

Social Affordances of Mixed Reality Learning Environments: A case from the Science through Technology Enhanced Play project (STEP)

Noel Enyedy*, Joshua Danish**, David DeLiema*, Asmalina Saleh**,
Christine Lee*, Noelani Morris*, Randy Illum*
*UCLA, **Indiana University

Abstract

We describe the design of the Science through Technology Enhanced Play (STEP) project. In STEP, we explore the potential for dramatic play—a form of activity that is particularly familiar to early elementary students—to promote meaningful inquiry about scientific concepts. We report on the first round of design experiments conducted with 120 first and second grade students who investigated how and why different states of matter have different properties. Pre-post analyses indicate that the majority of students learned the content and demonstrate how the affordances of the socio-technical system promoted the transition from individual observation to collective inquiry, how play as the root activity provided agency within that inquiry, and how the teacher and the social norms of the classroom reinforced these productive social processes.

1. Introduction

Designing digital environments that support and extend existing social processes to promote learning is not a new idea. Educators and learning scientists have been studying how to design socio-technical systems to promote learning through collaboration and discussion since the birth of the field of computer supported collaborative learning in the mid 1990s [1]. But relatively little attention has been paid to the challenges and opportunities of socio-technical systems used by very young children (age 5-8) in a classroom setting. In particular, designing for early elementary classrooms requires considering how to work with and leverage large groups of students, even the full classroom as a collective. This paper investigates how the affordances of a developmentally appropriate, mixed-reality (MR) learning environment sparked and supported social processes that in turn led to learning about states of matter (e.g., gasses, liquids, and solids). Using computer vision, the mixed reality environment translated the physical motion of 6-12 children into a visualization of the state of matter of water, which was projected on a large public display. We framed the activity to the children as socio-dramatic play. Each

child pretended to be an individual water particle, and collectively they became gas, liquid, or ice. This paper explores how our play-based, embodied, mixed-reality learning environment promoted student agency during science inquiry.

2. Theoretical framework

In early elementary science education there is a great opportunity to improve how children are taught. Too often misunderstandings of developmental psychology have limited science education to a caricature of scientific practice [2]. Instead of having children engage in science like scientists do—asking questions, modeling the phenomena, and arguing with evidence—early elementary science education has focused almost exclusively on memorization, unstructured investigations, and concrete experiences [3]. While it is true that young students may have trouble designing controlled experiments on their own, children can still engage in hypothetico-deductive reasoning, the ability to use evidence to support and test hypotheses, or evaluate abstract representations of data or causality [4]. For example, in their everyday activities young children regularly engage in arguments, although these arguments are not often recognized as scientific [5]. In developing arguments, students often provide justifications for their claims, which is one of the key practices of science [6]. In one study, children as young as three were shown to argue about their ‘rights’ to engage in certain activities and provide justifications that were based on an understanding of the consequences of their actions [7]. Likewise 4-5 year old children were shown to frequently provide justifications during disputes in class and on the playground [8].

It is on the playground that we found the inspiration for this project. A core strategy for pedagogy is to build on the existing capabilities of the learner [9]. For 5-8 year olds, that capability is their expertise in and desire for socio-dramatic play. While at first blush socio-dramatic play seems to be an unlikely method for science education, below we outline the parallels between play and some of the core practices of science: inquiry, modeling and argumentation.

We argue that play is best defined not by the pleasure it brings but by the orientation one takes towards the activity, what Bateson called a meta-communicative stance [10]. This stance towards one's own and other's activity marks play as a context where the normal meaning of events and acts do not necessarily hold. For example, when children play superheroes, they do not interpret playful punches in the same way they interpret real punches. Meaning becomes flexible, making play a creative and safe place within which one can experiment and share ideas. An interesting feature of children's socio-dramatic play is that children often spend more time arguing and negotiating the rules of a play situation than they spend actually "playing" their parts [11]. Because of the constant negotiation and justification of what they did during play, why they did it, and what happened as a result, children make the rules that govern a situation visible and explicit. However, play is also a place where one can be wrong, and even purposefully break the very rules that define the play situation. In socio-dramatic play, one either adapts to the new rules or re-negotiates them. Because of the stance one takes in play, the activity is fluid and re-negotiable and the stakes are never high.

