Exploring Multimodal Scaffolds Supporting Middle School Students' Construction of Causal-Mechanistic Scientific Explanations

Nitasha Mathayas and David E. Brown
mathaya2@illinois.edu, debrown@illinois.edu
University of Illinois at Urbana-Champaign

Abstract: Computer simulations help students visualize abstract scientific concepts. Yet their effectiveness depends upon the kinds of supports students receive. In this study, we explore the verbal and gestural supports we provided to students as they viewed a computer model of molecular conduction and constructed causal-mechanistic explanations for heat transfer. Using a complex systems and embodied approach to students' conceptions, we conducted a cross-comparison case study of four students' experiences with the simulation. By comparing students with richer scaffolding interactions to those with weaker scaffolds, we found that directing student attention towards causal elements in the simulation along with requesting them to gesture about the function of those elements helped students develop sophisticated explanations. We describe these cases and reveal ways these scaffolds can and cannot be enacted with the simulation. Implications for instruction and future work are described.

Introduction

In the United States, constructing causal explanations is one of the eight essential practices listed by the Next Generation Science Standards (NGSS Lead States, 2013). Computer simulations can help students to visualize hidden and unobservable elements underlying several physical phenomena, such as the motion of air molecules causing pressure or the function of light rays in the working of mirrors, the formation of shadows, and in the occurrence of seasons. Moreover, with technological advancements providing immersive experiences for learning (Lindgren & Johnson-Glenberg, 2013), students can partake in abstract scientific concepts in embodied ways where they can physically enact the behaviors of unobservable elements (e.g. Johnson-Glenberg, Birchfield, Tolentino, & Koziupa, 2014). However, the effectiveness of a simulation depends upon several factors such as the kinds of support provided to learners, the design features of the simulation, and the role of the teacher in guiding students through the simulation (Smetana & Bell, 2012). Hence while immersive technologies continue to advance into the educational sphere, understanding the role of facilitation with and without technology is still a priority. In this sense, our work is aligned with the goals of this conference where we are developing gesture-augmented computer simulations that support the construction of causal-mechanistic explanations (Braaten & Windschitl, 2011), while also examining how we can facilitate conceptual engagement using these simulations.

Our research is part of a design-based research project developing gesture-enhanced simulations about heat transfer, air pressure, and the causes of the seasons over the course of four years. In the first year, we explored how students engaged with a mouse-controlled computer simulation that depicted a molecular model of heat transfer. We observed how students naturally gestured during their explanations and we explored different ways we *scaffolded* (Wood, Bruner, & Ross, 1976) the development of these explanations. The analysis of this data was then used to develop gestures that supported students' scientific explanations in the successive years where a gesture-enhanced simulation was used. In this paper, we focus on different ways we supported student interactions with the mouse-controlled computer simulation, and we examine how our interactions with students helped them use relevant ideas from the simulation to construct scientific explanations of heat transfer. Our research questions are: (1) Did students' explanations improve after they interacted with the computer simulation? And (2) How does multimodal (i.e. verbal and gestural) scaffolding influence student construction of causal-mechanistic explanations?

Theoretical orientation

Students' conceptions in science

Brown (2014) has proposed that knowledge is a complex system composed of a large number of knowledge elements that are dynamically interacting with one another. Conceptions are structures that emerge from the dynamics of this system, and stable conceptions are robust structures that persist through changes in the system. There is also mounting evidence that scientific concepts are grounded in embodied schemas (Amin, Smith, & Wiser, 2014). Our sensorimotor perceptions inform and intuitively guide conceptual development. This perspective implies that learning is a dynamic, evolutionary and nonlinear process where conceptual structures are embedded in larger knowledge systems involving both perceptual and mental states.

