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Learning in embodied activity framework: a sociocultural framework for embodied cognition

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Abstract

This paper proposes the Learning in Embodied Activity Framework (LEAF) which aims to synthesize across individual and sociocultural theories of learning to provide a more robust account of how the body plays a role in collaborative learning, particularly when students are learning about a collective phenomenon where coordination between and across students is important to their learning. To demonstrate the uses and limits of LEAF, we apply it to data from several iterations of the Science through Technology Enhanced Play (STEP) project. This project involved first and second-grade students using an embodied, mixed-reality simulation to learn about the particulate nature of matter. We use data from this project to demonstrate the ways in which students' embodied actions serve as a resource in understanding their embodied activity both individually and collectively. We demonstrate how both dimensions provide insight into student cognition and learning. Supported by this analysis, we present LEAF as a useful tool to help researchers, designers, and instructors thoughtfully design collective activities.

Keywords Embodiment · Play · Science education · Mixed reality · Activity theory

Introduction

Over the last two decades, numerous fields have shown increasing interest in the role that the body plays in learning and cognition, revealing some key overlapping concerns shared by studies in the Cognitive Sciences, the Learning Sciences, and the Computer-Supported Collaborative Learning (CSCL) communities (Baker et al. 1999; Lindgren and Johnson-Glenberg 2013; Newen et al. 2018; Steier et al. 2019; Wilson 2002). Increasingly ubiquitous and affordable motion-tracking technologies, such as the Microsoft Kinect and Leap, have

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supported the design of innovative activities that leverage students' movements as a resource for learning in computer-supported learning environments. However, existing work continues to focus heavily on how individual students learn with their own bodies when acting alone or in small groups (Alibali and Nathan 2012; Flood et al. 2015; Howison et al. 2011; Lindgren and Johnson-Glenberg 2013). Although this work has provided great insights into the role of the body in learning for individual students, it does not always explicitly acknowledge how individual cognition is situated in sociocultural contexts, or how students engage in understanding their joint embodied activity (Danish and Gresalfi 2018; Greeno and Engeström 2014; Ma 2016; Ma and Hall 2018).

In this article, we aim to use Cultural Historical Activity Theory (CHAT[1]) to extend theories of embodied cognition beyond the individual body's role as a resource for learning. That extension will explore how multiple bodies in a collaborative group with a shared motive can also play a role as a resource for learning. Our intent is to elaborate on theories of embodied cognition to account for collective activity without erasing and replacing the individual's role as part of the collective. Our second goal for this article, then, is to provide a friendly amendment to CHAT by making explicit how the body can play a role as a tool or mediator of collective activity. Typically, CHAT has focused on physical and conceptual tools that mediate a group's coordinated activity, but our research shows that one's body can play an important role in shaping how one acts with peers and the meaning the group assigns to that activity. We label this kind of coordinated activity "collective" because we are interested in part in how the combined actions of those in the activity system produce an aggregate result. Collective activity is, at times, collaborative but it does not have to be.

Extending embodied cognition to address collective embodied activity is important because it will bring theories of embodied cognition into better alignment with our current theories of collaborative learning. Embodied cognition asserts that all cognition is embodied; by extension, this means all learning is embodied as well (Gallagher and Lindgren 2015; Goldin-Meadow and Alibali 2013). However, formal education typically works hard to erase the body from the learning process by making students sit at desks to learn, often without talking to one another. This takes a large set of potential resources for learning off of the table. To the extent that the field of embodied cognition has made inroads into education, it has been hampered by a focus on individuals. This is because educators, designers, and research communities have increasingly recognized the importance of the sociocultural context of learning—why people learn (Kris D. Gutiérrez and Jurow 2016; Philip et al. 2018), how students learn in interaction with others (Enyedy 2003; Graesser et al. 2018; Järvelä et al. 2016; Jeong and Hmelo-Silver 2016), and how cultural resources are central to the ways that students make sense of academic concepts (Kris D Gutiérrez and Rogoff 2003; Lee 2017). If embodied cognition cannot be brought into conversation with sociocultural theories of learning, it will remain at the edges of conversations about how to design formal educational environments and will thus remain under-explored in the field of Computer-Supported Collaborative Learning (CSCL).

As designers of formal learning environments, we also prioritize designing for the realities that most classrooms face, even while pushing the boundaries of instructional design. There is little practical guidance to support the design of learning environments that explicitly aim to

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[1] Note that many scholars use CHAT and "activity theory" interchangeably. We are not aware of a consistent distinction between the two and thus have opted to use the term CHAT in this manuscript as it is more commonly cited in the CSCL literature, though our use of CHAT can be considered synonymous with the term "activity theory."

leverage embodiment in support of cognition and learning in these classroom settings (For a discussion of how classrooms have been conceptualized in CSCL see Hod and Sagy 2019). One common constraint in formal education is increasingly large average class sizes, which the Organization for Economic Cooperation and Development lists as 20 students for primary grade classrooms in 2017. Educators interested in supporting embodied cognition in these real-world learning contexts are challenged to balance the role of the body as an individual resource with the complexities of larger social spaces. Although there are some exceptions within the CSCL literature, collaborative embodiment beyond the dyad has not been discussed extensively (For exceptions in CSCL, see Davidsen and Ryberg 2017; Enyedy et al. 2012; Enyedy et al. 2015; Steier et al. 2019).

This paper argues that, in order to understand embodied cognition (i.e., learning using the body), we need to account for how embodied cognition is both influenced by, and helps to shape, the relationship between individuals and their social contexts. This is well-aligned with both sociocultural theories and theories of group cognition that recognize the inter-relationship between individuals and the groups in which they are working (Stahl 2010). Our new framework, Learning in Embodied Activity Framework (LEAF), is intended to help support synthesis across individual and sociocultural theories of embodiment and thus to provide a more robust account of how the body can play a role in both individual and collective cognition and learning. While we believe that this framework is particularly valuable in CSCL contexts, we also think it can apply to collaborative learning environments where embodiment is not tied directly to the computer.

Moreover, although embodied learning may play a role in all learning (Barsalou 2003), not all learning environments are intentionally developed to leverage embodied learning. For example, students discussing particles in motion may use the areas of their brain related to movement to understand that idea. However, we are more interested in understanding designs where students are explicitly asked to move their bodies to understand how particles in motion behave. Therefore, LEAF was developed to design for and analyze experiences in which students *explicitly* use physical movements that are tied to conceptual ideas or which help them to make connections to new conceptual domains. These movements can be mirrors of prior actions (e.g., a student thrusting their hand forward in a pushing gesture to represent a force) or more metaphorical uses of the body (e.g., a student gesturing with two hands to demonstrate a balance scale when solving an equation; c.f., Alibali and Nathan 2012). By explicitly centering the body in this way, LEAF provides more robust guidance to designers and theorists interested in exploring how body movement can be used intentionally to support learning. We believe LEAF may have similar value in other collaborative environments where embodied activity is less salient, but our focus is in exploring those activities where embodiment is central and explicit.

This manuscript illustrates and explores LEAF in the context of over a dozen studies conducted as part of the Science through Technology Enhanced Play (STEP) project (Danish et al. 2015; Saleh et al. 2015),[2] which builds on our previous work with the Learning Physics through Play (LPP) environment (Enyedy et al. 2012; Enyedy et al. 2015). Although embodiment has always played a key role in STEP, our initial design focused on sociodramatic play, which is positioned by sociocultural theorists as the leading activity of childhood (Griffin and Cole 1984) and a natural form of inquiry which leads students to reflect upon the ideas with which they engage (Youngquist and Pataray-Ching 2004). We focused on play because of how

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[2] For a full list of citations see the methods section below.

it leverages the natural abilities of young learners to represent and re-represent the world as they learn about it. For example, as students pretend to be particles in motion, they appear to intuitively explore the notion of how energy impacts their speed, which can then serve as a starting point for exploring the role of energy in states of matter.

Embodiment was initially one aspect of how students learned through play within this broader framework, but as we iteratively refined our designs and theories, we became increasingly interested in the role of the body in supporting students' learning both through play and inquiry. We believe the benefits of embodiment transcend play and can be leveraged in a wide range of activities. LEAF was thus developed as a post-hoc account of how the body plays a key role in learning within collective embodied activity. In developing LEAF, we have looked at data from a wide range of STEP implementations over the past 6 years in order to create an account that we believe applies across all of our designs, and those of others interested in collective embodied activity.

These wide-ranging activities have included embodied STEP activities that support learning about both states of matter (Danish et al. 2015) and honeybees collecting nectar (Danish et al. 2018; Danish et al. 2017a). We are currently in the process of developing additional content areas ranging from aquatic ecosystems to the water cycle. We have also explored the relationship between different content areas and their impact upon embodied learning (Danish et al. 2019). For the sake of clarity in articulating the theoretical dimensions of our framework, our current account focuses on the implementations of STEP: Particles. In STEP: Particles, students pretend to be water particles and their physical motions are tracked by Kinect cameras (see Fig. 1, left), which generate a simulation of water particles in motion (see Fig. 1, right). The students work together to create solids, liquids, and gases on the screen by coordinating their movements.

Background: Learning in embodied activity framework (LEAF)

To explore the relationship between the individual and collective dimensions of learning, LEAF builds on Cultural-Historical Activity Theory or CHAT (Engeström 1987, 1999). CHAT takes collective activity as its unit of analysis, representing cognition and learning as existing at the intersection of the individual (a subject) and the collective, or community (other individuals who are pursuing the same object or motive). Although individual and social frameworks are often positioned in opposition (Danish and Gresalfi 2018), our framework builds on those

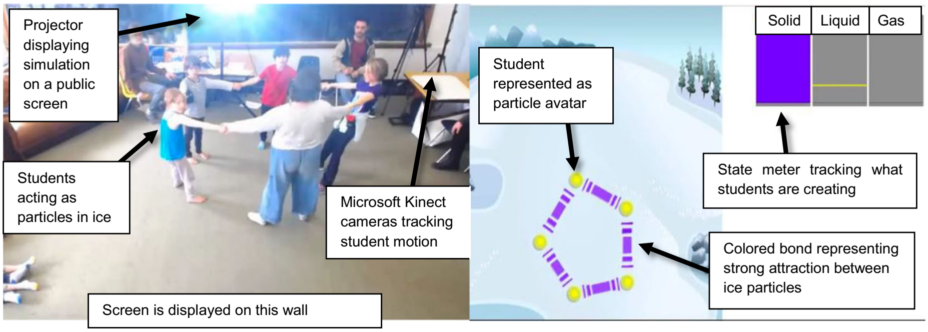


Fig. 1 Students embodying particles in the classroom during STEP Study 6 (left) and the STEP simulation that is projected on the screen to reflect their activity (right)

sociocultural theories of learning that posit that the individual and their learning within a social context is inseparable from the role individuals play in simultaneously shaping those contexts (e.g., Engeström 1987; John-Steiner and Mahn 1996; Vygotsky 1978; Wertsch 1985).