Play is also a form of informal inquiry. If you think of children's pretend play, you often think of playing superheroes, school, or house. Most of these contexts are familiar, but not fully understood. For example, when children play "house," they become mothers, fathers, babies, or pets, and they act out familiar scenarios such as when mom gets sick. However, when they begin playing out the scene, they do not fully understand the rules of parenting. It is through play that they attempt to make sense of what parents do and why. That is, through play they inquire into an aspect of their lives they do not fully understand.

Finally, play can be seen as a form of modeling. Scholars who study socio-dramatic play have commented that it can be thought of as a form of simulation [12], which we contend is a sub-class of the broader practice of modeling. By modeling, we mean the construction, testing, and refinement of representations—in this case a play scenario—that are in some way analogous to the real world, which can be used to explain these systems and to generate predictions [13]. The similarity rests on the fact that a common type of scientific model is to characterize the world in terms of a series of rules.

This is exactly how Vygotsky defined play, as a context that always includes an imaginary situation and a set of rules [14]. Returning to our previous example of "playing house" children typically regulate their actions based on a set of rules about what mothers, fathers, and babies do. For example, one child may tell

another, "Because the mother is sick, the daddy has to cook and clean." In this simple conditional statement, the child has made a rule of parenting explicit, as well as their assumptions about the gendered roles that parents adopt. The children then use these rules to regulate their own actions in the play context and run out the play-as-simulation to see if the rules ring true to their experience. This type of explicit statement and negotiation of the rules that describe a scientific system is what we intended our system to promote by having students engage in play-as-modeling.

3. Data sources and methods

3.1. Mixed reality learning environment

We designed the mixed reality system to help enhance play by directing students' attention to key aspects of the rules that govern state changes as the students engage in discovering these rules and negotiating how to test and articulate them. Mixed Reality refers to spaces that fuse together the physical and virtual worlds. In the mixed reality environment we designed, students can manipulate virtual objects (e.g., water particles) by actions they take in the real world (e.g., the speed and direction of their own motion in the room). In MR learning environments physical movement and interactions become tied to conceptual understanding through simulations and visualizations that students become part of, for example taking on the role of an asteroid, molecule, or ball in a simulated world with virtual actors or processes [15,16].

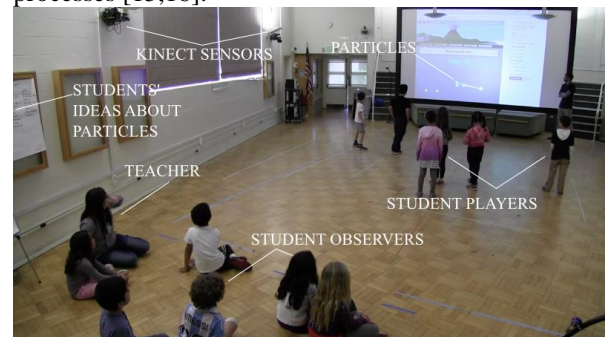


Figure 1: The social and technical components of the STEP system

The Science through Technology enhanced play (STEP) environment (see Figure 1) was designed to support students as they explored and reflected on science content through embodied play. Microsoft Kinect cameras were placed around the classroom to capture student movement, and the STEP software used students' movement to control aspects of a computer simulation of water particles assembling in different states of matter. As 6-12 students moved around the space, each one was assigned a representation in the shape of a particle, and these

particles interacted with one another to create solid, liquid, and gas. As the students moved around, they saw the lines connecting each particle to its nearest neighbor change color, with each line color representing a different type of bond (white for solid, blue for liquid, and red for gas). Three state meters on the side of the screen also showed students what percentage of the bonds within the current simulation were currently representing solid, liquid, and gas at any given time (see Figure 2).

