Extended Embodiment: Physical and Conceptual Tools in a Mixed-Reality Learning Environment as Supports for Young Learners' Exploration of Science Concepts

Xintian Tu[1], Indiana University, tuxi@iu.edu
Chris Georgen[2], Boston University, cgeorgen@bu.edu
Joshua Danish[1], Indiana University, jdanish@indiana.edu
Noel Enyedy[3], Vanderbilt University, noel.d.enyedy@vanderbilt.edu

Abstract: Past studies have demonstrated the utility of embodied activity with mixed reality (MR) for young students' science learning. In this study, we integrate physical objects ("props") into the MR environment as additional sensemaking resources during full-body science learning activities. We analyze how the props complement and extend embodied activity as participants collectively organize, model, and discuss how water particles move during state changes. Students in a combined 1st and 2nd grade classroom (n=22) participated in a seven-day Science through Technology Enhanced Play (STEP) curriculum. We apply interaction analysis to offer a close look at how the students take up props in ways that complement their current embodied understanding of particles and extend their sensemaking to support new conceptual understandings. Findings demonstrate the potential of props as supplemental tools to support student sensemaking around challenging science concepts within MR environments.

Keywords: embodiment, science education, mixed reality

Introduction

In recent years, advances in motion tracking technology have led to an increased availability of applications that can leverage embodiment as an interface, and this has led researchers to explore new ways to leverage embodied learning in technology designs. There is widespread agreement around the importance of body in cognition and learning, previous studies in embodied cognition explored how body movement support the sensory and perceptual systems (Horn, Crouser, & Bers, 2012). Building on this, researchers have demonstrated the utility of embodied activity within mixed-reality (MR) environments that can provide visualizations and feedback in response to learners' embodied activity (Enyedy, Danish, Delacruz & Kumar, 2012; Lindgren & Johnson-Glenberg, 2013).

Theoretical framework

In this study, we build on theories of embodied cognition to explore how students take up and use props as sensemaking tools. Decades of research in the Learning Sciences and related fields recognize that learning depends, to some degree, on embodied interactions and experiences (Enyedy, Danish, & DeLiema, 2015). Broadly, embodied learning research suggests that cognition exists at the intersection between individual physical characteristics and movements and mental representations. On the one hand, this strand of research attempts to identify how the body shapes or provides access to some aspects of cognition. On the other hand, individual aspects of cognition exist in relation to sociocultural contexts. Across a wide range of contexts and social practices, research on embodiment in learning and social interaction demonstrate the central role the body plays in coordinating joint work (Goodwin, 2000; 2017). This collective dimension views the body as a locus in learning *across* people and tools within their environment. Taken together, this raises the possibility that embodied learning can be understood as situated across both individual and collective levels.

To investigate embodiment as both an individual and collective experience, this study draws on the Learning in Embodied Activity Framework (LEAF; Danish, et al., 2019). LEAF places explicit emphasis on the role of embodiment in learning by unpacking how the body both shapes and is shaped by collective activity. Positioned at the intersection of individual and collective activity in this way, LEAF builds on both individual approaches to embodied cognition that explore how mappings between embodiment and underlying concepts can support cognition (Lindgren & Johnson-Glenberg, 2013) and sociocultural frameworks for analyzing how embodiment is always situated in rich sociocultural contexts. To highlight the intersection between these individual and collective dimensions, LEAF also builds on activity theory (Engestrom, 1987) with a focus on two specific guiding principles. First, the unit of analysis is collective activity—defined by an activity system made up of individuals (the *subject*) who act in relation to a shared goal (the *object*). The relationship between individual actors and the shared goal is further mediated by the available *tools* (both physical and conceptual), *rules* for participation with the *community*, and *division of labor* that describe how distinct roles work together to make joint activity possible. Second, all embodiment is goal driven. Participants simultaneously embody actions toward their individual goal (e.g., moving fast because it is fun) and a collectively agreed upon goal, referred to as the object in activity theory (e.g., moving fast to represent gas).