Given the label "sociocultural," it is easy to overlook the fact that CHAT and other theories within the sociocultural tradition place a great deal of importance on understanding learning from the perspective of the individual and not just the collective (Engeström 1987, 1999). What sets these theories apart is not that they focus solely on the sociocultural context, but that they explore the mutually constitutive role of the individual within the cultural context and vice versa (Wertsch 1985; Wertsch and Penuel 1998). For example, when one student in our study gestures as if throwing a ball at another student, the receiving student might begin to walk more quickly. To understand this potentially confusing set of individual actions, it helps to know that the two students discussed this gesture previously, and agreed that it meant that the gesturing student was giving energy to the second student, who would then move more quickly. The second student may choose to interpret this action in the agreed-upon way, and can still interpret how much they speed up on their own, but their action is nonetheless shaped by the shared agreement that a throwing gesture implies the giving of energy. To address this kind of inter-connectedness, LEAF explicitly recognizes the role and impact of embodiment for individuals and collective activity, all while recognizing the role of local contexts in shaping these activities.

Given that collective activity is the unit of analysis, CHAT focuses on how individuals (*the subject*) engage in activity within a *community*. The collective activity is identified by pursuit of a shared *object* or motive (Wertsch 1985). The nature of the shared object mediates or transforms one's actions to achieve the outcome(s) and interactions with others. For example, the students above might be passing energy along with the intention (object) of producing a model of liquid, or to produce a model of gas, each of which might lead them to select different amounts of energy to "give" to their peers (See Fig 2). Participants' interactions within activity are further *mediated* by the *tools* they are using, including both physical tools and conceptual tools. For example, the students in the above example might gauge their success at producing the desired state of matter (their object) based on a computer display (a tool) that represents their motion as particles in part by color-coding the bonds between the particles. *Rules*, such as allowing other students to suggest changes in how people are moving also help to organize the *community* of participants within the shared activity. Finally, the *division of labor* describes how the participants within an activity organize themselves with different rights, roles, and responsibilities, such as whether the teacher decides the intended state to produce, or whether the students can all suggest a desired state and then vote on which one they'll attempt to produce. These two approaches lead to very different outcomes, especially if students have the opportunity to argue for the reasons behind their choices (another rule that mediates their division of labor).

Within CHAT, individuals simultaneously experience and act at multiple levels, performing individual *actions* within collective activity (Wertsch 1985). Prior CSCL literature has noted the importance of viewing group activity as the emergent result of individual actions building up over time, while being shaped by collaborative efforts (Stahl 2010, 2017).

LEAF, therefore, further recognizes: 1) that individuals move continually between an awareness of their own individual goals and actions, and an awareness of their collective *embodied* activity system organized around a shared object, and 2), the system as a collective unit is constructed in part through their ongoing individual actions. LEAF aims to articulate the role of embodiment in learning by explicitly identifying the impact of each of the key mediators of activity noted above, and by articulating how each is understood at both the

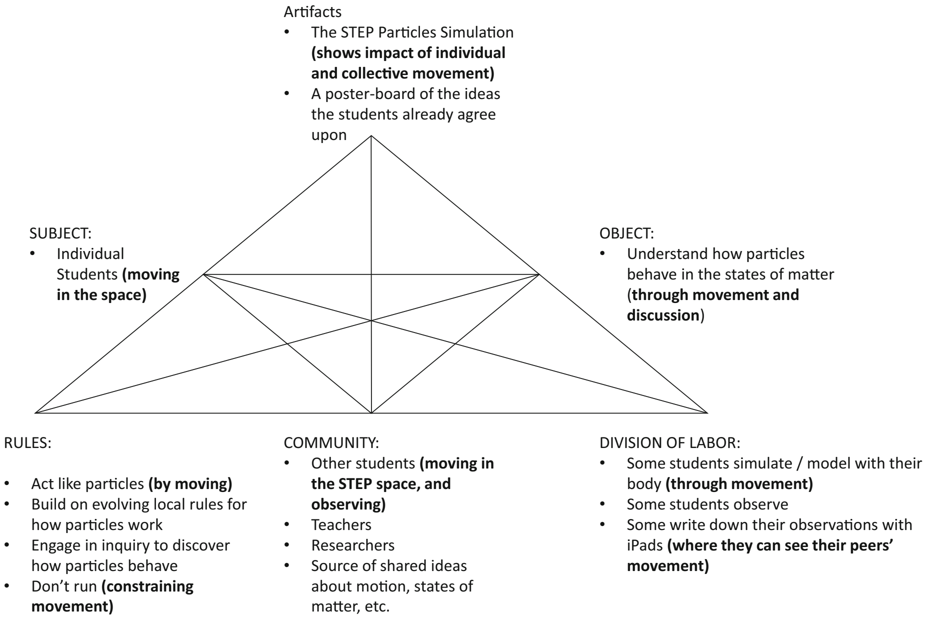


Fig. 2 An activity triangle representing the STEP learning environment

individual and collective level while recognizing that these are, by definition, mutually constitutive. The mediators are: 1) the subject or individual participant, 2) the object or motive that organizes individual activity, 3) the tools that the individuals use including computational tools, 4) the community in which they interact, and both 5) the rules and 6) division of labor that help define and structure those interactions (Engeström 1987, 1999; Engeström et al. 1999). These mediators are laid out in Table 1 where we present guiding questions that help unpack how each mediator influences students' experiences at the individual and collective levels.

As noted above, LEAF builds upon CHAT and thus our presentation of the LEAF framework parallels many discussions of CHAT by articulating the definition and role of each mediator in sequence. However, there are two key distinctions. First, LEAF focuses on *embodied* activity, and thus articulates how CHAT might be extended to include this embodied dimension. Second, while CHAT recognizes the importance of individuals in activity, we have found scholars rarely *explicitly* articulate the relationship between individual and collective experience of activity, a relationship that we view as particularly salient in recognizing how embodiment is related to learning in collective activity. Therefore, our presentation of LEAF aims explicitly to highlight this relationship and articulate the role of individual and collective experiences of embodiment around each of the CHAT mediators. In doing so, we aim to articulate how LEAF builds on and extends scholarship that views embodiment as a largely individual experience while also leveraging scholarship that focuses on the collective nature of activity.

The subject in LEAF

The subject in CHAT represents the individuals who are engaging in activity. Within LEAF, we further extend this to focus on the role of embodiment for those individuals, as well as the

Table 1 Guiding questions to help explore how each mediator might influence individual and collective embodiment in unique ways within LEAF

Mediator	Role of individual embodiment	Role of collective embodiment
Subject (student)	**Individual motion:** • How do learners' immediate individual experiences of motion and embodiment shape their understanding?	**Collective and Relative Motion:** • How does the experience of relative motion amongst others who may also be moving lead to new kinds of insights? • How do collective patterns in movement by multiple learners lead to distinct kinds of insights?
Object (motive)	**Individual goals and perspectives on the object:** • How does each individual learner's emerging understanding of the object lead them to participate in new ways? • How does each individual learner's position relative to others shape how they make sense of their movements and the concepts they are exploring? • How are individual bodies tied to the object?	**The shared collective object:** • How does the pursuit of a collective object source new forms of participation, coordination, and understanding? • How is the collective object selectively negotiated and taken up or resisted by the different participants? • How is the collective object tied to collective or individual movement?
Tools (material and conceptual)	**Individual tools:** • How do the tools in the space, both physical and virtual, shape how individuals participate and make sense of their movement? • What underlying ideas and concepts help shape this use of tools and movement for learning?	**Collective tools:** • How do the tools in the space, both physical and virtual, shape how students move collectively, and make sense of their collective embodiments? • How do underlying ideas about aggregate motion shape learners' participation, and how are they developed?
Rules (explicit and implicit norms)	**Rules of individual action:** • What rules and norms appear to govern how individuals regulate their own movement and the movements of their peers? (e.g., don't run in the classroom)	**Rules of collective action:** • What rules or norms appear to shape efforts to coordinate joint motion, or allow for more individual motion? • Is there consensus about these rules, how they are developed, and how they shape learners' experiences?
Community	**Community as passive:** • How does the individual learner orient toward their peers as an audience in their interactional moves (movement, talk, gesture)? • How does the individual learner orient toward their peers as a model that they can follow, pick up, and build on?	**Community as active:** • How does the community go about reaching consensus (or not) about how to move, and how to interpret different patterns of movement? • How do community ideas about embodiment influence individual notions?
Division of Labor	**Individual roles:** • How do individuals embody their specific roles, or resist that embodiment? • How does the context shape which roles are more salient to individual students?	**Roles in relation to each other:** • How do individual roles build upon, or influence other roles? • How do the collection of roles lead to a new form of embodiment that emerges from individual roles? • What power / authority do different roles have and how do they impact embodied activity?

Intersection of individual and collective roles of embodiment

- How do individual embodied experiences lead to new collective experiences? Similarly, how do collective embodied experiences shape or constrain individual motion in ways that transform those individual experiences?

Table 1 (continued)

Mediator	Role of individual embodiment	Role of collective embodiment
• How do individual goals align with or contradict the collective, and what impact does this have on individual and collective experiences? • How do tools (physical, virtual, and/or conceptual) shape how students map their individual embodiments to the collectively-oriented tools and vice-versa? • How do rules oriented toward individual or collective behavior align, contradict, and influence each other? • How do individuals act to be part of a community, and thus help to shape the community, in ways that are related to locally ratified forms of embodied activity? • How do students' individual performances of their roles produce new collective opportunities? Similarly, how does a focus on collective aspects of embodiment lead to new individual roles?		

relationship between their individual embodied actions and the collective activity. Given the prior focus of scholars examining embodied cognition on individuals, a number of theoretical frameworks can inform how we think about the subject in LEAF.

Individuals in motion

One of the most productive areas of research into embodiment has taken place at the level of individual cognition (Barsalou 2008, 2010; Goldin-Meadow and Alibali 2013; Goldin-Meadow and Beilock 2010). Research in grounded cognition, for example, highlights how our understanding of the world is derived from perceptual and motor experiences, which are acquired from observing or interacting with others (Barsalou 2003). Although there are numerous theories of grounded cognition, we focus on two strands for the purposes of expounding our embodied framework; that of situated simulation theories (Alibali and Nathan 2012; Barsalou 2008) and body cueing (Lindgren 2015). Cognition according to situated simulation theories involves a form of mental simulation of embodied action. This approach assumes that mental simulations involve processing information via multiple modalities such as the visual and auditory senses. There is, however, a particular focus on how some concepts are treated as analogous or connected to specific bodily actions or experiences, and thus those experiences serve as a resource for sense-making around those concepts. These specific embodied actions are called body cues, which are also predicated on the assumption that simulations underpin our cognition. Lindgren (2015) argues that by identifying body cues that reflect target concepts, instructors can support student learning. Lindgren further notes that computer-supported learning environments such as Mixed Reality (MR) tools can facilitate this process by helping students to link their embodied experience to the target concepts. LEAF therefore aims to build on this research and extend CHAT by explicitly attending to the body as a unique resource for supporting cognition and learning at the individual level. This is realized in our design of the STEP environment by leveraging technology to support students in using their body and motion to explore complex science concepts.