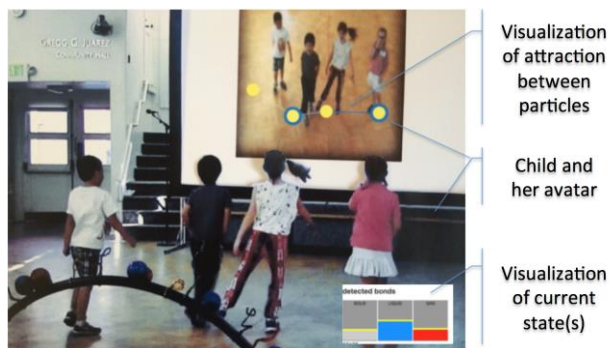


Figure 2: The students' perspective of the visualization

3.2 Activities

Students collaboratively used their physical movements to explore particle behavior, using the feedback displayed on a projected screen to adapt their actions in line with the goals of each activity. Those students who were not participating in the simulation were cast as observers whose job was to reflect on connections between their classmates' actions and particle behavior occurring in the simulation. The visualization was simple. It displayed particles that were gas as interconnected red dots. It displayed liquid as blue. It displayed solids as white. Impossible states were displayed as yellow. The rules that the students had to uncover were also fairly simple. The state of gas was determined solely by the speed of the water particle. If a student-as-particle was moving fast, the particle would be displayed as red. To become liquid students had to move slowly and keep close together. Solid water appeared when students stood fairly still and about one meter apart. These rules reflect a fairly accurate simplification of the rules that govern the various states of matter for water, but not necessarily other materials. For other materials solids are usually denser than liquids. However, we made a conscious choice to build on the material that was most familiar to the children rather than the material that followed the simplest set of rules. Like any model there were some distortions. We chose to focus on accurately representing relative speed and distance at the expense of accurately representing density.

The progression of activities began with what was most familiar: the qualities of states of matter that we can directly experience, such as the feel of the temperature, the hardness of the state, and the degree to which it retains its shape and progressed towards aspects of states of matter that are not directly observable. First, the students began by exploring the effects of hot and cold environments on the macro level properties of matter. For example, one group of children pretended to be in a frozen world trying to get over or through an ice wall that was too hard to break. Next, students transitioned to a micro level view of matter in which each student controlled one particle and the class reflected on the particle behavior. This activity is the focus of this paper. Finally, we switched focus to the impact of energy on particle behavior, with each student controlling an energy wand that heated up or cooled down any particle it touched.

Table 1: The three play activities: * is the activity included in current analysis

Activity	Learning goals
<i>Macro-level costume play</i> : Students selected characters and play-acted how they would move past an ice wall.	<ul style="list-style-type: none"> • Introduction to macroscopic state changes. • Introduction to causal relationship between temperature and state change.
<i>*Particle-embodiment play</i> : Students acted out how they felt particles of water might behave.	<ul style="list-style-type: none"> • Matter is made up of tiny particles, which are too small to see. • Particles are always in motion. • Motion and arrangement of particles affect state of matter.
<i>Energy-embodiment play</i> : The students acted out being sources of energy and attempted to change the state of matter in the simulation by giving energy to simulated particles.	<ul style="list-style-type: none"> • Temperature is related to heat energy which affects the motion of particles (e.g., when temperature is higher there is more energy and more motion and vice-versa) • A change in energy is required for state changes to occur.

3.3 Data sources and methods

Participants were from three mixed-age first and second grade classrooms (ages 6-8). There were a total of 120 children who engaged in the intervention—58 1st graders and 66 2nd graders, almost evenly matched in gender (54% girls). Four teachers participated and each had more than six years of teaching experience. The intended role of the teacher was as a facilitator of student directed inquiry. In our training sessions with the teachers we asked the teachers to follow the student's emergent goals and to limit the degree to which they called attention to aspects of the simulation that were important but that the students had not yet

noticed. We wanted the discovery and exploration to start with the students' observations. Similarly, while the researchers' main roles were to run the tech system, we often asked probing questions that built on what the students said or noticed. Still there were qualitative differences in how the teachers engaged in their facilitator role. The two most obvious differences in the teachers' styles were a) the degree to which they engaged in play with the children in the space and b) the degree to which they documented the children's discourse and evolving ideas on the large sticky notes we provided at the back of the room.

