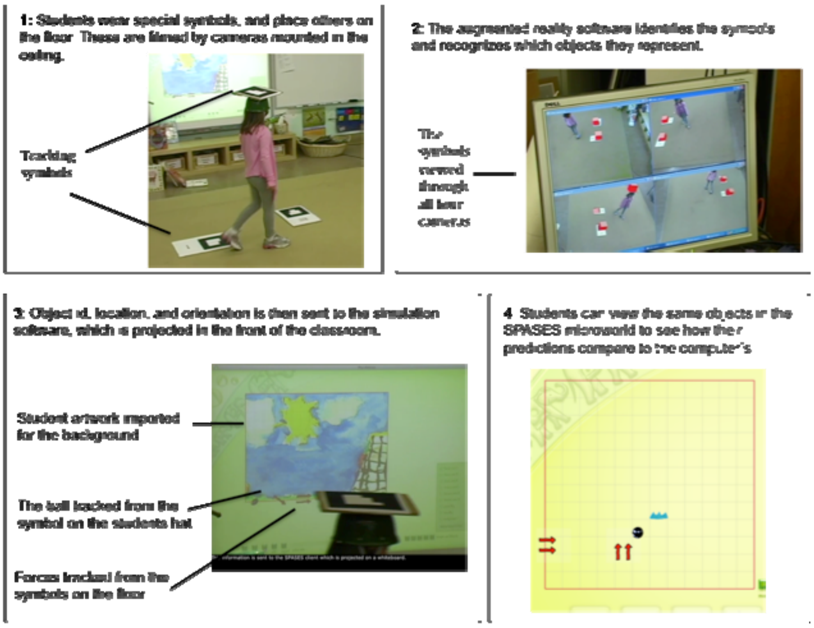

Figure 1. The Progression from Physical Objects and Motion to a Physics Microworld in SPASES.

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

Susie, "playing" the role of the ball, demonstrated her prediction by walking across the rug wearing the symbol for a ball on a hat. As she walked, she responded to the forces she encountered by speeding up. The system tracked her movement in real time. While the students saw her move across the rug, they could also see a ball projected in the SPASES microworld move across the whiteboard, mimicking her movement in the physical classroom. As Susie-as-the-ball passed arrow symbols, her peers were also involved through evaluating whether they agreed with her prediction. Did she speed up and slow down in the right places? By the correct amount?

After Susie finished, the students were invited to debate her embodied prediction. They began by discussing how many forces were in each location and what their impact would be on the ball. Some students expressed common, but incomplete or inaccurate, intuitions while others shared more idiosyncratic ideas. The students then had the chance to compare their embodied predictions with 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 see if they were right was reposition Susie-as-the-ball back to the beginning and press a button to run the simulation. Now the physics engine took over Susie's ball and displayed what would happen for that same scenario in a Newtonian world using the same space and representational system as the children's pretend play. Ultimately, everyone was surprised when their predictions did not quite match the computer simulation, and in the ensuing discussion students made explicit some of their implicit thinking. This discussion provided a key building block for a series of activities that led to the majority of the students in the group to build on what they already knew (or thought they knew) about how things move and to begin to reason in a more normative manner about how forces contribute to an objects motion. Thus the students started the activity using pretend play skills, but by the end of the activity were engaging in a discussion about modeling and concepts of net force. Through this game-like experience, SPASES makes it possible for 6-8 year-old students to interrogate their own understanding and explore these physics concepts. We now turn to the broader theoretical framework that guided our design.

Design Principle #1: Play and Participatory Modeling

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

In addition to nascent symbolism, young students have another important competency at their disposal for 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).

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

To incorporate play into the SPASES curriculum, we 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 engagement that has been seen in participatory simulations (Colella, 2000) while shifting the focus on rules to be more explicit and reflective for the participants. By identifying these play activities as participatory modeling, we are highlighting the fact that students were presenting, through embodied enactment, their model of how the ball would move.