Collective and relative motion

Once we have established the importance of exploring embodied cognition at the level of the individual, the LEAF framework then asks how one might conceptualize an embodied subject in collective activity. For the purposes of this manuscript, the term collective here highlights the organization of students as not simply co-present, but as organized in such a way that they need and want to attend to and coordinate their work with each other. Body position, body language, and gesture are always relevant to how people orient to one another and coordinate to work together (Goodwin 2000; Hall and Stevens 2015), and are central to what students produce.

To understand how individuals respond to embodied collective activity while also helping to produce it, we look to Interaction Analysis (IA, Jordan and Henderson 1995). IA is often viewed purely as a methodology, but it is also based in a rich set of theoretical and epistemological assumptions (Hall and Stevens 2015). Specifically, this tradition notes that when interacting with other people, humans are continually monitoring the people around them, adjusting their own talk, gesture, and motion in response to what is happening and how they are being interpreted. Talk, including gesture and body motion, is produced sequentially while being continually re-evaluated and changed (Goodwin 2000, 2017; Hall and Stevens 2015). That is, individuals engage with emergent goals, adapting their talk, actions, and goals to the shifting environment around them. Understanding group cognition thus necessitates an examination of the sequential production of talk within the group (Damşa 2014; Stahl 2010; Stahl et al. 2014).

This perspective, derived from IA and related methodological approaches, plays a crucial role in both the design for and the analytic approach within the STEP environment. From a learning design perspective, we leveraged this feature of human interaction to provide a context in which students continually receive and provide meaningful feedback to each other. By having students work together to produce the states of matter, we assumed they would be observing each other and continually adapting. Students' actions were thus supported by the designed mediators—the rules, and division of labor that oriented them towards developing collective models, and the software tools that helped to make the underlying science concepts in their emergent model more clear to them. We then analyzed how and when students responded to each other, and how they were supported by these mediators in doing so.

The object in LEAF

CHAT explicitly recognizes that individuals may engage simultaneously from both individual motivations—their goals—and from collectively determined motivations—the object around which the activity is organized (Wertsch 1985). Furthermore, individuals pursue their own emergent understanding of the collective object, which may not always mirror the understanding of the collective, or of other individuals within the collective. In fact, CHAT scholars have noted that many activities are productively accomplished because individuals pursue goals that may seem contradictory to each other, but which ultimately support the collective object (Engeström et al. 1999). Similarly, Tissenbaum et al. (2017) note the importance of exploring how emergent and seemingly contradictory individual goals might lead to productive collaboration in CSCL environments.

Both individual goals and collective objects mediate activity for the participants simultaneously at the individual and collective levels. For example, although the "object" of the activity may be to articulate a set of rules that describes how states of matter form, in a given moment, students may be attempting to accomplish much more modest goals, such as getting everyone to represent ice. Although the larger object of the activity remains stable (and perhaps develops over time), the individual goals that students pursue may shift over time as students begin to achieve them, or in some cases re-negotiate them. For example, a student may notice that the particles in the simulation turn red, which happens to be their favorite color, when the students run quickly, leading them to take on an emergent goal of having fun by running around. The group might then attempt to convince the student to return to the collective model, or they might determine that seeing what happens when they all move around is more fun!

One way in which LEAF extends the CHAT framing is by explicitly focusing on whether and how the body and motion are tied to the object of activity. The body might be part of the object, central to achieving the object, or not explicitly tied to the object. For example, if the object is to "use our bodies to make a model of gas", then there is no way to accomplish that without embodiment. If the object is instead to simply be able to "describe how particles move" then it might be something that students leverage their body to accomplish, but we can imagine instances where they choose not to, which may impact how embodied resources support their understanding. The object thus suggests certain roles for the body, which may influence how it is used.

Related to this, we are particularly interested in whether the object requires individual or collective embodiment to achieve it. For example, if the object is to show how particles move quickly, each student can demonstrate this individually, and they may not need to attend to each other in their embodiment. In contrast, to show a "solid" in the STEP environment many of the students need to stand still and near each other (but not too near). That is, the collective object requires them to consider their individual goals relative to each other and to arrange their bodies and actions accordingly. We have found that having an object that requires and / or benefits from coordination in this way further helps mediate students' embodied activity, and provides unique opportunities for them to learn about concepts that are not as intuitive when acting as an isolated individual.

The STEP software platform (i.e., tool) was designed specifically to support students in exploring collective objects related to the target learning goals. For example, students can read the current state of matter from a simple icon so that they might explore how their motions create the three distinct states of matter. However, it was ultimately up to the students and the teacher whether they pursued each of these states as an object within a specific class session. This meant that students could develop and pursue individual goals of interest to them, and also that these goals were often negotiated amongst the students. Furthermore, just because a student agrees to the collective embodied Object of producing a particular state such as gas, does not mean that they fully understand what that means. Whether the students initially understand how gases behave or not, to produce gas within the STEP environment requires a student to recruit, and coordinate with, several peers. The result is that students' individual goals and understanding of the object often drive the collective object in new directions, and vice versa as students move within the STEP environment. These new directions then serve to make students' emergent understanding visible as a basis for reflection and refinement.

The tools in LEAF

Within CHAT, the artifacts refer to both the physical and conceptual tools that participants use as they engage in their collective activity (Cole 1996). These tools mediate an individual's engagement with the activity system by providing new forms of interaction both physically and conceptually. In LEAF, we assume that these tools, which include computer technologies, might support learners either by making aspects of the phenomena more visible, or by helping them to find new solutions to challenging problems, thus providing new insights into the tool, problem, or both (Ritella and Hakkarainen 2012). By making phenomena more visible, these tools also allow students to map between embodied actions and the concepts being learned.

A well-known form of computer simulation that has been used to support students in engaging in collective activity are participatory simulations (Colella 2000; Wilensky and Stroup 1999). In general, a participatory simulation is one in which students each take on a unique role within the embodied system, follow simple rules to interact with their peers, and consequently produce a collective phenomenon. LEAF and the STEP project build on the closely related notion of a participatory model (Danish 2014)–a variation on participatory simulations where students are explicitly attempting to model a phenomenon by attending to their understanding of how it works. Participatory models and participatory simulations share the need to focus on how a phenomenon with multiple agents (participants) unfolds rather than focusing solely on following the "rules" of the simulation in which they are embedded, while also integrating an explicitly representational focus that orients the students towards creating a communicative model. In both cases, computational tools can support students by helping to provide new insights into how their interactions within the simulated system might impact each other individually, or the aggregate features of the collective model.

For example, in a commonly cited example of a participatory simulation, students act as people who may be infected with a disease and attempt to interact with as many of their peers as possible (Colella 2000). When they do so, however, they run the risk of contaminating their peers. Individuals in the simulation adopt an empowered first-person perspective by which their physical movements (e.g., where they stand, who they talk to) have consequences in the simulation. The combination of experiencing the activity system from a first-person perspective and then reflecting on it in aggregate afterwards as an object of group inquiry and consensus proves quite powerful for students. In particular, Colella (2000) noted that the collective nature of these simulations means that every individual has to participate and recognize how their activity is shaped by those around them (e.g., it is difficult to recognize how a disease spreads without interacting with other people). By taking on a role within the embodied activity system, students make powerful emotional connections to it.

In STEP, the software tools in the environment were designed to help students understand their own actions as individual particles, the relationship between particles, and the behavior of the entire system of particles, by visualizing elements of these relationships. For example, thick white lines show the attraction between slow moving particles forming ice; thin blue lines show the lesser attractions between medium moving particles that form liquid. These tools are physical in the sense that they are materially produced on a shared display, yet they are embodied in the sense that they directly result from children's movements within the space. Additionally, they are also conceptual in that they refer to states of matter and not just children's bodies in motion. These tools also operate at both the individual and collective level. For example, a student may call out his observation that running fast produces red lines on the shared display. However, because the students are in a sustained activity system together, the meaning of the tools is also produced collectively through interaction. Not only do the students collectively test and refine the idea that red is fast, they develop the idea into an association of red with the gaseous state of matter. Individuals use tools, but how they learn to use them properly and the meaning of the tools is socially negotiated.

The rules in LEAF

Rules within CHAT refer to the official and explicit rules and the implicit norms that people use to regulate their own actions (Engeström 1999). These rules inform individuals' interactions with each other, their peers, the teacher, and the software. By organizing these interactions in specific ways, individual participation is mediated, allowing participants to see new and different aspects of the phenomenon being studied. It is often easiest to see the rules that are present in a system when they are violated and other members of the community step in to correct individual behaviors. Thus, we can see that students have a rule of trying to work together when they are admonished by the teacher for not coordinating their activity.

In LEAF, rules and norms have an explicit embodied component. We want to understand how rules do or do not shape the role of the body in interaction, thus increasing or decreasing the likelihood that it will play a role in sensemaking and learning. For example, the STEP environment reifies a “rule” that particles can only form ice if they are positioned at an intermediate distance and moving only slightly. This is not simply a rule that students police; rather if the students move too quickly or slowly, they see that the system itself will change how their particles are displayed, and what the state is that they are forming. As with the other elements of activity, rules and norms have both an individual component and collective aspect, and although an individual within an activity system takes on a particular position, governed by rules and norms, those rules and norms are defined by the community and can and often do change and develop. The rules of behavior in an embodied collective activity, such as those promoted by STEP, are particularly powerful because, by following the rules they have identified, students indicate how they believe a scientific phenomenon should be represented. For example, as students begin to recognize and follow the rule that you need to move quickly to produce a gas in STEP, they are supported in reflecting on the relationship between speed of particles and the states of matter.

The community in LEAF

The community within CHAT refers to the collection of people who share an object, which encourages them to collaborate and develop a shared set of tools, rules, and roles to ease their collective work (Engeström 1999; Engeström and Sannino 2010). To help capture the active role of the community in shaping individual and collective activity, we find it productive to recognize that the community plays two overlapping roles as both audience and pool of collaborators. As the audience, the community provides individuals with a set of expectations about how they should communicate their ideas, and what kinds of responses they might expect. As collaborators, the community represents the potential for multiple participants who might even engage through differing roles (the division of labor) to accomplish the collective activity. Individual students can also find within the community models illustrating how to act. From a CSCL perspective, the community includes both those whom are part of the collaboration (e.g., the students) and those who might be relevant to or supportive of the collaboration (e.g., the teacher). Within the LEAF framework, we maintain this understanding of community, but focus in particular on how the community develops and reinforces shared norms about embodiment and how embodiment might be interpreted.

The division of labor in LEAF

The division of labor captures the ways in which multiple participants within an activity system may engage in different but complementary roles as they work together towards the shared object (Engeström 1999). A division of labor is both collective and individual by definition. An individual's role is only sensible in the context of the others' roles. Adopting unique roles is often central to how we might understand the interface between individual actions and collective activity, but roles also can have an embodied dimension. For example, for many children in elementary and secondary school, seating arrangements in the classroom or cafeteria often function as a marker of individual identity and roles within that community (Eckert 1989).