Adding physical resources to Mixed Reality (MR) environments

The increasing prevalence of mainstream digital technologies such as the Microsoft Kinect that use physical activity as an interface into digital applications has made this kind of activity more accessible for many learners. In previous studies, we have found that a focus on mapping physical and digital actions helped us explore how intuitive embodied actions support learners as they interact with each other and the system within MR learning environments (Lindgren & Johnson-Glenberg, 2013). Moreover, we see this approach as an important step in identifying how the body plays a role in supporting sensemaking. In the present study, we focus on the Science through Technology Enhanced Play (STEP) platform, a mixed reality environment that leverages a student's physical action in space as a way of controlling a simulation (Danish et al., 2015). In earlier work (Enyedy, Danish, Delacruz, & Kumar, 2012), we found that learners construct meaning in a MR environment by laminating ideas and assumptions from a combination of physical materials, digital tools, and social dynamics. Our goal in the present study was, therefore, to attend to how different kinds of physical materials might play a role in supporting embodied activity by providing learners with cues as to how to act and interact within the MR space. A central aspect of mixed-reality learning environments is making salient to learners' how their actions influence the system (Rogers et al., 2002). Our experience is that it is quite intuitive for students to map their actions to the simulation, both because it happens in real-time, and because many of them are familiar with video game systems that rely on similar interfaces. However, we have sometimes found that students did not orient towards the aspects of the content that we wanted them to. For example, students might recognize quickly that the speed of their movement was important but did not connect that to how much energy they were expending. This led us to explore the possibility of new physical objects to help further mediate student learning within STEP.

Our goal in adding physical objects to the STEP environment was not simply to provide a tangible resource (Horn, Crouser, & Bers, 2012). Rather, we were hoping that the physical objects might help mediate learners embodied activities, helping them to orient their embodiment in new and powerful ways (Enyedy, Danish, Delacruz, & Kumar, 2012). We aim to explore how these objects might support or inhibit students' reasoning in ways that differ or align with other features of the embodied learning environment. In designing this study, our goal was to see how physical props might augment the already successful design of STEP (Enyedy et al., 2015). Therefore, we identified an important concept that has previously proven challenging for young learners: intermolecular attraction. Despite its foundational importance for understanding the particulate nature of matter, attraction is conceptually challenging for young learners. Therefore, we wanted to focus on the transfer of energy between particles, and how this energy influenced the behavior of individual particles and thus the states of matter being produced. We ask how different types of props mediate learners embodied and digital engagement in modeling in STEP as they learn about the transfer of energy between particles.

In this study, we pay attention to props as *tools* that mediate collective sensemaking within embodied activity. Through grounding our analysis in LEAF, we explore how props function to extend embodiment by shaping individual and shared goals within the activity system—opening collective activity to new forms of social interaction and conceptual understandings. The ways individuals might orient to a prop is shaped by both their individual experiences with its affordances and the shared goal of activity. For example, at first participants might view a bucket as a "hat" and place it on their heads as they move throughout the STEP simulation. However, given the collective goal of "taking away heat," buckets become bails to remove energy from the system.

Design

The STEP mixed-reality environment (Danish, Enyedy, Saleh, Lee & Andrade, 2015) uses Kinect cameras to track students' movement and transform it into the movements of particle avatars in a computer simulation that is projected on a shared screen (See Figure 1). As students move, they can see themselves as particles interacting and changing into different states of matter. For example, if the students stand relatively still and relatively close to each other, they will see mostly still particles forming ice. However, if they are moving quickly, they will see rapidly moving particles forming a gas.