Embodied cognition

Research in cognitive science, MRI scanning, and psychology has shown that human cognition has deep roots in sensorimotor processing (Wilson, 2002). Barsalou (2008) described cognition as grounded in "simulations, situated action, and on occasion, bodily states" (Barsalou, 2008, p. 619), in which the brain's modal system for perception (e.g. vision, audition), action (e.g. movement) and emotion are involved in the formation of a mental simulation. In addition, Smith (2005) described cognition as a complex dynamic system where "intelligence emerges in the interaction of an organism with an environment and as a result of sensory motor activity" (Smith, 2005, p. 278). Consequently, conceptions are hypothetical entities representing stable states of a dynamic system. These stabilities emerge from the dynamic coupling of the body with the environment, and stable states gain resilience when corporal modalities are synergistically linked with each other and with the physical event experienced at that moment in time.

Applying ideas from both domains, we think of students' explanations as dynamic constructions in which prior knowledge and sensorimotor experiences contribute to the dynamic formation of a conception. For instructors supporting students during their active construction of mechanistic explanations, scaffolding that addresses embodied resources and integrates multimodal representations can be particularly fruitful in fostering stable scientific conceptions. However, this perspective does not explain what scaffolds look like in instruction, or how, and when they should be implemented. Taking Wood, Bruner, and Ross's (1976) notions of *scaffolding functions* as a guiding principle for this study, we conducted a preliminary investigation about the role that scaffolding played when we facilitated students' use of gestures and a computer simulation while constructing causal-mechanistic explanations. We identify these scaffolding moves in this paper and describe the multimodal nature of these scaffolds.

Methods

For this study, we conducted a collective case study (Creswell, 2013) using select student interactions with the computer simulation. In this method, multiple cases are examined to better understand the phenomenon or event. While there is redundant information across the cases, this redundancy is either used to draw more compelling arguments (Barone, 2011), or it is used to investigate the nuances between cases that leads to a better understanding of the phenomenon. We applied the latter meaning in our work, where we examined four students to better understand how scaffolding interactions in some cases led to complete causal-mechanistic explanations, while other interactions led to partial explanations. In the following subsections, we describe the context of the study and how our cases were selected.

Context

In the first year of the larger project, the team of researchers interviewed 36 middle school students (grades 6 to 8) from the surrounding public schools of a large Midwestern University in USA about their understanding of three scientific phenomena: thermal conduction, air pressure, and the cause of seasons. Of these, 24 students (15 boys and 9 girls) were interviewed on the topic of thermal conduction. The interviews were designed to be semi-structured with three general phases: before, during, and after viewing a computer simulation depicting a molecular model of thermal conduction. Following are details of the conductive heat transfer interviews.

Interview structure

Phase 1

The interviewer introduced a silver spoon partially immersed in a cup of hot water and let the student experience heat transferring along the handle of the spoon. The student was then prompted for an explanation of how the handle of the spoon got warm even though it was not in contact with the hot water. In cases where students were not thinking of a molecular model of the spoon, the interviewer suggested that they consider a zoomed-in view of the spoon. Hence, the first phase of the interview involved exploring students' initial explanatory ideas of heat transfer.

Phase 2

The interviewer showed students a simulation depicting two blocks of molecules vibrating at different temperatures (Figure 1a). The purpose of showing this was to prompt students to think in terms of dynamic molecular structures of solids at different temperatures, and to understand that molecules vibrate more at higher temperatures. The second part of the simulation depicted these blocks connected to each other through a bar of molecules (Figure 1b). This simulation started out with the left block of molecules at a higher temperature than the right block, but when played, vibrating molecules on the left side collided with adjacent molecules in the bar prompting them to collide into their neighbors causing a chain reaction of molecular collisions to spread to the right block of molecules. This made the right block of molecules vibrate more making the temperature gauge on the right rise until the system achieved equilibrium. In this phase, the interviewer was prepared with prompts to guide the development of causal-mechanistic explanations. These prompts involved helping students connect representations of temperature with molecules, asking for predictions before the simulation was played, prompting students to use their hands to represent the movement of molecules, and making connections between the simulation and the spoon. In this exploratory phase, the interviewers added other forms of questions that they thought would help students. These explorations are included in the analysis of this study.