In LEAF, we attend to embodiment in relation to the division of labor, and are sensitive to the body as a site of representation for others. In prior embodied work, roles are often to support individual cognition, but not *explicitly for and with others*. We build on the collaborator and audience roles highlighted earlier to design for roles that allow participants to interrogate each other's ideas as made visible through their public action (Goodwin 2017). In STEP, students can self-assign roles when they choose to embody a particular phenomenon, their roles can be assigned by the simulation via a virtual costume, or their roles can be given by the teacher (who can appoint a particular student to be the director from within the play space or an observer at the edge of the space). Even as students engage in individual roles moving through the simulation, their shifts in movement lead to new embodied configurations, which can in turn transform their roles. For example, a student who is running quickly across the space to embody a gas particle might decide to (or be encouraged to) switch their role into acting as part of ice as they pass their peers. Similarly, moving off to the side of the space often places students into a position where they gain a new perspective on the space and then elect to shift their role to being one of "director" instead of solely a "participant".

Within the STEP environment, students also define themselves in terms of how they contribute to the classroom's progress in understanding the underlying rules that govern how different states of matter form. They want to contribute to the work of the class by making observations, making inferences, suggesting experiments, and deciding between competing theories. Individuals take pride in their original contributions, but they are contributions to the collective work. Individuals are recognized by others by their ability to talk in the right ways, make states of matter happen, and their ability to explain their own thinking. By drawing on shared experiences, both proximal and distal, to help students connect to the content being studied, the teacher also plays a role in shaping the community and recognizing the impact of its history within the inquiry environment.

Design

The STEP: Particles simulation was designed to help students explore the relationship between states of matter at a macroscopic level and the behavior of the microscopic particles that produce these states. To accomplish this, we designed the STEP environment to support students in the task of embodying their conceptions of how particles behave (See Fig. 1, left) and then seeing the impact of their embodiment within a projected simulation (See Fig. 1, right). Our goal was also to leverage the benefits of collective activity, and thus we designed the environment in a manner that required students to collaborate with one another and notice how certain interactions with their peers (representing other particles on the screen) resulted in different outcomes.

In order for students to successfully enact a particular storyline that they had in mind or create different states of matter, they had to be aware of how their peers were acting as well.

Although students could individually explore the space, should they choose to, successful outcomes required them to plan and coordinate with their peers (e.g., to produce a block of simulated ice, the majority of the students needed to be relatively still and slightly spread apart). An overarching aim across activities was for the students as a collective to come to a reasoned consensus on the rules that governed each state of matter.

To facilitate the design of the STEP environment, we first identified the *primary embodied agent*–the element within the system that students would control and enact. This agent had to be both central to the phenomena, and one where the use of embodiment to control the agent would help reveal underlying rules of the phenomena. In this case, we chose water particles because we believed that students would benefit from focusing on how the motion of water particles produces the macroscopic states of water that we observe, and that discovering and enacting those motions would help students to understand them. One challenge that arises in embodied modeling, however, is that students can do whatever they want because they have complete control of their bodies. In this case, that means that they can produce completely unrealistic states of matter! Although unrealistic models are an important step in the process of developing a normative model, we also wanted to scaffold the process of progressively supporting a more normative account. We did this through three primary methods.

First, we scaffolded students experience by building representational infrastructure into the STEP simulation environment that helped them think about their models, and iteratively refine them. This included features such as a state meter where they could see what state their interactions would likely produce. In later iterations, we included colored lines that connected the particles and indicated whether two particles were acting in a way recognized by the computer to be solid, liquid, gas, or unrealistic. Second, the teachers helped structure conversations in ways that helped move students toward a normative account, in part by discussing underlying mechanisms that might help explain those behaviors, such as discussing how particles are attracted to each other and may form structures that are resistant to being disturbed unless energy is added to the system.

Third, to contrast the students-as-particles role, we created a STEP mode where students could occasionally take on the role of what we are referring to as the *contextual agent*. The contextual agent is another agent within the system that students could control, allowing them to influence the conditions surrounding a computer-controlled version of the primary agent (See Fig. 3). In this case, students could become “energy wands” that moved around the space giving additional heat energy to (or taking it away from) the particles they passed as a “heat wand” or “cold wand” respectively. The computer-controlled particles would then react in a normative way programmed by the computer.

For example, when a student-as-heat walked near computer-controlled particles that were acting as ice particles with strong attraction, the particles would gain energy and begin to speed up. The computer-controlled particles will eventually move fast enough and overcome their attraction to form liquid and then gas if the student-as-heat did not move away from the particles. We first introduced this role to students using the term “heat,” because students knew that heat melted ice. In subsequent discussions, students explored how heat is a form of energy and that as wands they could choose to either give or take energy from particles. For clarity, we will refer to this role as “student-as-heat” or “heat wands” throughout the paper. This set of interactions was intended to allow students to explore a more normative scientific account and then use the results of those explorations as a way of informing their own model development once they had an initial model. This shift in roles, however, naturally led to a shift in how the students experienced their embodied interactions within the system, and we will highlight

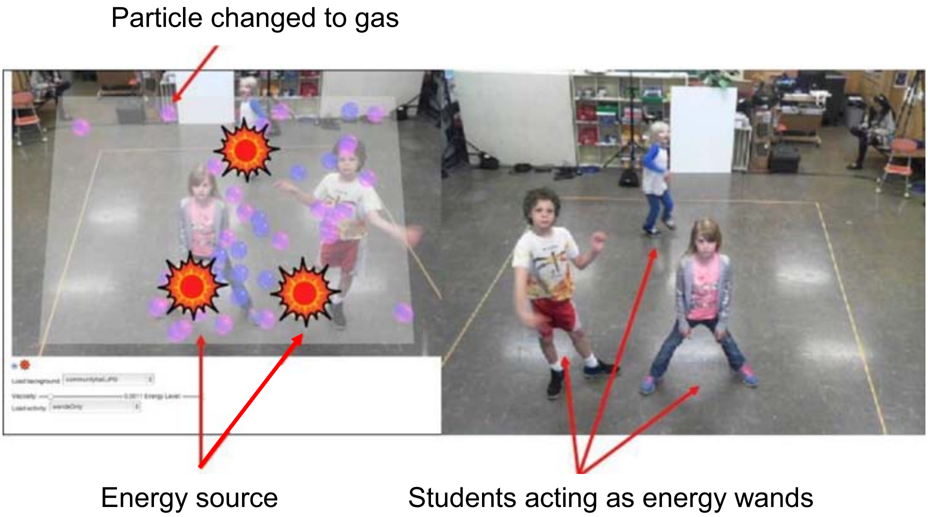


Fig. 3 Students in Study 1, acting as heat wands, giving energy to computer-controlled particles

these differences below as a way to help shed light on the different ways that embodied activity can support learning, even within the same system.

Methods

As indicated above, our goal in developing LEAF was two-fold. First, we aimed to extend CHAT by explicitly articulating the role of embodiment in understanding learning activities. Second, we wanted to understand how the inclusion of a focus on collective activity (the focus of CHAT) would enhance analyses of embodied learning. Thus our goal in applying the LEAF framework to analyze our prior STEP implementations was to understand how LEAF helps to make these ideas visible, showing how embodiment does play a role in understanding learning activities, and how exploring embodiment as both an individual and collective phenomenon can shed new light on learning within embodied learning environments. To explore these ideas in our work using LEAF, we analyzed implementations across a span of 6 years (from 2014 to 2019). Studies included the following: Study 1, an initial pilot study (Danish et al. 2015), Study 2, where we added game-like features and explored different forms of play (Davis et al. 2019; DeLiema et al. 2016; DeLiema et al. 2019), Study 3, where we compared gestural and full-body motion inputs (Saleh et al. 2017), Study 4, where we developed iPad-based observational tools for creating representations of embodiment (Humburg and Danish 2019; Humburg et al. 2020), Study 5, where we compared structured and unstructured prompts for the use of these iPad tools, Study 6, where we investigated the use of objects to augment embodied activity (Tu et al. 2020), and Study 7, where we investigated how embodied community resources can be used to support scientific inquiry (Georgen 2019). As we moved from one implementation to the next, we iterated on the STEP design and the accompanying curricula based on lessons learned from our experiences in the classroom and analysis of classroom video data.

The studies took place in several different public and private school classrooms in a small Midwestern city in the United States and in a large city in the western United States, with a mix of first- and second-grade students. Each of these studies involved the collection of multiple days of classroom video data and had previously been analyzed using a mix of methodologies including interaction analysis (IA) to understand how the participants engaged with the underlying science content via their interactions with each other and the mixed-reality environment. In developing LEAF and analyzing classroom interactions, we examined the temporal organization of activity across the multiple implementations, exploring how the individuals worked together to create collective knowledge (Jordan and Henderson 1995; Stahl 2010). This focus allowed us to understand how LEAF as a theoretical framework could be utilized to understand the designed activities as they were implemented across multiple years. We first identified similar activities where students took on the role of a particle or heat (i.e., student-as-particle or student-as-heat). By examining these similar activities (e.g., being a particle or being a heat wand), we were able to determine how each mediator supported individual and collective embodied activity.

We further wanted to understand the variations within these activities, especially at the individual and collective levels. After selecting these activities, we iteratively cycled between proposing an overarching framework to describe students' embodied interactions, and then analyzing episodes across the prior studies to see how the framework would apply in practice. We used both content logs and our prior experiences in the classroom to select episodes that captured the nuances of the different mediators. These episodes were also clear moments in the temporal sequence of activities that highlighted both member relevance and procedural consequentiality, that is, how the design of activity and mediators shifted how participants coordinated their activity or vice-versa (Hall and Stevens 2015), as well as those times when divergent forms of interaction nevertheless led to new moments of knowledge production (Tissenbaum et al. 2017). We vetted our developing hypotheses with the larger research team, who had significant classroom experience across implementations. A number of earlier theoretical iterations were also presented during research talks and in conference presentations where we received feedback that helped us to refine our framework (Danish et al. 2019; Danish et al. 2018; Danish et al. 2017b). These iterative cycles of analysis and feedback give us a robust account of how students used their bodies across implementations without necessitating a full re-analysis of all six years of video data. Our analysis aims to illustrate the resulting LEAF framework.

Findings: Using LEAF to explore the role of individual and collective embodiment across implementations

To demonstrate how LEAF can help us understand the dynamic relationship between individual and collective dimensions of embodied activity, we use two core STEP activities to explore each mediator in LEAF (See Table 2). In the students-as-particles activity, students embodied the role of a water particle and explored how their actions in the physical space influence the water particles in the STEP simulation. In the students-as-heat activity, students took on the role of a heat wand and explored how heat transfer causes state changes when their heat wand avatars came close to simulated particles within the STEP simulation, causing them to speed up. These two activities were used across multiple years of implementations and serve as powerful examples of how seemingly small changes in one mediator can impact how multiple aspects of embodied activity unfold. For example, looking at both activities we see the importance of recognizing students' individual embodied actions as a key influencer of activity. In the students-as-particles activity, it was a powerful resource, helping students think about the motion of a particle and how it might be related to energy. In the students-as-heat activity, embodiment was intuitive but at times confusing for students as they attempted to move quickly to represent heat rather than realizing that by giving heat to particles they would cause the particles to move quickly. Students' embodied ideas about how to move in the space continued to mediate their actions even when the software tool suggested a new form of action. Thus, there is value in attending to the additional layer of embodiment in CHAT, given how individual *embodied* actions mediate students' actions in nuanced ways that cannot be explained solely by reference to other mediators such as the tools in the environment.