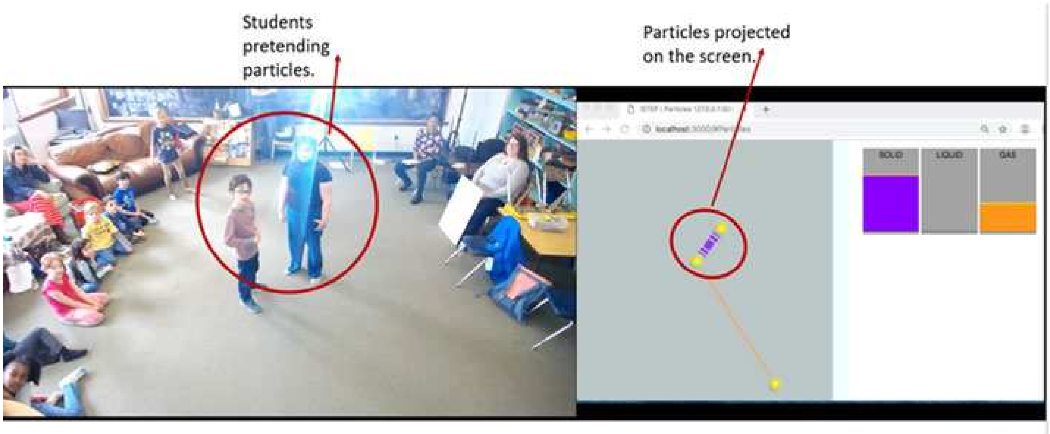

Figure 1. The STEP Environment: students act as particles (left), projection showing student-particles (right).

In the present iteration of STEP, we provided three different types of props to students within STEP in subsequent activities so that we could explore how they used these different props to engage with the content they were modeling within the STEP environment. These props were: 1) blocks that students used to “add” and “take” away energy from snowman in the simulation; 2) large foam “noodles” (pool noodles) and a bucket, that students used to “add” or “take away” energy from simulated virtual particles; and 3) pool noodles that students hold between themselves and their peers who were acting as other particles to represent bonds between particles. Our preliminary analysis indicated that the noodle on its own helped to constrain students’ embodiment in powerful ways that helped to highlight the attraction between particles. Therefore, the present analysis focuses on how this prop facilitated that process, and how it could then be removed while helping students to continue to explore the relationship even without the props.

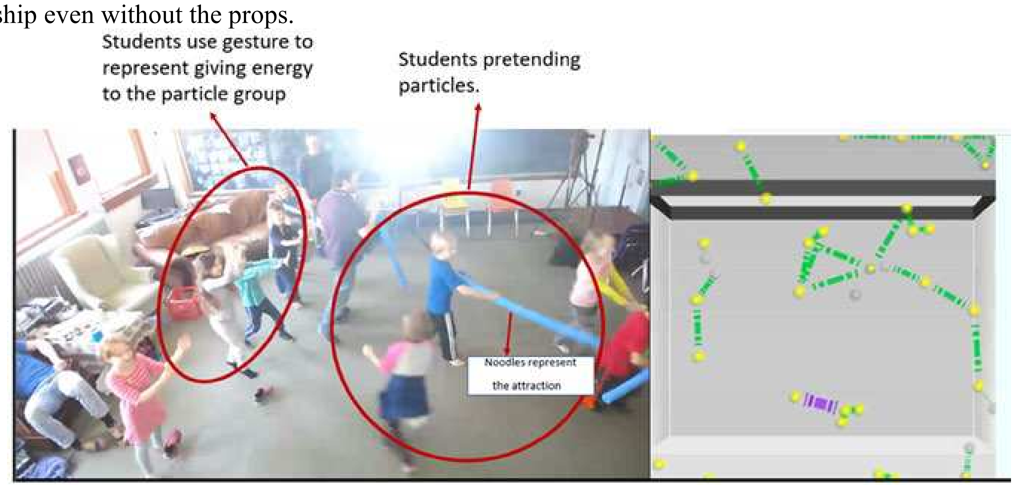

Figure 2. Students interacting with pool noodles in the STEP (left), projected screen showing students-particles (right).