Content understanding was assessed in pre-post interviews, which included 17 questions about states of matter and a free-form drawing of a state change. Content understanding was operationalized as descriptions of particle behavior in the different states of matter (matter-type codes) and the mechanisms behind state changes (change-type codes). These codes were derived from our earlier study [17] and other similar research interventions [18]. Students were asked about how particles behaved in different states as well as the mechanisms behind state changes. A total of three coders analyzed and categorized the pre-post video data. Interrater agreement between pairs of coders with Pearson's correlation ranged from .798 to .849, whereas the intraclass correlation for individual raters was .851.

Our qualitative analysis centers on analyzing how exactly the socio-technical system of STEP was enacted, and the details of how social processes that were promoted by the system in turn facilitated learning. Our data for this preliminary analysis uses a single case from early in the unit. We chose this case because it was very playful, at times chaotic, but ended with the students' first major discovery about the rules that govern states of matter. Given the rationale for our design (outlined above), we analyze the video case in terms of: a) What affordances does the technology provide that sparks or supports social processes and productive conversations? b) How is play-as-inquiry organized and how does the activity of play encourage certain types of social behavior and conversations? c) How does the teacher and the social norms of the classroom promote collaboration and productive conversations?

4. Findings

A paired-samples t-test was conducted to compare students' pre-post scores. There was a significant increase in the scores between pre ($M=15.29$, $SD=6.84$) and post-tests ($M=27.18$, $SD=8.55$); $t(119)=-16.54$, $p < .001$, $d = 1.548$. As part of the pre-post test the children were asked to draw "what happens when solid ice changes to liquid water" (see Figure 3). To

focus just on if there was any growth shown in students' drawings we ran a mixed ANOVA. Results indicate that there was significant gain in pre and post scores, ($F(1,114) = 114.24$, $p < .001$, $\alpha = 0.05$). As these statistics tests indicate, the intervention as a whole was successful in promoting learning. From interacting with each other in and out of the MR environment the students learned not only the properties of various states of matter, but also *why* those properties were they were (e.g., solids retain their shape because the particles are not moving and fixed in an array).

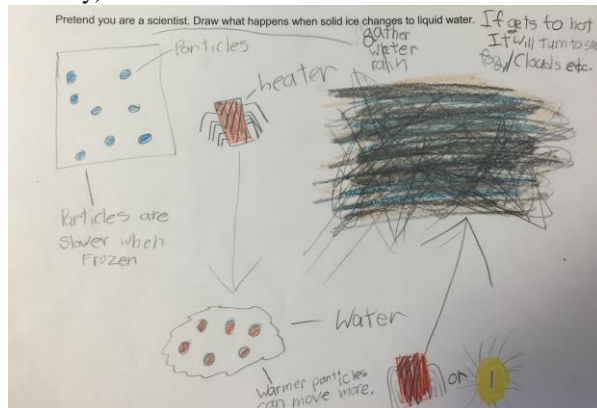


Figure 3: An example post-test drawing of a state change

We realize of course that gain scores without a control or comparison group are of limited value. However, evaluating the efficacy of this intervention is not the intent of the project or this paper. Instead, our goal is to better understand how this type of technology is taken up by the students and teachers. Particularly, we are interested in what types of social interaction are most common during technology enhanced play and how these different social processes contribute to learning.

Toward this end our qualitative analysis of the social and technical affordances of the STEP system begins on the second day (of six) of the intervention. This was the first day that students pretended to shrink down into individual water particles and the first day they encountered the visualization described above. The students were not given any instructions beyond that they needed to figure out the rules that govern each state of matter. Further, they were not told anything about the visualization itself. The teacher introduced the activity by saying, "Today, you guys are going to be particles." Moments later, Ms. Jones shifted the simulation in a playful direction: "We are going to shrink you down with a special magic shrink machine," in reference to a hula-hoop decorated with spray-painted styrofoam balls (depicting particles). "The rest of you, your job is to notice what happens. If

you have observations, say them out.” As the students entered the space, they saw their own water particle avatars appear and follow them wherever they went. They saw that their avatar sometimes changed color (red, blue and white) and that sometimes a bar that varied in color and thickness connected their avatar to their friend’s avatar. It was entirely up to them to construct meaning within the constraints that the initial spoken directions and software system provided.