At the same time, looking at collective activity in both cases was also powerful in that students' efforts to coordinate their actions help explain the value of embodiment for learning in this kind of activity. For example, when acting as water particles, the students' need to coordinate their motion made ideas about the relative speed and distance of different particles more salient to them, and the need to coordinate their impact upon the simulated particles when acting as heat helped students see the patterns in how particles responded to the introduction and removal of heat. Thus, we see the value in adding an analysis of embodied learning to CHAT's focus on collective activity.

In the following sections, we further demonstrate the value that this focus on combining CHAT and embodied learning in the form of LEAF can provide for analyzing learning in embodied learning contexts. To support this, we provide a detailed explanation of how the different mediators listed in Table 2 played a role in shaping individual and collective activity when students engaged as the primary agent (water particle). We then explain how this mediation process was different within the contextual agent (heat wand) activities. In doing so, our goal is to highlight how embodied activity is shaped by all six mediators at both the individual and collective level, thus illustrating the value in using LEAF both to design for and analyze collective embodied learning activities. In each section we illustrate how the mediators help to explain embodied activity in the unique individual and collective ways (for a summary see Table 2) based on the framing and the questions posed in Table 1.

Subject

Subject -- Individual

In LEAF, focusing on the subject allows us to examine how individuals experience their motion via their bodily sensations. One of the central concerns in designing these experiences was to address how students' immediate experiences of motion and embodiment shape their understanding. In the students-as-particles activity, students are encouraged to move about the room and experiment with different movements to see how they impact their respective particles on the screen. Across all the STEP classroom implementations, students most commonly remarked on the speed of their particles rather than the distance. This suggests that the most salient feature for them was speed. For example, when students first explore what it meant to be particles in Study 1, they would direct one another to either "stay there!" or run around "zig zag" (DeLiema et al. 2016). Students seemed to find it easy to run, walk, tiptoe, and jump to explore what it means to be a particle, and began engaging in these embodied actions with little or no prompting. Students' subjective experiences in exploring the STEP simulation physically meant that they could start mapping the relationship between their movements in the classroom space and the particle behaviors projected by the computer. For instance, in the first year of the STEP implementation (Danish et al. 2015), students typically

Table 2 A LEAF-based summary of the key roles of each mediator in shaping students' experience within the different STEP activities

Mediator	Student role	Dimension of experience	
		Individual	Collective
Subject	Particles	• Students experience speed as they move around the classroom.	• Students experience relative distance in relation to their peers' movements.
	Heat	• As energy sources, students explore how computer-controlled particles react as they move their bodies to different locations.	• Students coordinate and distribute locations of multiple heat sources and explore how the computer-controlled particles react.
Object	Particles	• As students develop a sense of the emerging object, they pursue different goals by moving around at varying speeds.	• The group collectively decides on what state to create and how to pursue it.
	Heat	• As students develop a sense of the emerging object, individuals focus on giving heat to (or taking it from) individual clusters of particles.	• The group collectively decides on what state to create and how to pursue it.
Tools	Particles	• Representations of particle behavior (e.g., color, distance, speed) orient students towards the way their individual movements change their associated particle.	• The state meter orients students towards the impact of their collective movements on the states of matter being formed across the entire simulation.
	Heat	• The motion and color of computer controlled particles orient students towards how their presence as heat changes the particles.	• The state meter orients students towards the impact of their collective heat source locations on the state of matter being formed.
Rules	Particles	• Traditional classroom rules govern individual behavior (e.g. don't run too fast). • STEP-specific rules also govern behavior (e.g. stay inside the particle tank, pay attention to your particle on the screen). • Students also begin exploring what they believe are the rules for how each particle behaves.	• Traditional classroom rules govern collective behavior (e.g. don't run into each other). • STEP-specific rules govern behavior (e.g. pay attention to the other particles, coordinate speed and distance to form the right state). • Students explore how all of the particles behave and attempt to develop a consensus explanation / set of rules.
	Heat	• Traditional classroom rules govern individual behavior (e.g. don't run too fast). • STEP-specific rules also govern behavior (e.g. stay inside the particle tank, pay attention to your heat wand on the screen). • Students also begin exploring what they believe are the rules for how each particle is impacted by heat changes.	• Traditional classroom rules govern collective behavior (e.g. don't run into each other). • STEP-specific rules govern behavior (e.g. pay attention to the other energy wands, coordinate heat location to form the right state). • Students develop a consensus explanation for how heat energy impacts the behavior water particles.
Community	Particles	• Students might change individual movements in response to peer and teacher feedback.	• The group collectively negotiates how to coordinate multiple bodies so as to achieve shared goals.
	Heat	• Students might change individual locations in response to peer and teacher feedback.	• The group collectively negotiates how to coordinate multiple wands to change the particles.
Division of Labor	Particles	• Students take on the individual role of a particle in water. As particles, students explore how they think particles should behave.	• Students coordinate the speed and distances of individual particles to create different states of matter (e.g., solid, liquid, or gas).

Table 2 (continued)

Mediator	Student role	Dimension of experience	
		Individual	Collective
	Heat	• Students waiting for their turn to embody particles take on the role of scientist-observers. • Students take on the individual role of a heat source (i.e. heat wand). As heat wands, students explore how giving and taking away heat impacts states of matter. • Students waiting for their turn to embody heat wands take on the role of scientist-observers.	• Scientist-observers use their observations to help the particles coordinate their actions. • Students coordinate their locations as heat sources to make collective change to the states of matter being made. • Scientist-observers use their observations to help the heat wands coordinate their actions.

started moving their bodies for fun. As they moved quickly or slowly, they commented on how the particles on the screen mirrored their speed. In subsequent designs and implementations (Davis et al. 2019; DeLiema et al. 2019), we added lines between particles to indicate the strength of attraction between particles. As students moved, they noticed that the lines connected to their particle became thinner. When students slowed their movements, these lines became thicker. This additional cue allowed students to map their experiences of speed to the impact that these movements have on the attraction between particles, recognizing that thicker lines represented the stronger attraction between particles in a solid, and thinner lines represented the more tenuous connections in a gas.

To further unpack the importance of these individual experiences of motion, we shift to the students-as-heat activity. As students embodied heat sources, the speed of their motion was less relevant, but their position in the space became central to how they produced change in the simulation. When a student playing as a heat source passed over a group of computer-controlled particles, the particles would begin to move faster and farther apart from one another in response to the student's presence in that area of the simulation. Here we see how students continued to use their motion to control the simulation, but they quickly noticed that speed was not as relevant, and in fact could be problematic as they needed to remain close to the particles for a period of time to heat them up. Thus, students' individual embodiment continued to support their inquiry in this set of activities, but they did not rely as heavily upon their embodied intuitions of speed so much as their chosen positions in virtual space.

For both particles and energy wands, students built on their experience of moving individually in the space to uncover the rules of particle behavior, but the different roles impacted what sorts of scientific concepts were most available to them for individual exploration (Tissenbaum et al. 2017). In the first case, where students acted as the primary embodied agent (the water particles), the movement of the body was a direct analogy for the movement of the water particle (Lindgren and Johnson-Glenberg 2013). In the latter case, when students were the contextual agent (the heat wands), the body is a metaphoric resource, or an invisible event between heat and particles. The wands give heat energy to water particles, which they then use to move faster, and by doing so change the state from solid to liquid to gas. Like the first case, the body is a resource for understanding, but it is not a direct mapping of one's own motion to the motion of a conceptual object. Looking across these examples, we can see how the body is a unique mediator of student learning. Specific designs connect embodied movements to exploration of the underlying phenomena, either through the kinds of motion experienced, the position that students take up, or other forms of movement not yet explored in our analyses.

Subject – Collective

Although individual experiences played a significant role in how the students explored different aspects of how the states of matter are impacted by particle behavior, each individual movement also contributed to a collective experience of particle behaviors. In their explorations, individual students tended to focus on a single dimension of particle behavior (speed or location). However, as students moved around the room with their peers, their collective movements also supported new realizations about the relative distance between particles, and the impact of taking on similar speeds (producing a single state of matter) or different speeds (a mix of states). Because distance is an inherently relational concept, students were better able to map distance to aggregated movements through collective action (Lakoff & Johnson 2003) even when their actions were not intentionally coordinated (Tissenbaum et al. 2017). An embodied experience of relative speed and distance requires the collective, because it gives students the experience of being packed tightly together or spread far apart, and requires attention to both one's own body, and the bodies of peers. For example, when trying to create solid ice in Study 1, students noted that "we should arrange ourselves into a rectangle or a square". Students also suggested that they need to be barely moving to indicate how the particles should move when arranged in a lattice structure. The point here is simply that some ideas require more than one person to accomplish. Attending to the distance between water particles requires two points, and therefore requires students to attend not only to themselves but to how they relate to others in the room. Additionally, students have to make the leap that a state of matter does not just describe a single particle but is a description of a set of particles all moving in a similar manner. That is, some phenomena are themselves "collective", and benefit from collective embodied activity to help students understand them.

In contrast, when the students took on the role of energy wands, their relative distances were less important for effecting the simulation. Students instead explored how switching between giving energy and then removing it would cause particles to change (e.g., heat made them speed up, and removing heat made them slow down). Students' new coordinated motions gave rise to explorations about the different effects of energy. For example, by moving into or out of the space, the students could see what happened with the presence or absence of energy. For example, in Study 5, as the students were using cold wands to keep a snowman frozen on a hot summer day, the teacher prompted them to move out of the space: "Let's move away from the snowman – let's see what happens when the energy wands are not there taking energy away." After all of the cold wands moved to the edges of the space, an observing student shouted, "It's melting!" Collective experiments such as this helped students make connections between their movements together and the ways that this coordination changed the state of matter they were creating.

Subject -– Interconnected

Another important question to ask here is *How do individual embodied experiences lead to new collective experiences?* The individual experience of speed and the collective experience of relative distance were inherently linked in the STEP activities. Students' individual experiences of motion impacted how they participated in the collective movement of particles, and the ways that they experienced relative speed and distance also changes the ways they experimented with their own movements. In Study 2, students-as-particles would often suggest directions for the group based on their individual experiences of a particular state, such as when one student directed the others to "Be sleepy...be tired" when they were trying to coordinate their motion to create liquid, a state that requires slow-moving particles (See Fig. 4).

Similarly, in the students-as-heat activity during Study 1, the students decided to create ice. One student suggested spreading out so that they could touch all the particles, whereas another student recommended clumping together based on her prior experience of being a particle. Because of these students' different experiences as heat and particles, students were able to explore how their individual actions impacted the collective activity and in turn, negotiated how other particles or heat-wands impacted their individual actions. In this instance, we observe how both dimensions are essential for helping students understand how and why particle behaviors impact changes in states of matter.