Method

A single mixed-age classroom of 1st and 2nd grade students from a small mid-western city in the U.S. engaged in the seven-day STEP curriculum (n=22). Each session included 30 minutes within the STEP environment and 30 minutes of supplemental activities designed to let students continue exploring how particles behaved in a playful way such as rolling large dice with different states of matter and then play-acting those states. Changes in students’ understanding of the content was evaluated by 14 multiple choice questions that explored questions such as how particles move between one state and another (we used a modified version of the measure in our prior work, Davis, Tu, Georgen, Danish, & Enyedy, 2019).

All classroom activities were video recorded for later analysis. We used interaction analysis (Jordan & Henderson, 1995) to analyze students’ interaction with the STEP environment and props. First, we logged all videos to identify the major events, flagging the target content that was being discussed, and the primary forms of interaction. For the present analysis, we then reviewed the episodes tied to the use of the props and began to take notes generating hypotheses about how the props supported students' understanding of the content. We iteratively reviewed the video and refined these hypotheses. As we had hoped, students were able to explore the role of attraction as a result of their engagement with the noodles. So, students' interactions with the pool noodles became the ongoing focus of our analysis. Given our focus on attraction, the present analysis spans the three days that students were exploring the concept of attraction between particles in the classroom. On day 5, students were divided into two groups: energy source group and particle group. Then in day 6, students were pretending particles moving in different types of containers. Later, on day 7, a snowman was shown in the simulation. Students moved together to collectively represent the behavior of particles inside the snowman as it melted and reformed.

Results

Learning gains:

We ran a paired t-test on 14 items, there was significant improvement from the pre-test score (M = 5.5) to post score (M = 11.2), $t = -8.72$, $p < .01$. We also found the average score of the two items assessing attraction was improved from pre-test (M=0.59) to post-test (M=1.68).

Extended embodiment as a physical tool

On day 5, we introduced the concept of "attraction" between particles to students. Students were divided into two groups: 1) energy group and 2) particles group. Students in the energy group used their gestures to represent adding or taking away energy from the particle group, while particles group were holding pool noodles to represent the movement of particles, changing their behavior to reflect changes in their energy level as the energy group students gave them more energy or took it away. As we described the introduction, the pool noodles ultimately helped the students to re-orient their embodiment in a way that helped them to attend to how the states of matter are determined by interactions between particles, not by individual particles.

At the beginning of the activity, students noticed that particles with lower energy had thicker bonds (displayed in the visualization of attraction between the particles in the STEP interface). Bonds between particles in the simulation are also related to the positions and relative speed of particles, meaning that students cannot simply embody this relationship by themselves, but rather need to coordinate with at least one additional peer. Next, we introduced pool noodles to students as *bonds.* Initially the students held the noodles loosely while moving only slowly. In this moment, Calvin, the facilitator, asked "Do you think you can move if your bonds (pool noodles) are like that?" Then he suggested the energy group try "giving more energy to the particles group." Once they did, the particles group responded by pretending to turn from solid to liquid, by speeding up and running in the space. However, they quickly noticed that they had difficulty doing this because they were holding onto catch other's noodles, leading them to loosen their grip or let go entirely (see Figure 3). Henry, one of the students in particles group, mentioned that "it was faster, and our bonds were looser." The other facilitator, Joel, asked, "What happened to our bonds?" Henry answered, "It broke." The difficulty of holding onto the pool noodles while moving quickly helped students to realize that they couldn't both maintain stable, rigid bonds and speed up and move quickly around each other.

In the second round, the particles group and energy group switched their roles. This time the particles group tried another way of pretending to be particles in a gas. Sammy, a student, suggested "bumping into each other" to represent that gas particles moved fast and with no certain direction. With "bumping into each other" Sammy's group ran even faster than the first particle group, which led them to drop their noodles to ground. When James dropped his noodles, he called out "it's disconnected," and their teammate Mark, also used the word "disconnected". The concept of "disconnect" became a central concept of the group's reflection and explanation of why liquid particles are less attracted to each other, and thus could move apart and flow in ways that differed from solid particles.