4.1 From Individual observation to collective inquiry

Initially, the students explored the system in very playful ways jumping and dancing and making silly noises to imitate moving particles. Almost immediately they also began to call out observations such as, “I am red” or “We are white.” You can see in Figure 4 that the students’ attention was primarily on the screen (visible in the left of the frame). At first they investigated and made observations as individuals with little collaboration or discussion.



Figure 4: Students playing and observing as individuals

However, before long the students began to act collaboratively. In Figure 5 we see that the students began to dance and direct their observations to how their collaborative activities affected the visualization. This is import to learning the correct science because no student acting alone can become a state of matter. States of matter describe collections of particles, not individual particles. It is also important socially. The teacher had told the students that they must all agree on a list of rules that tell how particles behave to make the different states. That is, the inquiry of the classroom and its social norms were oriented towards producing a collective product.

The MR system, the organization of play, and the teacher/classroom norms all contributed to this transition from individual observation to collaborative activity. The mixed reality system provides a large public display that makes both one’s own action visible as well as the actions of everyone else. Additionally, the simulation’s display connects particles/students based on their relative distance and speed to one another. Thus the virtual elements of the public

display tune the children into looking at their physical relationship to other people in the space. As they dance together, they will often become water because the state of water is defined by particles that are close to each other moving at a medium speed in relation to each other.

However, the social aspects of the system are also contributing to the transition from individual to collective action. As noted above, play involves children discussing and negotiating what the play context is and how one must behave in that situation. The children, encouraged by the teacher who asks what they are noticing, begin to share their individual observations but quickly move to listening to and building on other’s ideas.



Figure 5 Students playing particles in pairs

4.2 Agency, play and testing ideas

After a minute or so, three students initiated a sidebar conversation with the teacher. The teacher said, “Okay, I’ve heard a couple people say that.” Ms. Jones stopped the class’ activity by counting down: “5, 4, 3, 2, 1, freeze.” This transitioned the students from play-as-inquiry to the more traditional participation structures of science classroom inquiry. The students from the sidebar then shared their idea that the color of the particles and connectors depended on one’s location in the room. Additionally, they proposed their idea for testing whether location determines color (state) by having the boys stand on one side of the room and the girls on another. With the class split in half, the girls requested that the boys stopped running around because their constant movement was interfering with the test, the boys stop moving, the students observed the screen, and everybody on both sides of the room was either white or yellow. The teacher asked if the idea was correct, and students responded in chorus: “No!” In the sequence so far, the class had moved from play, to observation, to conjecture, to experimentation, to drawing a collective conclusion from their “data.”

To summarize, up to this point in our analysis the discourse started with students making simple observations of their own movement and of how that movement was visualized by the system. The

discourse as well as the activity became more social and coordinated as time continued. In addition to sharing their ideas, the students had to organize themselves and coordinate their activity to test their ideas. In this way, both the technology and the teacher play essential roles in promoting student agency. By tracking each student individually, the technology gives students agency to explore the space and their own body movement. And by promoting the ideas students generate during this exploration, the teacher initiates another layer of student agency, allowing students to see their ideas carried out in the whole class.

The affordances of the technology, the activity of play, and the classroom norms all encourage the transition from observing to testing conjectures. The generation of novel ideas and sharing them with each other is a fundamental aspect of the organization of play. This is encouraged by the teacher who stops the class to listen to one another and perform their experiments as a group. The technology affords this transition from observation to inquiry because it provides a space to conduct the experiments, but more importantly because its visualizations provide clear answers to the questions the students are asking.