What is important to note here is that individual acts of creativity do not stay private. They are shared with the group. In our data, sharing often meant explicit attempts to organize a group of students to coordinate their actions in order to produce a shared goal within the simulation. That is, the girl above tried to get her peers to all be sleepy particles in order to get them to walk more slowly and therefore produce more liquid in the simulation. Individual insights based on one's own personal embodied experience are transformed into collective plans of action—a type of cultural tool—to help the group achieve their desired outcome. Therefore we believe that approaches such as LEAF are crucial because they highlight this set of connections, articulating how a focus on collective activity is often necessary to make sense of how individual embodiment can be leveraged by students for sensemaking within a classroom context where they are supported in exploring new concepts in interaction with their peers.

Fig. 4 A student in purple swings her arms and shuffles around slowly as she tells her peers "Be sleepy...be tired" (left). Her peers take up her suggestions and begin to swing their arms and droop their heads as they shuffle along (right)

Object

Object -- Individual

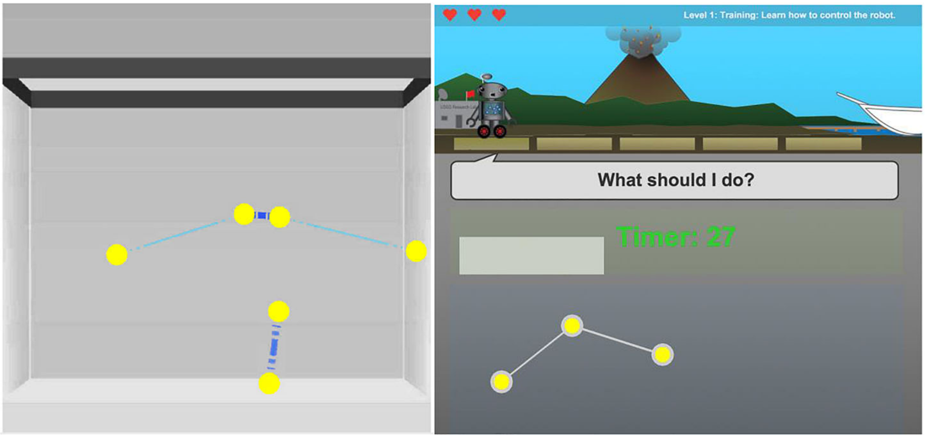
A core idea in CHAT is that human activity is always goal directed, and the goal for collective activity is referred to as the object. In LEAF, we explicitly reflect on how individual and collective ideas about the object of activity are related to their embodied actions. In the STEP activities, students were initially asked to simply begin exploring the space. They were not told to do anything in particular or how exactly the simulation represented gas, liquid, and solid. Their initial understandings of the object of their activity was, by design, quite loose and arose from their own individual perspectives. Given this flexibility, students appeared to explore whatever interested them (i.e., their own goals, such as moving fast because they could). This was true in both student-as-particles and student-as-heat activities wherein the initial day would be spent with students simply figuring out the relationship between their movements and their nascent understanding of particle behavior. Given the freedom to move about the classroom in playful ways, individual students often appeared to be guided by the desire to move in ways that they found to be fun and personally compelling, such as jumping up and down, or spinning in circles. From their individual goal-directed activities, the students began to notice many relevant things about how the simulation worked.

Object -- Collective

STEP was also designed with a collective object, which we anticipated would in turn shape students' individual goals. Specifically, STEP was designed to support student understanding of states of matter, and as mentioned earlier, a state of matter describes a set of particles, never a single molecule of water. Therefore, the group often recruited their peers to pursue their goals, aiming to establish shared goals for what they wanted to create using their collective movement – sometimes through teacher direction but often also through shared decision making. For example, in the particle activity, the class might decide that they want to form a solid, and this collective object might align nicely with students who also want to playfully vibrate in place. Although students-as-particles mainly explored how they could create different states with their movement, the collective object for students-as-heat became figuring out how heat could shift the movement of the particles (and thus, create a change in state more indirectly). In both activities, students worked together to decide what they wanted to do with their joint influence, and the shared objects that they decided upon had significant influences on how the rest of the embodied activity unfolded.

The importance of understanding the influence of collective objects on embodied activity became exceedingly clear to us when we shifted the collective object to a more game-like scenario in Study 2 (Davis et al. 2019; DeLiema et al. 2019). While the initial particle activity was organized by the collective object of forming particular states of matter, the game version of STEP was designed so that the overarching collective object was to rescue a robot from a volcanic island (See Fig. 5).

Students needed to form a particular state of matter at a precise time to help the robot dodge falling lava and escape. Although our intention in designing this game mode was to encourage playfulness in the students' embodiment, the shift in object encouraged students to organize their embodiment toward winning the game instead of pursuing emergent research questions about how particle movement might lead to different states of matter. This new object came at



What should I do?

Fig. 5 The more freeform STEP free-play interface (left) versus the game-play version of STEP that gave them a collective goal of protecting the robot using ice, liquid, and gas (right)

the expense of exploring the science deeply. Thus, this new collective object of winning contradicted the prior collective object of learning about particle behavior and led students to focus less on the mechanisms of particle behavior such as how energy and attraction produced different states. Fortunately, the presence of multiple mediators accounted for how students still learned in this condition. Although the embodied activity did not surface as many of the underlying rules of the phenomena, the teachers were able to help highlight these ideas in the classroom debrief, thus resulting in similar learning gains despite what appeared to be rather different sets of classroom activity. In subsequent iterations, we further built on this realization by explicitly using the game as a way for students to demonstrate the understanding that they developed in the less structured version of the environment (Saleh et al. 2017).

The important point here is that there is a designed push—by the simulation itself, by the teacher, and by students who want recognize they need to work collaboratively to test their ideas—to negotiate a collective object of activity and shared goal. This collective activity can then have a dramatic impact on both students' interactions and their individual embodied actions, which are then evaluated with respect to the collective object. This further strengthened our belief that embodiment can't be understood without being situated within collective activity.

Object – Interconnected

There were times when individuals pursued their individual motives at the expense of attempts to recruit them to pursue a collective object of activity. Sometimes this led to chaos that the teachers attempted to help restructure, and sometimes it actually created new and unforeseen opportunities for students to discover new aspects of the phenomena through their individual pursuits (Tissenbaum et al. 2017). For example, in Study 2, the group had decided to form a "caterpillar" together to see what happens when particles are close together (See Fig. 6). However, one student chose to dance away from the group, leading another student to shout, "Look it's red! It's red! When you're close to each other it's yellow and when you're far apart it's red."

The student's observation, sparked by a deviation from the group object, highlighted for the class how changing the distance between particles can impact the state of matter being formed.

Fig. 6 Student breaks away from the "caterpillar" that the rest of the group is making, causing the attraction line for his particle to turn red (indicating that he is creating gas)

Such productive deviations occurred in both the particle and heat wand activities, because in both cases the students had the freedom to move their own body together with the group or off on their own. In this way, individual goals for movement, even when they contradict the collective decision, can lead the class as a whole to make new revelations about how particle motion is connected to changes in state. In other words, this supported our belief that it is important for a framework that aims to understand learning through embodied activity to maintain awareness of how individual embodied experiences, desires, and actions might lead individuals to behave in ways that do not initially align with the shared sense of collective activity.

Community

Community -- Individual

In CHAT, the three pillars of an activity system are the subject, the object, and the community. The community is commonly defined as the group that shares a common object of activity and consists of people with various histories, roles and levels of experience in the activity system. From an individual student's perspective in our environment, the community consists of other individuals who students can model their own actions after. In this way, the community functions as a mirror, or the looking-glass self that provides the context for individual students to orient their actions (c.f., Cooley 1902). The students can also target their actions toward their community as an audience for their specific actions. In Study 2, a student chose to act as a parody of an "old man", hunched over and shuffling slowly as a way to both maintain the slow movement of liquid and entertain his peers, who in turn laughed at his antics. Taking on the entertainer role might influence other students to mimic the actions of that student, as with the example in Study 2, where the whole group chose to also move slowly via playfully pretending to be old people. In this way, innovations in movement often percolated through the community as individuals focused on how to move their own individual bodies. Said another way, from the individual's point of view the community provides a source of practices that the individual can attempt to emulate and appropriate in their individual embodied activity.

Community - collective

At the collective level, the community is typically something that persists beyond the participation of any single individual. Communities typically form and exist for a span of time and then work to attract and enculturate new members. However, classroom communities are unique in that they are formed anew each year with a completely new set of members save the teacher. Still, in the STEP classroom the students developed a sense of themselves as a collective that jointly constructed an understanding of how states of matter worked. Each class developed their unique way of explaining which motions produced which states of matter and negotiated them with the teachers' help. For example, while one class said that liquid was formed by slow moving particles because slow walking was a "fluid movement", another class described slow walking as "sleepy and tired". Each class negotiated a unique way of describing the same set of ideas and used that set of descriptions as shared practices to coordinate themselves when they wanted to make the simulation produce a specific outcome such as liquid. In a sense, this classroom community was defined by the knowledge and practices it produced for describing and making states of matter within the simulation.

Community – Interconnected

The individual and the collective of the community are interconnected in the sense that it is a desire to belong to and have a place within the community that motivates students to want to learn and appropriate the shared set of practices that signify membership. The collective community provides the place where one can belong, and the individual brings the desire to belong. This sets in motion opportunities for students to perform or show whether and how they belong. Recall the previous example in Fig. 4 when one girl invented a practice to help everyone move the right speed to make liquid by saying, "Be sleepy...be tired". She showed that she was part of the community by making the suggestion. More importantly, when her peers took up her suggestions and began to swing their arms and droop their heads as they shuffled along, they showed that they were part of the community because they were able to enact the successful practice to make the simulation produce liquid. Thus, the community can serve as a support, inspiration, and guide for individual embodied activity, while at the same time drawing its own collective norms from those individual embodied actions that have proven successful.

Tools

Tools - individual

To support learning of particle behavior (e.g., speed, distance, and attraction), we included a number of virtual tools in the form of representations within the simulation that oriented students towards the ways that their movements impacted these variables. In the initial design (Danish et al. 2015), particle color alone represented the state that students were achieving (e.g., purple for solid, green for liquid, orange for gas; see Fig. 7). In more recent implementations (Danish et al. 2019; Davis et al. 2019; DeLiema et al. 2019), we introduced the concept of attraction and represented the states as lines between a particle and its nearest neighbor. Each particle was linked with other particles via lines that changed in color and thickness depending on the speed and distance of the particles connected to it, which gave

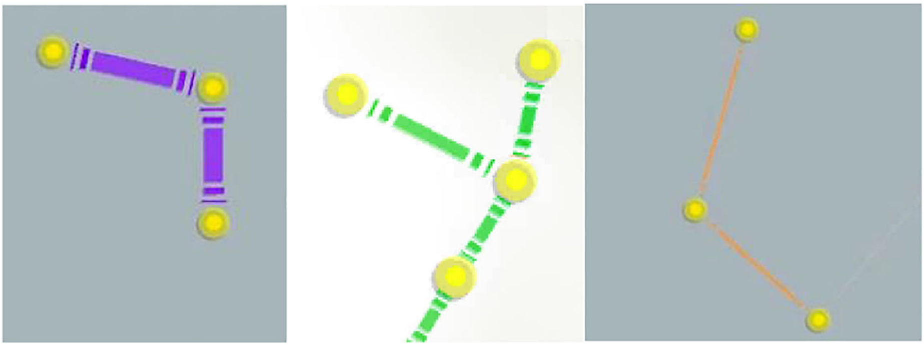


Fig. 7 Particles forming solid (left), liquid (middle), and gas (right), with colored lines and varying bond thicknesses to represent differing levels of attraction

students feedback about how their changes in speed and distance changed the state of matter being made.