To facilitate productive modeling throughout the curriculum, SPASES began with a first-person experience—an important building block for young students' scientific understanding—where one student pretended to be the ball and used his/her own physical motion to predict and represent the motion of the ball. It has been shown that when learning difficult science concepts, students benefit from examining the system from multiple perspectives, particularly in computationally supported environments where the technology can help students take perspectives beyond their own perceptual capabilities (c.f., White, 1993). Like traditional computer simulations, SPASES offers the outside observer's perspective as well, where one can look down from above and observe forces, friction and motion, running experiments and measuring the phenomena (see Figure 1). However, given the age of our students, SPASES began with a first-person experience and then transitioned to an abstracted third person perspective.

Design Principle #2: Progressive Symbolization

An additional intersection between play and scientific activity is the role of symbolism in play. 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, making 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.

In SPASES the artwork and symbols that populated the system were all invented by the students themselves. Like previous work in progressive symbolization (Enyedy, 2005), the students refined their symbols as a group, determining which aspects of the phenomenon would be captured in a symbol and iteratively refining those symbols so that they would be effective in their future modeling activities.

Design Principle #3: Cycles of Activities and Semiotic Resources

After making embodied predictions, the students seamlessly transitioned into a physics microworld to compare their embodied predictions to what would actually happen in a perfect Newtonian world. Students positioned objects within SPASES using either the shared interactive whiteboard, or the augmented reality objects. Like prior effective microworlds (c.f., White, 1993), SPASES allowed students to see and manipulate a situation in ways impossible in the real world (e.g., turning off friction). Asking students to place objects on the whiteboard or in the physical classroom had the added benefit of creating public and open tools for discussion (Danish & Enyedy, 2007; Hutchins, 1993). This openness was an important feature of SPASES, allowing students to interrogate their peer's choices or propose alternative predictions for what they thought would happen.

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

Methods

Participants

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

The curriculum lasted 15 weeks (2/18/09 through 6/8/09) and consisted of 26 one to two hour sessions. The average length of a lesson was 90 minutes. Four major topics were covered; force and speed (5 lessons), net force in one dimension (11 lessons), friction (4 lessons), and two-dimensional motion (7 lessons).

Procedures

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

The pre- and post-test interviews were transcribed and coded for degree of conceptual understanding. Reliability for each item was determined by calculating the Intra-class Correlation Coefficients (ICC) for each item. Five of the 34 items were dropped because of low inter-rater reliability. An additional ten items were dropped due to a high proportion of missing answers. These missing answers were due in part to student attendance, but also due to variability in the way that various members of the research team administered the interview, and the difficulty in parsing the continuous transcript into discrete answers. As a result, the final pre-test and post-test scales were comprised of nineteen items. Reliability analyses were conducted on the pre-test and post-test items to ensure that the data had a unidimensional structure. The Cronbach's alpha for the *pre-test scale* was .34. The Cronbach's alpha for the post-test scale was .57. Two explanations may account for the low alpha values. First, the sample size was small; with a larger sample reliability estimates are expected to be higher. Also, our participants were young children who had very little knowledge of the concepts prior to the study. For example one student thought acceleration was a type of vegetable. Therefore, the low consistency among items on the pre-test may be an artifact of their age and understanding, rather than poor inter-item correlation. This assertion is supported by the dramatic increase in reliability after the intervention.

Results

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 ($SD = 1.55$) out of a possible of nineteen points. The average post-test score was 8.60 (SD = 2.07). 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, $t(42)= 10.43$, $p < .005$. 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 1).

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

For the topic of force and speed, we analyzed the question that asked students "What is a force?" The highest value was given to answers that reflect the understanding that either force makes something go proportionately faster or slower, or that forces change the speed of an object. Partial credit was given to answers that describe forces as a verb (e.g., it makes something move) or as a noun (i.e, provides an example of a force). The sign test indicated that 28 (65%) of the students received higher scores on the post-test than on the pre-test, $Z = 4.83$, $p < .005$.