After their mini-experiment the students returned to their playful exploration. As mentioned above, many students spontaneously decided to explore together in pairs. This tendency towards collaborative activity in play carried over into the moments when the teacher paused the visualization to discuss the students' current ideas and conjectures. In Figure 6, below, the students had been exploring how hugging effected the visualization. Again, similar to the event above, one student had a sidebar with the teacher and the teacher asked her to share her idea with the whole class. The class paused their play but remained in their pairs. The student shared her idea: "when you get close, super close, you become one particle."

The STEP motion sensors are vision based, and so when students get too close together, the occlusion of one student to another causes the simulation to lose track of some of the students making it look like the water particles merge. The students were intrigued by this and were working to explore when and why particles would disappear. To do so they paired up, and these naturally pairings persisted when the activity transitioned between playing particles and the meta-activity of articulating their model of the simulation (and eventually their rules for states of matter).



Figure 6 Students pausing to discuss their ideas

It is important to note that even though this exploration of hugging was not directly on the solution path to the three rules for states of matter described above, the students' playful activity was accepted as legitimate inquiry. This evidence of children's agency—the agency to decide what questions to pursue as well as the agency to decide on what the class "knew" about states of matter—is an affordance of play. The agency inherent in play is reinforced by the norms of the classroom and by the teacher's choice not to contest this agency—even when the choices the students are making differ from what the teacher hoped for or intended.

Importantly, these off-topic investigations sometimes led to discoveries that were directly related to the lesson objectives. For example, at one point, the teacher quieted the class and handed the floor to a student: "Molly has an idea she wants to test out." Molly wanted to pursue what would happen if more than two students hugged. Molly said: "Um, if we can make a caterpillar, and um, we can see if it's one particle or many particles." During the first presentation of the hug (mentioned earlier in the "super close" quote), the teacher had attempted to dismiss the idea as an uninteresting technical limitation of the camera. Now, in Molly's proposed experiment, we see that the students have continued to pursue this line of inquiry. The activity of play afforded children listening to children. Eventually, the whole class lined up to make a caterpillar and squeezed together, but they were unable to make the visualization show only one particle (Figure 7).

However, as they stood together in their caterpillar formation, one student at the back of the line, Carl, broke free (Figure 8) and danced with a smile on his face to the opposite side of the room. As he did so his avatar turned red due to the average speed between his particle and his neighbor's. The teacher noticed this and called everyone's attention to the naturally emerging controlled experiment that was happening.



Figure 7 Students coordinating their activity to test a conjecture

Another student in the center of the caterpillar pointed to the screen and provided a crisp statement about how distance determines color (Figure 9). “Look, it’s red! It’s Red! When you are close to each other it’s yellow and when you’re far apart it’s red.” This observation, while technically incorrect for gas, which is determined by speed, led the class to attend to the distance between particles as a possible contributing factor to their state, which is true for both solids and liquids. The agency afforded by play allowed students to pursue their own emergent goals, but the affordances of the technology’s visualization steered this off-topic inquiry back to the science concepts that the teacher intended them to learn. The play frame, the technology,

and the teacher made possible Carl’s off-topic exploration in the first place, and yet the technology (in automatically showing Carl’s movement as a red particle) and the teacher (by asking Carl to repeat the deviation) equally turned the moment into a learning opportunity.



Figure 8: The visualization of a student breaking free from the “caterpillar”