In the student-as-particle and student-as-heat activities, these representations helped students explore their individual understanding of particle behavior – they would see their own lines changing when they embodied particles at different speeds and distances, and they would see computer-controlled particles rapidly change colors in response to their movements when they embodied heat wands. In addition to visual representations, we also encouraged students to create energy-giving and energy-taking gestures that they could use to make sense of how their individual movements were changing the particles (See Fig. 8). These gestures became both physical and conceptual tools that students used to orient themselves to how the heat wands transferred heat to the particles and caused them to speed up and form a gas (Ritella and Hakkarainen 2012; Steier et al. 2019). At one level tools are used to focus students on their own actions and the consequences of their actions on the system.

Tools - collective

To support collective reasoning, an additional virtual tool was a state meter (See Fig. 9) that consisted of bar graphs, which presented students with the state of matter they were forming together as a group (See Fig. 10). In both particle and heat wand activities, students used the state meter to coordinate their movements and to provide feedback on what the group should do as a collective to achieve the desired state. This often led directly to students needing to coordinate with one another to make a shared state of matter. Each individual particle was fundamentally linked to their peers. In other words, a single student cannot embody a particle in a solid without the network of other particles connecting to them to form the lattice structure in solid.

These collective configurations were usually formed when one student proposed an idea and convinced the group to experiment with them. For example, in the middle image in Fig. 10, the student in the striped shirt convinced his peers to clump together by whispering "Guys, let's get together!" and pulling several of his peers towards his own body. The rest of the group followed suit by gathering around him, to see whether this tightly packed configuration would change their on-screen particles to solid ice. When this tactic was unsuccessful, the group soon splintered apart, and a different student suggested that they try spreading out more. In this way, the group negotiated their individual particle roles in order to build something that none of them could create as individuals alone.

Fig. 8 Students putting their hands together (left) and pushing their hands outwards towards another student (right), signifying an "energy-giving gesture" that the class invented to communicate their heat wand role

To further support collective reasoning, we designed a set of iPad-based tools in Study 4 that helped students observe different aspects of their peers' embodiment while they waited their turn to embody a particle (For a full discussion of these tools see Humburg and Danish 2019; Humburg et al. 2020). In this 2017 iteration, students could use annotation tools to evaluate collective representations that helped the group make sense of how particles in different states of matter behave. Figure 11 shows some examples of the sorts of collective representations that were projected on the screen for students to consult as they embodied particles and reflected on this embodiment as a class.

Both the state meter and the iPad representations provided students who were embodying particles and heat to assess the extent to which the group succeeded in achieving their collective object. For example, in Study 4, when a student noticed that the on-screen graph generated by the iPads was depicting the low attraction levels of gas particles, he yelled to his classmates, "They think it's gas!" and instructed his peers to slow down. At the collective level, some tools specifically direct student attention to the aggregate and how large numbers of particles behave together to produce a state of matter.

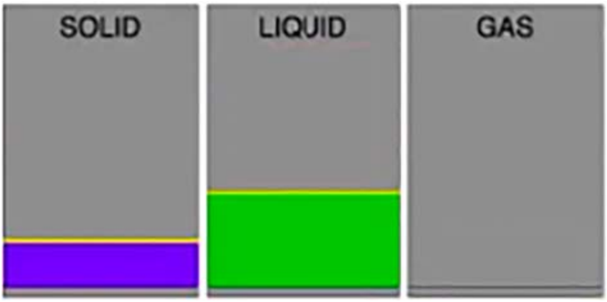


Fig. 9 The state meter, which updated in real time to tell students what proportions of each state the group was making together

Fig. 10 Students in different iterations of STEP experimenting with collective configurations to create solid ice (Study 2, 4, and 6, from left to right)

Tools - interconnected

Given the importance that we have ascribed to attending to both individual and collective embodied activity above, it is therefore valuable to understand how tools such as the STEP environment can support students' engagement with ideas that are both individual (their own motion as represented by an individual avatar) and collective (the shared state that they have produced). Naturally, the way in which these tools are sequenced and linked is also important for how learners engage with the concepts that they are meant to make salient. For example, we typically introduced students first to the features of STEP that helped them understand their own localized embodiment (the representations of particles, heat, and particle behavior). Once they had connected to these, we then introduced the more collective representations such as the state meter. Once the collective tool was introduced, however, students did not simply abandon

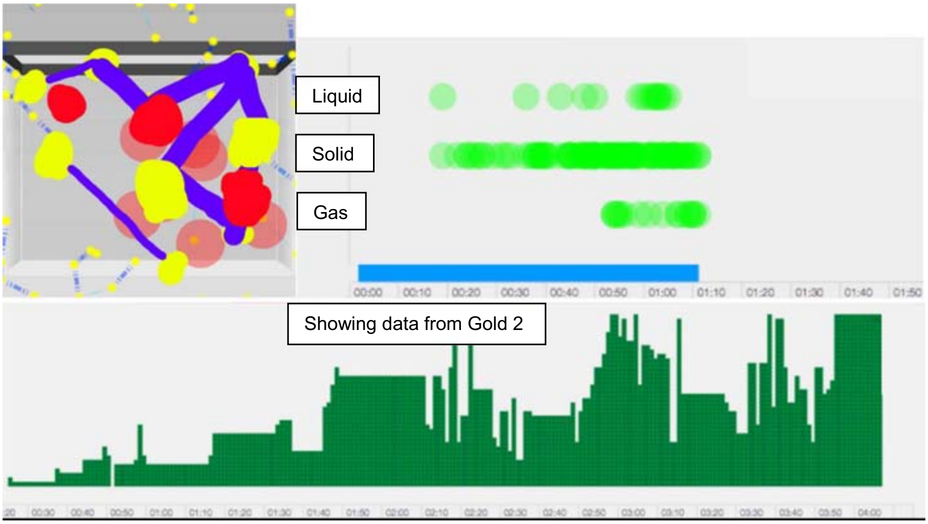


Fig. 11 Some shared representations that were projected on-screen, generated by observing students with iPads. Students shared freeform drawings (top left), tracked states of matter using button presses (top right), and measured levels of attraction between particles using graph-generating slider tools (bottom)

the individual representations. Rather, they appear to have used both representations as feedback on how individuals and the group should move to achieve the desired state. Individual students were able to use the colors and lines of their own particle to figure out what it looks like to be solid, liquid, and gas, which then allowed them to use these emerging understandings to evaluate and direct the performance of the group, using the state meter and iPad representations as guideposts for their evaluations. At the same time, moments when the collective representations showed that the group failed to create the target state also encouraged more individual investigation of particle colors and lines, to figure out what exactly the group needed to do to shift their overall state of matter.

Rules

Rules - individual

For both student-as-particle and student-as-heat activities, the rules that governed students' individual movements fell into three categories, classroom, STEP simulation, and science rules (e.g., rules of particle behavior, rules of inquiry). Classroom rules included encouraging individual students to pay attention to the screen and to the ways that their peers were moving. This meant that feedback was provided to individual students, and they could choose to listen or ignore their peers. When using the simulation, individual movements were constrained in that students could not move outside of the designated tank area, or their movements would not be tracked. Similarly, as students began to learn about particle behaviors, individual actions became more scientifically normative. In the initial activities, students could experiment with making solid, liquid, and gas in whatever ways they wanted. However, as the class discovered rules of particle behavior (e.g., that you have to vibrate in one place to form a solid), students had to conform to these rules. For example, in Study 5, once the students had figured out that particles in a solid needed to remain relatively still, a student who was moving all around the tank was chastised by the teacher: "Bailey, you just went out of the container - is that how ice would behave?" And after the student admitted that he was not acting like ice, the teacher replied: "Then you should change what you're doing." Though the rules guiding individual behavior were flexible at first, they guided students' behaviors more strictly as the class reached consensus on how particles should move. This example demonstrates how rules are often invented by individuals to self-regulate their own activity and also how they can be used to regulate others. Thus, individual embodiment is often structured by rules that, while they may originate with individuals, are often enhanced, and agreed upon collectively.

Rules - collective

However, using rules to regulate others does not necessarily mean that the students are acting in coordination with one another. At the collective level, the normative class and science rules were the most salient. Normative science rules were built into STEP and thus governed how students needed to coordinate with one another to form the desired state of matter. When students tried to accomplish tasks such as changing the computer-controlled particles to ice via removing their heat sources from the tank, this required the collective coordination of all students in the space to achieve the desired effect. If a single student decided to stay in the middle of the room and continue giving heat to the particles with their energy wand, then the collective would fail to create a full tank of ice. The teachers also frequently worked with the students to create an external representation of their understanding of the science rules built into STEP in the form of a public description on a large writing pad. This was intended to be both a repository of the shared understanding and a guide for ongoing activity (Ritella and Hakkarainen 2012).

Additionally, rules of inquiry were also critical to the activities. Students engaged in phases of investigation, observation, and prediction as they explored the STEP environment (Danish et al. 2015). Rules of inquiry however, sometimes clashed with classroom rules. As observers, students have to provide feedback to their peers who are moving in the physical space. However, because students were calling out at the same time, this went against typical turn-taking norms where students might wait before talking. Additionally, classroom rules were based on the norms for students' everyday class behaviors, such as not colliding with classmates while embodying particles. The typical classroom rule of not running indoors was lifted so that the group could embody gas. However, the rule of no collision contradicted normative rules governing particle behavior. For example, real particles in a gas collide into each other as they travel at high speeds, the classroom rules stipulated that students embodied gas by running in circles and avoiding collisions.

Rules - interconnected

Although the examples listed above separated between individual and collective rules, in reality, these rules were not as easily decoupled, and it is important to ask how they are interconnected (See questions in Table 1). Although rules can be codified, the nature of the STEP activities meant that the typical classroom or normative science practices often had to be renegotiated. An analysis of the intersection of individual and collective rules must therefore consider the nature of social negotiation, which inherently depends on individuals reaching consensus (or not). As noted in our data, this was especially true when there were contradictions between not only individual and collective rules but within each category (i.e., classroom, simulation, and science rules). Viewing the coordination of these different kinds of rules is, therefore, crucial to understanding how individuals make choices about embodied action within a collective activity.