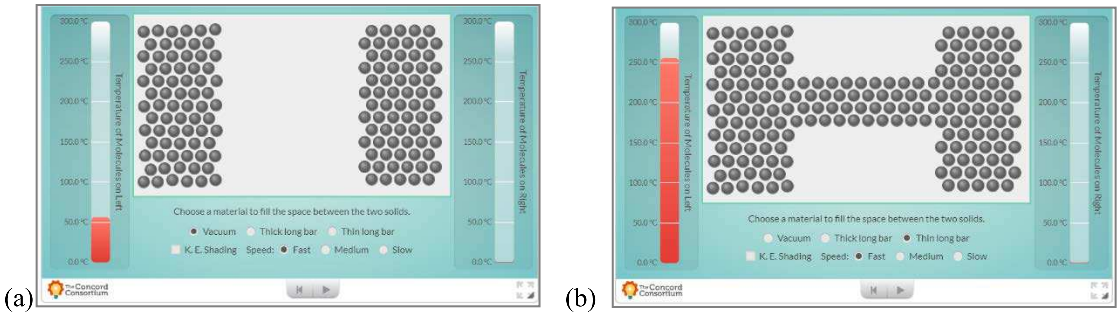


Figure 1. (a) Blocks of molecules at different temperatures. (b) Blocks linked through a thin bar of molecules.

Phase 3

The interviewer closed the simulations and asked again how the handle of the spoon got warm. After students attempted their first explanation, the interviewer explored different prompts to help students recall important features from the simulation including gestures they had previously used, and then had them reexplain the phenomenon using their new tools.

Analysis

Each interview was video recorded and edited to include the screen capture of the computer simulation used in the interview. These edited videos were then transcribed and used for analysis. First, we segmented each student interview based upon scaffolding prompts included in our interview protocol. These moves are: asking for predictions (IP), testing the phenomenon (TRY), suggesting molecules (MG), requesting a drawing (DRAW), showing simulation Figure 1a. (S1), showing simulation Figure 1b. (S2), requesting for an explanation post-simulation (Post-Sim), requesting to show what you mean (SHOW), requesting to show how the phenomenon occurs (SHOW:X), using hands to represent a part (SHOW:PART) of the phenomenon, reifying student (SHOW:ST) gesture, and prompting student to use the interviewer's (SHOW:INT) gesture. When the interviewer employed one of these scaffolds, we marked this time in the transcript as the start of a new segment. While most of the scaffolds were used sequentially in each student interview, some scaffolds were more flexible (such as SHOW) and were used at different times, while some (such as DRAW) were not used at all. Thus, each student's interview is composed of the three phases described previously, but is a unique sequence of segments within the phases.

Next, we constructed a target causal-mechanistic explanation of heat transferring through the spoon, parsed this explanation into six main explanatory elements (Mathayas, Brown, & Lindgren, 2016), and then coded interviews for the presence of these elements. Interrater agreement for this coding was 91.8 percent. Finally, we organized the codes into a scoring scheme that emphasized increasing causal power of an explanation using a combination of the elements. The description of each score is in Table 1. A Wilcoxon's signed ranks test was applied to check for significant differences in scores before and after the intervention. These scores were also traced over the course of a student's interview to create charts depicting their evolving explanations. By the end of this process, we had 23 Explanatory Expression Charts that depicted each student's evolving explanations about heat transfer in a spoon (one student's interview was incomplete and was left out). Based on the results from this analysis, we selected cases for a closer inspection of scaffolding described next.