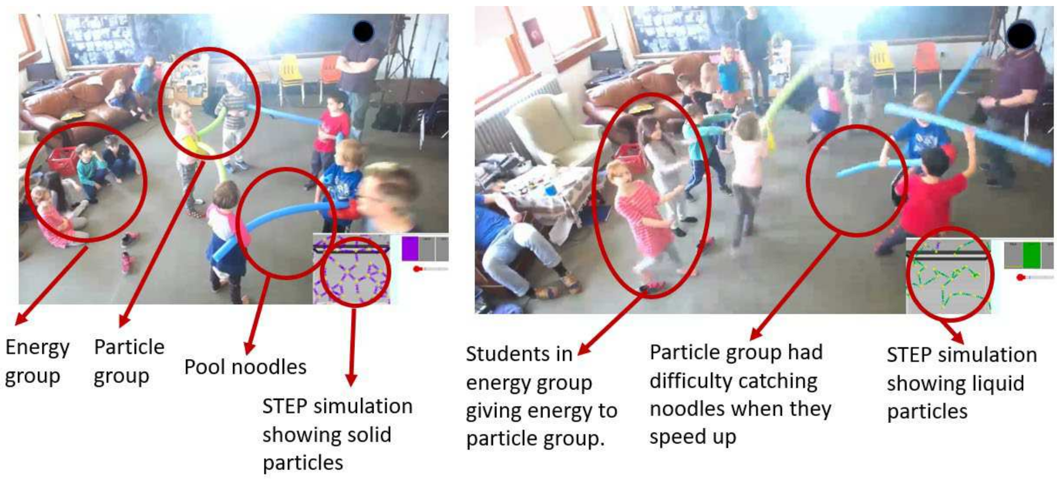

Figure 3. Student-particles in solid (left), student-particles in liquid having difficulty catching noodles (right).

After both groups interacted with the STEP environment, we invited them to sit down in the classroom and have a debrief session with Calvin. Calvin started with “remember we talked about the idea called attraction, what do we think about the attraction in solid?” Calvin had only mentioned the term “attraction” once before the students interacted in the STEP environment. This might be why there was a moment of silence with no immediate replies. However, later Calvin suggested students recall their experience with the pool noodles, and the students immediately answered with the term “lot of attractions” and “strong attraction”. In the transcript (See Table 1), it showed that students physical experience with pool noodles helped them to understand there were high attraction in solid, and attraction in liquid weren’t as stable as in solid. In Anna’s reflection, she talked about her experience as liquid particles holding pool noodles.

Table 1: Reflecting on attraction with props

1.	Calvin	Let's think about when we were holding our bonds when we were solid, do you feel like you were =
2.	James	Lot of ***attraction***
3.	…	
4.	Henry	Strong, strong ***attraction***
5.	Calvin	Yeah, strong. I'll call it a strong bond (visual representation in STEP simulation) and a lot *of* ***attraction***, those two things are related to each other. What does that mean for how our particles are behaving?
6.	Henry	they're ***vibrating*** a little bit
7.	Calvin	How about liquid? We said that liquid was medium energy. What does it mean for attraction?
8.	Anna	It's sometimes ***attracted*** and sometimes not.
9.	Calvin	Interesting, sometimes attracted and sometimes not. Can you say more about what do you mean?
10.	Anna	So like whenever it touches it connects, and whenever it *bumps into something else* then it ***disconnects and connects*** to that. and then if something else bumps and then it just stays there then it moves around on its own until it bumps into something else

Extended embodiment as a conceptual tool

Pool noodles offered an extension of students embodied understanding of attraction, which afforded opportunities to coordinate the digital bonds on the simulation, physical bonds represented by the pool noodles, and the embodied experience of being “connected” as particles. As participants recognize the pool noodle as a representation of attraction their individual embodied experiences of moving while connected helped build a collective experience (i.e., representing ice). This collective representation highlighted important relationships *between* particles. For example, to represent conceptualizations of different strengths of connection or how bond strength constrains possible arrangement requires more than a single particle. Our next goal was to help the students continue to reason about these relationships without the physical prop. Our hope was that students would continue to reflect on the underlying conceptual tools of attraction and bonds even when the physical tool was removed from the activity system. That is, while the physical tool no longer mediated the collective goal of representing ice, the conceptual understandings could shape how participants coordinated to meet the same goal. Removing the constraint of the pool noodle, and thus re-mediating the activity, required that the participants develop new ways of moving or coordinating to meet the representational goal.