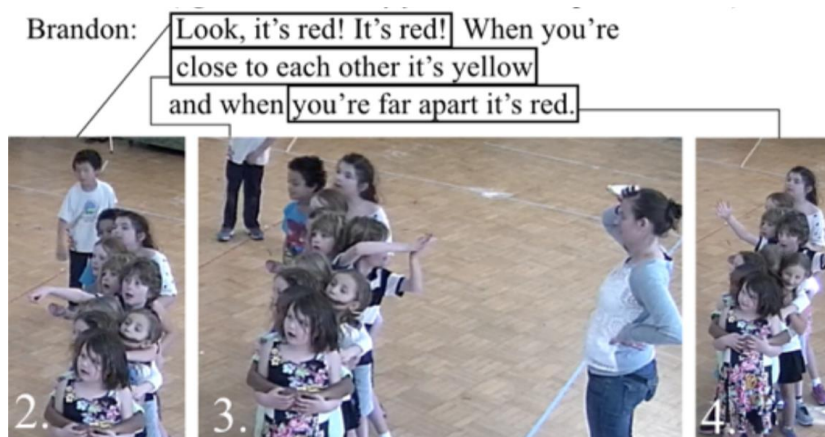


Figure 9 A student making sense of the visualization

4.3 Persistence of embodiment and the social processes when the technology is turned off

Near the end of class, the teacher pulled the students to the back of the room, turned off the technology, and begun a discussion intended to review and consolidate what the class as a whole had learned that day. In reviewing what the students thought they knew about making red/gas, one student identified the difficulty of using distance as the rule to change a particle red (i.e., gas). She observed, “If you’re all like far apart, you don’t all turn red. Because if you’re all far apart some people—they can try to be far apart but they are still a bit close and you don’t turn red.” That is, she noticed that in a confined space if you tried to run and keep away from one person you inevitably run close to another. This is in fact why the underlying model only uses the speed of particles to determine if they are gas and ignores distance.

However, the student’s point was not clear to the teacher or the class, and so three other girls tried to clarify the first student’s idea. To do so they got up and physically acted out her scenario (Figure 10). The girl in the pink top, Karen (Figure 10 below) explained, “So me and Deanna are close to each other and Mary and me are far apart from each other.” In response, one of the researchers asked, “And what happens in this situation?” The girl answers, “We turn red.” The other researcher asked, “Who turns red?” Deanna standing next to the student answers, “Mary” and then added, “and the line between Karen and Mary. And if you do this you’ll turn red too.” Deanna then ran over to Mary (see the bottom of Figure 10).



Figure 10 Students use their bodies (without the technology) to clarify another student’s idea about the rules for gas

Although the teacher was unable to get the students to draw clear distinctions between the speed of

particles and the distance between particles—both of which matter in determining the state of matter—this episode laid the groundwork for noticing and understanding each of these dimensions. It also showed how students were using their own bodies to make sense of the phenomena and construct their models even after the technology was turned off. This is important in that it indicates that the affordances of the technology to impact student thinking persisted after the technology was turned off.

Moreover, the students’ choice to migrate the embodied simulation outside the context of the technology highlights an important feature of student agency. By using the students’ own body movements as a core input to the simulation, the technology grounds the discovery and assessments of ideas in body movements that are both extremely familiar to students and always with them. Students thus have the agency to keep exploring their thinking even when the technology is turned off. The technology not only gave students a visualization of states of matter, but also made students comfortable exploring thinking as individuals and as a collective. The embodied model students create in Figure 10, which takes place outside of the context of the STEP technology, is nonetheless an extension of the agency that developed inside of the STEP technology: Students each play a part in the particle model, they create the model collectively, and they make predictions and justify their thinking about states of matter.

The students eventually articulated an accurate set of rules for each state, which were written down by the teacher and/or researcher to reflect the class’ continually evolving understanding (see Figure 11). It is interesting to note that many of the children’s rules fuse aspects of their personal bodily experience with more abstract rules. For example, see the emerging rule for solid: “White [solid] \rightarrow standing still, farther away, run in place, jump up and down.” This is a fairly accurate description of how water particles are positioned in a solid. It accurately captures the two abstractions of distance and speed as determining factors. However, these rules can also be read as directives to students so that they can as a group produce this state on demand. We think it is important that the rules retained a quasi-social dimension (e.g., directions for children in the play space) as it shows how the conceptual understanding the students develop in environments such as these will be grounded in their personal experience and therefore more likely to be understood at a deeper level.