Table 1. Scoring scheme

Score	Level of target explanation the student communicated

1	The spoon has molecules
2	Molecules of the spoon are in a rigid-structure and are position-dynamic
3	All of the above and molecules can interact and influence one another
4	All of the above and molecules wiggle more at a higher temperature
5	All of the above and faster wiggling molecules collide with slower wiggling molecules making them move more.
6	All of the above explained as a chain reaction along the length of the spoon

Findings

The Wilcoxon's signed ranks test revealed that students' Post-Simulation Scores were significantly higher than Pre-Simulation Scores ($Z = 171$, $p < 0.001$, $W = 0.783$). We also conducted this test to check for the effect of the simulation and found that During Simulation Scores were significantly higher than Pre-Simulation Scores ($Z = 185.5$, $p < 0.001$, $W = 0.661$). Therefore, in response to our first research question, students' causal mechanistic explanations improved after using the simulation. However, we noticed that half the students obtained a full score in the post-simulation phase, while the other half reached a score of four or below. Therefore, to respond to our second research question, we selected four students that were representative of this division. On taking a closer look at student scores, we noticed that there were similar forms of unplanned moves that interviewers used that were not captured in the charts, but these questions were asked in different ways for these four students. Thus, these students were selected for a cross case comparison study driven by the theoretical orientation of conceptions as dynamically emergent structures with embodied sources. The student transcript, drawing, video recording, coding, and graphs were all used to analyze the interactions.

We now report on our analysis of Andrew, Eric, Irene, and John (all names are pseudonyms). Andrew and Irene gave a full causal mechanistic explanation by the end of their interviews, whereas Eric and John gave partial mechanistic explanations. We begin with Andrew who had the richest scaffolding with the interviewer followed by Eric, who had the least scaffolding of the four. We then visit Irene, who had a variation of Andrew's interaction, and then John who had a lesser level of scaffolding compared to Irene. As we move through each focal student in this section, we begin with a brief description of each student's growth on the charts. The focal student description will introduce their explanations and then delve into their responses to interviewer prompts while interacting with the simulation. Each focal student description will conclude with a summary of the main scaffolds used in that interaction.

Andrew – Full explanation, rich and varied intervention

Figure 2a represents Andrew's evolving explanations while viewing the simulation. While he was scored low before he watched the simulation, there is considerable growth depicted in the graph around when he watched the second half of the simulation (Figure 1b). Before viewing the simulation, Andrew attributed heat transfer to a substance flowing through the spoon. He expressed this idea in a drawing where heat molecules travelled over the length of the spoon. However, when he watched the simulation, he expressed this notion of travelling again although the molecules in the simulation do not physically travel. The interviewer intervened at this point by replaying the second half of the simulation with a new question. An excerpt is shared below. These transcripts are partially edited to include relevant interactions, and the speaker's gestures are included in parenthesis.

Interviewer: Now remember that scientists think of temperature as how fast the molecules wiggle (raises both hands as fists and wiggles them), and so thinking about just the molecules themselves wiggling, how does that fast wiggling over here, on the left, make these molecules (points to molecules on the right of the simulation) wiggle fast?

Andrew: It's almost like, it's like a chain reaction. So, like the wiggling there (points to the hotter block of molecules on the left of the simulation). They're wiggling, they're bumping into each other, which makes them bump into that (points to the connecting bar) and travels all the way over to the handle side. (uses right hand to chop the air three times while moving to his right).

Interviewer: Okay. Can you show how that works?

Andrew: Um, let me think about it, so…I don't know how to show it.

Interviewer: Can you maybe use your hands to represent the molecules and show how the molecules on the left make the molecules on the right wiggle faster?

Andrew: So, what's happening is this hand is the molecules on the left (opens left hand up). and this is just going to be the spoon part (opens the right hand up next to the left with finger wiggling). So, they bump into each other (bumps both hands together), so this side (indicates left hand) is just bumping, they're all bumping into each other (wiggles fingers and touches them) and then since the spoon part is right there (indicates right hand) it bumps into those molecules here (bumps left hand's fingers into the right), which then if I move over (shifts both hands a little to his right), this (left hand) becomes the middle and that becomes the left (right hand) bumps into that side, making them keep wiggling (circles index fingers around each other).