Day 6 began with a discussion of magnets to help students reflect on how the particles might affect each other even at a distance, without a direct physical connection as simulated by the noodles. Participants held two magnets at a distance to notice the force as they came closer together. With the magnets stuck together, participants could consider what it would take to break the magnets apart, highlighting the relationship between distance, attraction, and energy. STEP activity begins with one group of participants in the simulation as particles in a snowy field and the other group outside the simulation as observers. Calvin, a facilitator, orients the particles attention to the screen, "Okay, particles, let's make an observation of where we are right now." In this moment, Calvin gives the particles the shared goal of making ice. Immediately, four of five participants begin to assemble into the arrangement from the previous day. In lieu of pool noodles, the participants reach out and hold hands to make the connections between particles rather than using noodles. This new arrangement meets the shared representational goal through establishing a physical connection between particles in the familiar arrangement. In Figure 4, we're showing a segment that students trying to present particles in solid.

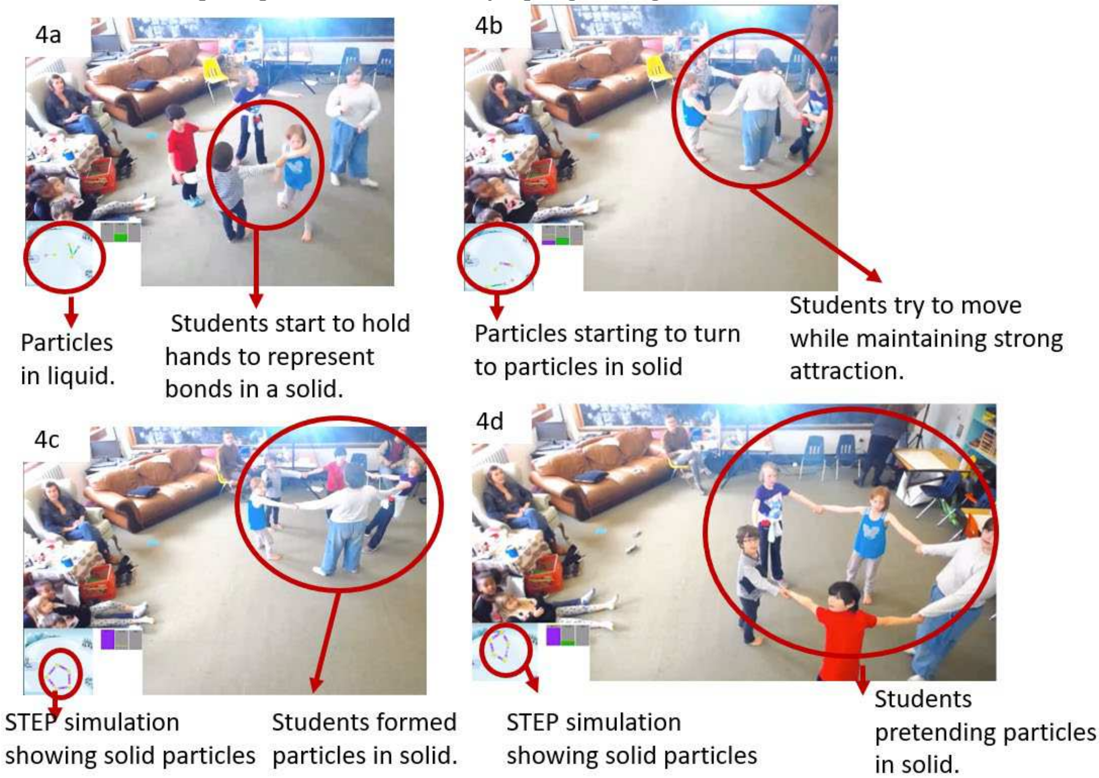

Figure 4. Students trying to represent particles in solid.