For the topic of friction, we analyzed responses to a scenario that asked students to explain why a moving soccer ball slows down when rolling on a grassy surface. The highest value was given to students who described the resulting action and the mechanism of the friction (e.g., "Because those things sticking out of it, it will hold them back, it will try to push the ball back and stop."). Partial credit was given to answers that either described the surface quality of the grass (e.g., "So that's why it slows on the grass, because it's a little bumpy.") or connected the change in speed to friction or the grass (e.g., "Because it's really high friction right here, that's where it stops."). The sign test indicated that 16 (37%) of the students received higher scores on this question during the post-test than on the pre-test, although the results were marginally significant, $p = .052$.

Table 1: Pearson correlations between background variables and test scores.

	Pre-test	Post-test	Age at start	Grade	Gender
Pre-test	1.00	.416**	0.26	0.21	-0.14
		0.01	0.09	0.16	0.38
Post-test	.416**	1.00	0.11	0.19	0.05
	0.01		0.48	0.23	0.75
Age at start	0.26	0.11	1.00	.835**	0.15
	0.09	0.48		0.00	0.35
Grade	0.21	0.19	.835**	1.00	0.23
	0.16	0.23	0.00		0.14
Gender	-0.14	0.05	0.15	0.23	1.00
	0.38	0.75	0.35	0.14	

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., "Same force 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 14 (33%) of the students received higher scores on this question during the post-test than on the pre-test, although the results were marginally significant, $p = .12$.

For the topic of two-dimensional motion, we analyzed the response to the modified FCI item that asked students to predict the path of a puck that received another hit (see Figure 2). The sign test indicated that 29 (67%) of the students got higher scores on the post-test than on the pre-test, $Z = 4.67$, $p < .005$.

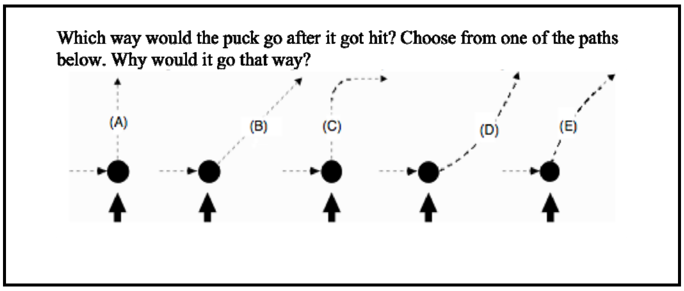

Figure 2. Modified FCI Question about 2-D Motion.

In sum, students demonstrated significant improvement on all of the key measures, including, the fact that 91% of the students showed a pre- to post-test gain ($Z = 5.71$, $p < .005$).

Conclusion

SPASES is an important proof of concept project. We aimed to demonstrate that young children can begin their learning trajectory in science off on the right foot—both in terms of the complexity of science content and the type of ambitious science instruction that will lead to generative inquiry skills and a robust scientific epistemology. Pre/Post-test results show that these 6-8 year old students were able to develop a conceptual understanding of speed, force, friction and two-dimensional motion.

What we have shown here is that the students are able, with the SPASES technology and activities to learn force and motion concepts at an earlier age than thought possible.

We were pleased to see that neither gender nor age were correlated to post-test performance. We were initially concerned that the SPASES environment might appeal more to and therefore provide a greater benefit for boys. The environment overlaps with many of the stereotypical interests and styles of boys'—it involves a mechanical topic, involves physical activity, and heavily depends on computer simulations and gaming. Nevertheless, from our videotapes we saw that girls were just as deeply engaged during the activities as boys and contributed substantially, if not to a greater extent, during the whole-class and small group discussions.

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

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

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

Endnotes

(1) We have adapted the term 'ambitious math instruction' (Lampert, Beasley, Ghousseini, Kazemi, & Franke, 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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