In figure 2a this interaction occurred from where Andrew scored a 6 at S2 up to SHOW:PART. On examining this interaction from an instructional perspective, we see the interviewer making multiple pedagogical moves. First, he directly instructed Andrew about the relationship between molecular movement and temperature. He referred to the scientist's notion of temperature to give his statement more authority. However, this instruction was meant to remind Andrew of information they had already established at S1, thus we do not consider this move as didactic, but a way to return Andrew's conceptual trajectory towards target concepts he established during S1. The second move was to refocus Andrew's attention to the wiggling of a single molecule. The interviewer achieved this using both speech and gestures, and thus redirected Andrew away from flow-like mechanisms to particulate mechanisms. Third, we see a causal question targeting molecules and their agency in effecting movement in other molecules. By asking "how does the wiggling on the left, make the molecules on the right wiggle more?" we see the interviewer leveraging the current focus on wiggling molecules into thinking about causes and effects. Andrew responded by using the simulation to build a causal explanation. However, this interaction does not end there, the interviewer executed two more moves related to the use of gestures. The first request was to use gestures generally to describe a chain reaction, but with Andrew expressing his struggle, the interviewer then grounded the question in the motion of molecules by specifying that Andrew gesture about the motion of molecules. This appeared to be fruitful for Andrew, who then described a chain reaction of collisions in both speech and gestures. In terms of our theoretical lens, we think this move helped reinforce Andrew's current thinking beyond what would have occurred had he merely stated it. Since he used both speech and gestures synergistically to describe the molecular collisions, we think that the interviewer's move was perfectly timed to help synthesize the new perspective Andrew had taken.

Summarizing this interaction, we see five scaffolds occurring in this interaction which are: 1) providing direct instruction about mutually established facts, 2) refocusing student attention to the movement of molecules, 3) causal questioning, 4) request to gesture to explain, and 5) request to represent molecules with hands to explain. We now consider these moves in the interactions that other students experienced.

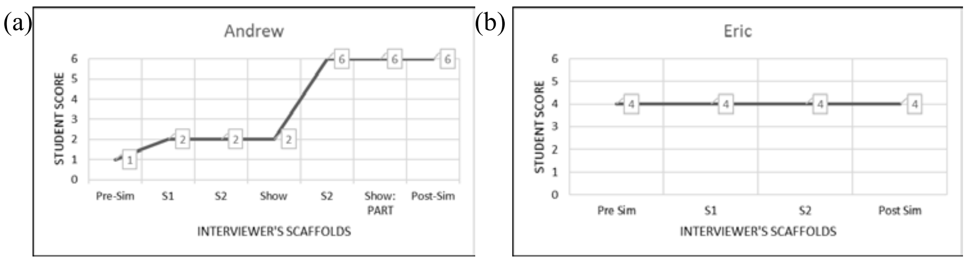


Figure 2. (a) Andrew's scores in response to interviewer scaffolding. (b) Eric's scores in response to interviewer scaffolding.

Eric- Partial explanation, minimal intervention

Eric's scores while watching the computer simulation (Figure 2b) appear unchanged across his interview. He expressed a molecular description of heat before watching the simulation, but he was scored for a partial explanation because he did not attribute causation to molecular collisions but to friction. As he watched the first part of the simulation, his explanation changed into a description of heat as molecules vibrating faster. Next, Eric needed to realize how molecular vibrations made the other molecules move. However, here we share what occurred when the interviewer used only planned scaffolding moves.

Interviewer: What I'm going to do is pause this for a moment, and I am going to connect these (clicks on connecting bar on the simulation), imagine that this is like, if this was the bowl part of the spoon on the left and if this was the handle part that now we have more metal of the handle connecting them. So, what do you think you're going to see now when I hit play?

Eric: The left are there vibrating, and they also go through the metal until it will go through the metal until it reaches the right.