Calvin noticed that one participant, Miriam, elected to run around the room and asked, "What setting are we in Miriam?" Miriam responded, "We are in a snowy setting." Miriam was then invited into the arrangement of particles with the outstretched hands of two other participants. At this point, the particles have arranged in a connected circle but still move in place—wiggling their bodies and waving their arms (Figure 4a). Noticing this movement, another facilitator, Alice, asked Henry, a particle in the simulation, "Why are you moving like that?" Henry responded, "I think it makes us (.) it gets us (.) if we stop moving, we won't become solid particles." In this interaction, Alice drew attention to a key conceptual understanding of solid particles (they are stationary but move, i.e., vibrate) by highlighting individual dimensions of embodiment. However, the individual goal of remaining in movement conflicted with the shared goal of remaining connected and in arrangement. Therefore, many attempts to move in space lead to breakdowns and reorganizations (See Figure 4b). However, one attempt leads to a new arrangement that meets the shared representational goal, clear by the results on the shared simulation screen.

As the particles explore different ways of moving while remaining connected, one particle, Lizzie, proposes they "stretch apart." Lizzie stepped backward, putting as much space between each particle as possible while remaining connected to create an expanded circle (See Figure 4c). This new arrangement was displayed on the simulation as stable solid bonds, which was praised by facilitators and observers for accomplishing the shared representational goal. Moments later, Calvin changed the background to a lake, prompting the particles to collectively represent water, followed by a desert prompting the particles to chaotically run around the room as gas. Calvin then changes the simulation background to snow, which the participants notice and quickly return to their previous formation of an extended circle (Figure 4d). Within this new representational infrastructure (fully extended arms in a circle), Alice built on their current understandings of attraction as it relates to the distance of the particles (See Table 2).

Table 2: Reflecting on attraction without props

1	Alice	Originally, we thought we had to be super close to be solid and a little further to be liquid, but now what are we noticing? What are we noticing about the distance?
2	Lizzie	You have to be a little further apart to be solid.
3	Alice	So solid particle have to be farther apart and this is something that can be kind of tricky just with water. Because water when it turns into ice the bonds are so strong that they can't bend. So if we think about being solid with really strong ice bonds
4	Calvin	You can't bend your arm at all
5	Alice	Can I get super close to Lizzie, if I am not allowed to bend my arm?
6	Henry	Then she would bend her arm.
7	Alice	Right, what if she can't bend her arm and both of us have to be super strong. Can I even get close to her if my bonds are super strong? So solid particle bonds are so strong they actually push the other particles away.

On Day 7, we aimed to help students connect the micro-level behavior of particles to the macro-level changes in states of matter. In this activity, we projected a snowman on the simulation. Thus, we removed another series of sensemaking tools (digital particles and bonds shown on the screen) to prompt students to again reorganize their collective activity. Students were asked to act out the behavior of the particles inside the snowman corresponding to the changes in the snowman's status (e.g., moving faster and loosening interconnections as the snowman appeared to melt). Here, the facilitators offered no suggestions of movement to students, opening the activity so that students could choose any embodied movement to represent particles in different states of matter. We found that when the facilitator asked about the particle's behavior, students would first change the way they hold their hands and answered with the "bond" behaviors. For example, when Calvin asked the students "how would we show liquid," the students immediately answered with "a little less weak bond." As students continued to interact and discuss in response to the melting or forming snowman, holding hands to represent the attraction remained as a key representation particles behavior. This suggests that the students likely saw some value in holding hands when representing attraction, and thus continued to employ this behavior while working toward new shared representational goals.