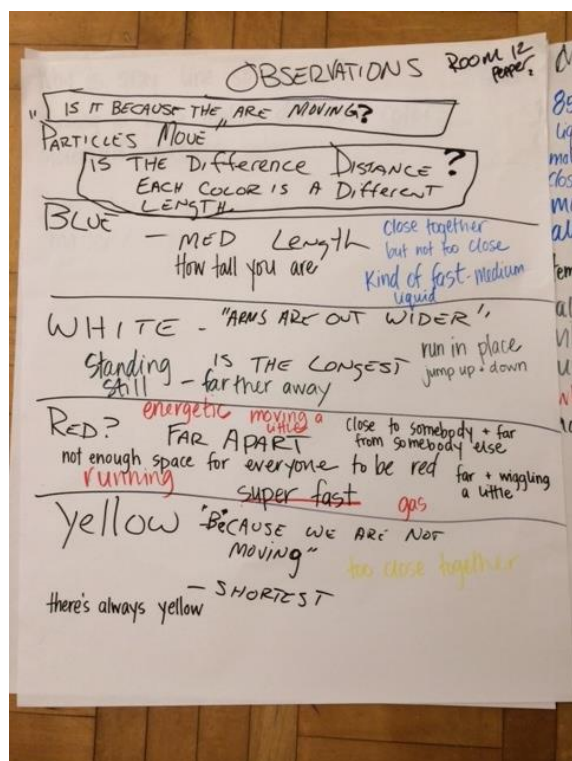


Figure 11 A public display of the students rules/model of different states of matter

5. Discussion

We believe this case shows that inquiry within the STEP MR environment is *organized around fluctuations between play and more traditional inquiry* in the form of experimentation. The case presented here was typical of our data. The teacher would send the children into the space with a very open-ended goal (if there was a goal at all). The children would play independently and in groups. From this playful activity, observations and conjectures would arise, often brought to the teacher's attention in the form of a sidebar conversation where one or more children would break off from their play and approach the teacher. This would often lead the teacher to help the students pursue their emergent inquiry goal by enlisting the help of the rest of the class in a formal test.

It is important to note that *the environment supports both individual and collective activity during play, but the traditional inquiry sequences almost always involve pausing the simulations to involve the whole class in discussion and testing*. This seems appropriate as science is a collective not individual activity. The practice of science is to construct explanatory accounts of the world and use data to convince the community of their veracity. Science as a field is the collective consensus about these explanations. From this

perspective science is inherently social and the organization of the classroom inquiry is consistent with this stance.

Agency is also a hallmark of the inquiry that goes on in STEP. Students generate emergent goals for their inquiry and they experimentally and opportunistically test new ideas. However playfully, the students select their own goals for inquiry. They also formulate how to experimentally test these ideas. The students think together about productive ways to test the idea and they execute the test with careful observations. Even when the students disprove their ideas, they make opportunistic progress uncovering salient dynamics in the simulation. In this case, even though clumping together into a caterpillar does not produce a single particle, one student's playful deviation from the caterpillar line leads to another student noticing that the deviation changed the particle color, and thus that distance might be in play. These two dimensions, speed and distance, are the two parameters that determine the state of matter in the STEP particle simulation. Despite that the students have not yet formulated the rules for speed and distance, they uncover both as relevant properties of state change.

6. Conclusion

Advances in vision-based tracking are opening up a new frontier for Mixed Reality for collaborative learning. Our findings show that, perhaps counter intuitively it is the social aspects of the space, not the technical aspects alone, that are critical to students' learning. In our case, the way in which students had agency to pursue their emergent goals and to decide when they believed they had achieved these goals were the defining features of inquiry within the STEP environment.

This agency is clearly an agreed upon social norm for how to behave in this new type of classroom. To be sure, the technology supported student agency. Through the visualization it provided ways for student play to generate observations and conjectures. Through the rules embedded within that visualization it provided feedback that helped the students converge on a normative understanding of the science concepts. However, we believe it was the simplicity of the technology that created room for the social dynamics to evolve in productive ways. Using the technology itself took little attention—students ran into the space and became particles. Further, the visualization itself was kept very simple, dots, connectors and one simple bar graph. Students could focus their attention on making observations and on each other, rather than on manipulating the technology. As the design space for how to use mixed reality to promote learning is

mapped out, we believe it will be important to always frame the design of mixed reality environments as the design of a social space first and foremost and to keep the uses of the technology simple so that the students and teacher can keep their focus on each other and their ideas.

8. Acknowledgements

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