In this segment, we see that the interviewer followed the prompts from the interview protocol where he established the link between molecular representation and the silver spoon and asked for a prediction. In response, we find that Eric's prediction is a partial explanation that he maintained after he watched the simulation, and again post-intervention. Even when the interviewer played the simulation for him, he repeated his response, clearly not seeing the molecules influencing the movement of other molecules in the simulation. We think that Eric's prediction influenced what he noticed in the simulation and thus prevented him from noticing collisions. In terms of scaffolding, the interviewer's moves directed Eric to use the simulation as a source for confirming his conception. No other prompts were used to direct him to use the simulation as a resource for constructing a new explanation. We think that this case provides a useful baseline for considering the effects of the other scaffolds. For example, viewing these prompts in contrast to the scaffolding Andrew received, we find that none of the five moves used with Andrew were used here. The two moves used here were 1) to establish the link to the spoon and 2) to ask for a prediction. Andrew received these two moves as well, but developed significantly with the other five moves. Thus, we are even more convinced of the need to focus student attention to single molecules moving, and to cue students to think causally.

Irene – Full explanation, partial and multiple interventions

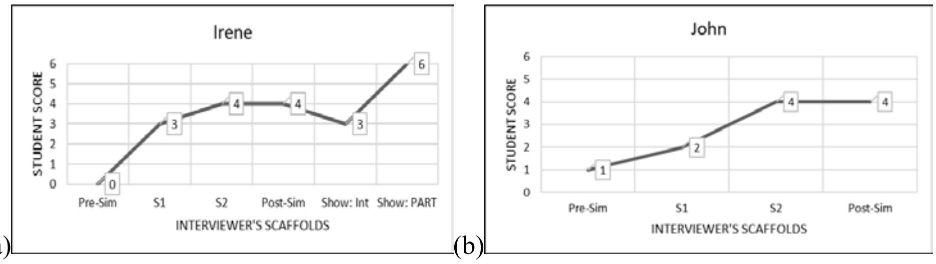
We turn to Irene to further investigate these scaffolds. We see that she did not achieve a full score during the simulation, but she did so after more interactions with the interviewer post-simulation. Since these scaffolds were similar in form to Andrew's questions we share her interview to explore how these scaffolds were enacted in a different way for her. On examining the interaction with the simulation playing, Irene was asked to describe what she noticed. Once again, she did not notice molecular collisions, but she noticed increased wiggling and the changes in the temperature gauges. At this point, the interviewer intervened with a question resembling one of Andrew's questions.

Interviewer: So maybe look at one of the molecules over here (points to the left block of molecules) and try to see, what do you think is making these molecules over here (wiggles the mouse pointer over the right block of molecule) start to move faster?

Irene: This side (points to the left block) is like pushing them (shifts index finger sideways a few times towards the right block) to the other side so like this side can start to move (points to the right side).

This is a new conceptual observation for Irene that we think was triggered by the interviewer's question. In this case we see that the interviewer refocused Irene's attention towards a single molecule. He then followed up by directing her attention to the causal agency of molecules by asking her "What is making these start to move faster?". We get a more causal-mechanistic response from Irene where she attributes molecular *pushing* as the cause of more movement. However, unlike Andrew, no further moves were made to reinforce this revelation, and given that her post simulation explanation is only partially complete, this idea was apparently not fully taken up by Irene. However, on looking beyond the simulation, we noticed the interviewer followed up on her explanation by requesting that she gesture about molecules in two ways. In the first way (marked as SHOW:INT in Figure 3a) the interviewer asked her to close her fist to embody a molecule and asked her the causal question regarding temperature, i.e. "Show me how the hot part makes the cold part hot?". Irene responded to this question by describing how dipping her hand in hot water made it hot, and she described increased molecular movement due to heat. Then the interviewer made a second request (marked as SHOW:PART in Figure 3a) and used his fists to represent molecules with one side wiggling faster than the other, and asking her specifically to describe using her hands how the cold molecules moved faster as the hot molecules bumped into them. Irene adopted this gesture and represented two molecules, one hand as a faster wiggling molecule bumping into a stationery colder molecule, while attributing causation to the movement by stating that "the warm molecule goes and hits the cold molecules, and they both move at the same time".

In summary, four scaffolds occurred in this interaction. 1) refocusing student attention to the movement of a single molecule, 2) causal questioning, 3) request to gesture to explain, and 4) request to represent molecules with hands to explain. Comparing this to Andrew, we see that all four were used in his interaction as well. Thus, we see an increased value in providing students context-specific gestures (such as a wiggling fist to represent a molecule) and cueing the mechanism through the use of their fists as important embodied resources that can strengthen their understanding of the molecular mechanisms. Next, we consider these moves again with John.