Conclusion and significance

By adding props to the STEP environment, we found that physical objects serve as both physical and conceptual tools for young children to explore complex science concepts in MR environment. At first, digital visualizations in the MR environment (such as colored bonds between particles) did not directly shape students embodied interactions. However, as we introduced props as representations of the connections between particles, students began to explore both the physical and conceptual connections between the physical world to the STEP environment. As a physical tool, pool noodles offered students the opportunity to experience the connection between particles. After establishing this physical tool as a meaningful feature of the shared representation, students were able to use this experience to explain their understanding of attraction between particles. After this shared and extended embodied experience, “being connected as attraction” became a conceptual tool for the students, although they no longer had access to the physical reminder of the noodles. Therefore, to reconstruct the conceptual space, students used their arms and hands to connect themselves to other students in order to show various degrees attraction across the states of matter. We believe that this work demonstrates the importance of offering both multiple forms of embodied experiences and opportunities to help students translate those experiences to concepts such that they can continue to reason with the ideas represented by those physical constraints even when they are absent.

References

Danish, J. A., Enyedy, N., Saleh, A., Lee, C., & Andrade, A. (2015). Science Through Technology Enhanced Play: Designing to Support Reflection Through Play and Embodiment. Paper presented at the Exploring the Material Conditions of Learning: *The Computer Supported Collaborative Learning (CSCL) Conference*, Gothenburg, Sweden.

Danish, J., Enyedy, N., Humburg, M., Davis, B., & Tu, X., (2019) Collective embodied activity and how different concepts map to social exploration. In Lund, K., Niccolai., G., Lavoue, E., Hmelo-Silver, C., Gwen, G., & Baker, M., (Ed.), *A Wide Lens: Combing Embodied, Enactive, Extended and Embedded Learning in Collaborative Settings:* The 13th International Conference on Computer Supported Collaborative Learning (Vol. 2.). Lyon, France: The International Society of the Learning Sciences.

Davis, B., Tu, X., Georgen, C., Danish, J. A., & Enyedy, N. (2019). The impact of different play activity designs on students' embodied learning. *Information and Learning Sciences*.

Enyedy, N., Danish, J. A., Delacruz, G., & Kumar, M. (2012). Learning physics through play in an augmented reality environment. *International Journal of Computer-Supported Collaborative Learning, 7*(3), 347-378.

Enyedy, N., Danish, J. A., & DeLiema, D. (2015). Constructing liminal blends in a collaborative augmented-reality learning environment. *International Journal of Computer-Supported Collaborative Learning, 10*(1), 7-34.

Horn, M. S., Crouser, R. J., & Bers, M. U. (2012). Tangible interaction and learning: the case for a hybrid approach. *Personal and Ubiquitous Computing*, *16*(4), 379-389.

Jordan, B., & Henderson, A. (1995). Interaction analysis: Foundations and practice. *The journal of the learning sciences*, *4*(1), 39-103.

Lindgren, R., & Johnson-Glenberg, M. (2013). Emboldened by embodiment: Six precepts for research on embodied learning and mixed reality. *Educational Researcher*, *42*(8), 445-452.

Goodwin, C. (2013). The co-operative, transformative organization of human action and knowledge. *Journal of pragmatics*, *46*(1), 8-23.

Goodwin, C. (2017). *Co-operative Action*. Cambridge: Cambridge university Press.

Paik, S. H., Kim, H. N., Cho, B. K., & Park, J. W. (2004). K-8th grade Korean students' conceptions of ‘changes of state’ and ‘conditions for changes of state’. *International Journal of Science Education*, *26*(2), 207-224.

Rogers, Y., Scaife, M., Gabrielli, S., Smith, H., & Harris, E. (2002). A conceptual framework for mixed reality environments: designing novel learning activities for young children. *Presence: Teleoperators & Virtual Environments*, *11*(6), 677-686.