(a) (b)

Figure 3. (a) Irene's scores in response to interviewer scaffolding. (b) John's scores in response to interviewer scaffolding.

John-Partial explanation, partial intervention

We bring up this final case to share the nuances of scaffolding that appeared to resemble the previous cases but did not lead to similar results. In John's case, the interviewer maintained focus on molecules but performed these moves before she played the simulation. We share a segment of this interaction where John is asked for a prediction before viewing the simulation.

Interviewer: What do you think would happen once I connected a bar of molecules in the middle over here? Between the hot and the cold?

John: I think that all of the hot would get stuck on each of the cold eventually heat it up. (indicates the left block moving towards the right block).

Interviewer: But you said that heat was also the moving molecules so, are the molecules doing anything to each other?

John: No. It's just the heat because when there is no heat it stays still. So, when there is heat added, the molecules move. So once the hot part of the molecules touch the cold one, it will eventually move the molecules.

Interviewer: (plays simulation and John watches it intently).

John: So, like I said. Um, kind of. Like that side (points to the left block) is moving a lot more. But, they are kind of getting, slower and slower (shifts hand along the connecting bar). But, the heat is also touching this (points to the right block), which is kind of rising there (points to the right thermometer) which is also moving it.

In this interaction, we see evidence of a few familiar moves. First, much like in Eric's case, the interviewer asked John to make a prediction. He responded by claiming that when the blocks touched, heat would transfer over to the cooler side. Then, the interviewer reminded him of the movement of molecules, a fact they had established at S1, and directed John's attention to them by asking the causal question "are the molecules doing anything to each other?". However, John merely claimed that they would wiggle the same way he had observed during S1. Thus, the interviewer used three scaffolds in this segment. 1) To ask for a prediction, 2) to refocus student attention to the movement of molecules, and the 3) to ask a causal question. These scaffolds are the same moves that were used with Andrew and Irene with the difference being that John was not asked to gesture. However, on examining this case, we think that these three scaffolds did not appear to be asked at the right time. In Andrew's and Irene's case, these moves were asked with reference to events occurring in the simulation. They were not questions investigating the student's conceptions. On the other hand, in John's case, these questions were directed at his current conception which was that heat is a substance that travels through the molecules making them wiggle more. Therefore, much like Eric, John was not directed to use the simulation as a constructive resource for developing an explanation. It seemed to be used as a resource to confirm his current explanation.

Discussion

When we review how we facilitated student interactions with a computer simulation, we noted seven unique scaffolds asked across these students. They are 1) establishing the link to the spoon, 2) asking for a prediction, 3) refocusing student attention to the movement of molecules, 4) causal questioning, 5) providing direct instruction about mutually established facts, 6) requesting for gestures to explain, and 7) requesting to represent molecules with hands to explain. Andrew was asked all seven questions, followed by Irene who was asked six. John was asked three of these questions while Eric was asked two. However, we do not think that a higher amount of scaffolding led to sophisticated student explanations. These cases revealed that these moves are time and context dependent, and that changing the order of questions did not lead to better explanations. For example, John was asked causally about molecules, just like Irene. However, since his questions were asked before the simulation was played, they did not have the same effect for him as it did for Irene. Moreover, we found that requests for gestures were productive for Andrew and Irene where not only did they ground the molecular motion in gestures, but they reified the causality of molecular collisions by helping students reflect on their ideas after viewing the simulation. This work shows how scaffolding interactions with science simulations by synergistically using verbal, visual, and gestural resources can lead to sophisticated causal explanations. While successful science environments benefit from synergistic scaffolding (Reiser & Tabak, 2014), creating the right balance requires careful and timely synthesis using multiple representations and modalities. We have shown how causal questions and gestures contribute to this synergy. Future work can examine this work in other scientific practices as well as with new immersive technologies.

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