Division of labor

Division of labor - individual

The division of labor is a key mediator because it offered insights into the intended roles for students, and how other roles might emerge that challenge the original division of labor created for students. In STEP, the two main roles offered to students were that of a particle and a heat source, but in practice students also embodied alternative roles that they saw as related to the embodied activity. For example, in the student-as-particle role, students sometimes shifted out of their role and started pretending to be an animal of their choice (e.g., a deer or a bunny). Although such actions were important in terms of student agency, these moments also created tensions in how to renegotiate the relevance of these actions. This was especially evident when student shifted from the student-as-particle to student-as-heat role. As particles, students had a direct mapping to particle behavior. As heat however, students perceived that they had a more indirect influence on the particles. Students could not directly move the particles, but rather had to observe the effects of students-as-heat on the particles. Thus, students often had to re-learn what it meant to move in the STEP space. In Study 4, students struggled to make this transition, and attempted to run quickly as heat sources in order to make gas – a rule for movement that worked well for a student-as-particle but not for heat wands. To help students adjust their movements to their new role, the teachers instructed them to hold their arms out to make themselves a "bubble" (See Fig. 12). This was intended to give them a physical reminder of their circular heat wand on the screen and to encourage them to slow down and observe what happened when their "bubble" touched the computer-controlled particles. The division of labor at the individual level emphasizes student attending to their own role and their own actions, while recognizing that each individual might therefore be focused on a different set of embodied actions or goals within the collective activity.

Division of labor - collective

Collective roles, on the other hand, focus the students on helping the group achieve their collective aims. Although these roles are individually assigned, coordinating, or shaping group activity depends on social negotiation. Thus, for the group to achieve their goals, the students acting as particles needed the feedback from their peers who take on the "observer role". In Study 4, we leveraged the role of an active observer. In terms of achieving the collective object

Fig. 12 Students making a "bubble" with their arms to remind themselves of their new role as heat wands

of learning, the active observer role allowed the group to collectively reflect on what the particles had done.

Division of labor – Interconnected

It is at the intersection of the individual division of labor and the collective level where disagreements about the collective focus became visible. This collective level recognizes members as having unique power or privilege in ways that can dramatically impact individual experiences. For example, in Study 1, the teacher decided to explicitly promote the notion of a "director" from within the group, and the director took on the role of telling the different particles where to go and when. This helped the students to coordinate their actions, but also led to a new form of hierarchy within the group, at least for the duration of that activity. Other times, the community of students resisted direction from their peers, or the teacher. In a more recent study, the researcher decided to explicitly leverage the community as a resource for sensemaking and intentionally ceded the floor to students using new forms of embodiment that might have otherwise been prohibited by the teacher. This allowed students to introduce and agree upon the use of dance moves such as the "floss" to illustrate the behaviors of particles (Georgen 2019). The floss then became the go-to method for demonstrating how ice particles vibrate while staying relatively still, a challenging but important concept for learners who often assume ice particles look and behave the same as their conception of macroscopic ice cubes. Studies focused on embodiment often ignore the role of power and privilege within these spaces, but these examples and others illustrate how the power, whether granted implicitly or explicitly, to influence the motion of one's peers can have dramatic consequences upon the collective embodiment.

The community as model and audience co-existed with the community as determinants of consensus, power, and privilege, and often fed off one another, because individual students shifted in and out of their roles as directors in the space and recipients of directions. For example, if one student playing as a particle chose to run quickly while the other students were moving slowly, the slow-moving particles (as the audience of this movement) could respond negatively to this deviance and encourage their peer to slow down and join them in making liquid. At the same time, an individual student can use their movements in the space as bids for new collective ways of moving, which might inspire other students to move quickly as well. As many different students offer up new ways of moving, the group negotiates through talk and movement to determine how the group will move in order to form the target state. Individual movements can influence this negotiation, and the decisions of the group can also be turned around and used to pressure individuals to change how they move.

Discussion

We developed the LEAF framework as part of our ongoing efforts to understand how the body can support cognition and learning. Specifically, LEAF was developed in an effort to combine frameworks for embodied cognition (i.e., focus on the individual learner) with CHAT (i.e., focus on collective activity). In combining the two, our goal was to explore the benefits of adding an explicit focus on embodiment within CHAT, as well as the benefits of exploring collective activity for understanding individual and collective embodiment in new ways. We believe that the results demonstrate the importance of understanding embodied learning as simultaneously individual and collective, and as mediated by tools, rules, community, and a division of labor.

We have endeavored to illustrate this relationship by drawing on seven different implementations of the STEP: Particles environment, which were implemented over 6 years of iterative design and research activity. Across these implementations, we have illustrated how embodied learning cannot be simply attributed to one body, or one embodied action. Nor can it be solely attributed to the technology that lets us track embodied movement and provide feedback to learners in real-time. Rather, we must try to unpack all of the mediators and activities in which embodied learning occurs, and explore these activities in ways that go beyond prior efforts from embodied cognition or CHAT. Similar to Tissenbaum et al. (2017), we see value in exploring how bodies in coordination, both convergent and divergent, can support sense-making. Our hope is that our examination of the different mediators of this activity, explored simultaneously at both the individual and collective level, helps to further elucidate the process for other designers and researchers of collaborative environments that leverage embodied activity.

Much of the literature on embodied cognition can be labeled as either individual (Lindgren et al. 2019), with a focus on how learners' bodies support their cognitive processes, or collective (Ma and Hall 2018), with a focus on the unique experience of ensembles attempting to coordinate their learning. We believe both of these branches of literature are quite valuable, and have attempted to build upon them equally. In fact, our goal has been to synthesize them into a new and unique account of embodiment that recognizes both of these traditions, building on studies of the body that focus on cognition and learning (Lindgren et al. 2019), as well as on communication (Goodwin 2000), and collective action (Ma and Hall 2018). The whole is, we believe, greater than the sum of the parts in that it provides new insights not only into how each of these dimensions operates separately, but also into how they are mutually constitutive, with individual experiences both shaped by, and helping to shape the collective experience.

At the same time, we have attempted to build on CHAT (Engeström 1987), a theoretical framework that has long been explored within CSCL (Ritella and Hakkarainen 2012). Here, our goal again was not to add a fundamentally new dimension, but to highlight some important insights that we believe are not always foregrounded in prior research. That is, CHAT has always, to our understanding, explored the dialectic between individuals and the collective. However, many accounts within this tradition inadvertently privilege one dimension over the other, orienting us toward the collective at the expense of the individuals who make it up or vice versa (Witte and Haas 2005). By explicitly characterizing and labeling the individual and collective dimensions as well as their intersection, our goal was to make this dialectic more concrete, and more visible, exploring how group cognition and individual cognition are intertwined (Stahl 2010). In doing so, we were challenged to articulate the relationship between the two, as well as their unique contributions.

The end result is, we believe, a framework that can help us to better understand embodied activity, not just embodied action, at these two levels (individual and collective) simultaneously without having to direct our attention away from either. Analytically, we believe this helped shed light on the impact of our design decisions, and how learners' experiences were shaped by them. We find that most of the existing approaches to embodied cognition focus on only one dimension or the other (individual or collective) or on a subset of mediators such as focusing narrowly on how the software tools support individual learning. In contrast, we believe that LEAF points to the value that attending to all of the mediators across the individual and collective dimensions might add to prior analyses and frameworks. The tools that learners use are impacted by the object of their activity, and the object is negotiated by the community who follows a shared set of rules, while organizing around a unique distribution of labor. Each of these impacts the others, and thus we feel that any analysis that leaves one or more out is fundamentally incomplete. Furthermore, we are conscious that many applications of CHAT are viewed as too vague or all-encompassing (Witte and Haas 2005), and believe that articulating our framework as an explicitly analyzable list of mediators and their relationships can help to make it more explicit and concrete in order to support future design and research efforts that leverage CHAT in CSCL and beyond.

Design guidelines emanating from LEAF

To further illustrate the concrete value of LEAF in supporting the design and analysis of embodied learning environments, we propose the following design guidelines that build on our ongoing work with the STEP environment and beyond:

1) Design for collective embodiment of collective phenomena.

Not all concepts or phenomena of interest can be meaningfully represented or explored at the individual level. In fact, it is beneficial to explore many phenomena as complex and collective, made up of many different elements (Hmelo-Silver and Azevedo 2006). This was the case with students' exploration and understanding states of matter in the STEP environment. We have found that collective embodiment where students must all coordinate their actions are particularly fruitful for exploring this kind of phenomena as their efforts to coordinate their motions help to make features of the aggregate more salient, such as the realization by students in STEP that multiple particles need to behave similarly for a state of matter to come to be.

2) Design for both individual and collective embodiment.

Our analysis indicates that embodiment has meaning for students both individually and within the collective. Therefore, it behooves us to design to support these two experiences in unique ways. In the case of STEP, being able to see their individual avatars helped students to coordinate their individual motion. At the same time, aggregate representations such as the state meters were important for helping them to make sense of their collective activities. Effective designs need to attend to both dimensions.

3) Design for the interaction of individual and collective embodied activity.

   As we note above, individual and collective activity exist in the same place at the same time, and recognizing this can help enhance our designs to capitalize on this overlap. In the STEP environment, this took the form of not only providing representations for both as in point 2, but in designing to support students in transitioning between the two, and in recognizing that some tools might support connecting the two. For example, the representation of the attraction between particles in STEP appears to have helped students to coordinate their individual actions with those of their peers in powerful ways as they attempted to impact the collective. It was often easier for them to aim to move in concert with one friend first, rather than trying to arrange 10 of their peers simultaneously.

4) Design to support collaborative reflection about how collective embodiment is tied to conceptual ideas.

We rarely saw students come to instantaneous conclusions about their embodied activity while engaging in it. Rather, they were busy acting, and often distracted by the many activities that occurred at once. In our earlier designs, having moments where the students could discuss their prior embodiment proved crucial to them recognizing the import of those interactions, interpreting them, and planning new actions. These moments allow students to collaboratively understand how individual and collective actions map to conceptual ideas. However, embodied activities are often particularly challenging to reflect on because they are fleeting and may not leave a trace in the environment. Therefore, in later designs, we developed annotation tools to support reflection by helping students to represent key aspects of their peers' embodiment for later consideration. In both cases, the opportunity to discuss and reach consensus seems crucial for students to recognize the key ideas that they were intuitively exploring through their embodied activity. For all designers, it will be important to consider how to support reflection on embodied activities which are fleeting, and which therefore do not lend themselves to consideration in the same way that static representations do.

5) Always attend to and design for embodied mediators of activity - not just the tool.

It is easy to think of ourselves as technology designers, especially after spending months focusing on how our motion tracking technology can be calibrated to recognize students' movement and then represent them in meaningful ways. However, the LEAF framework reminds us of the importance of attending to all of the key mediators of activity (rules, tools, community, and division of labor) in our designs. This is important both for helping our implementations and helping us modify our designs themselves. Thus, our attention to the importance of reflection not only helped us to think about how to help students make sense of their time in the embodied STEP simulation via distinct divisions of labor (e.g., alternating in the role of actor or observer), it also suggested next steps for our tool design (e.g., providing annotation tools to help connect the embodied activity and the reflection opportunities together more seamlessly) and for how we think about the entire community (e.g., working together with the teacher to develop consensus around norms that can further guide embodied activity).

Designing for computer-supported, collaborative, embodied learning environments is quite challenging in part because while embodiment is central to our lived experiences, it is often disconnected from how we have learned to use computers to support work and learning. With LEAF and these guidelines, however, we believe it is possible to consistently refine our designs to focus on how embodied learning is unique, and how it is situated in meaningful activity that we can also design for.

Conclusion

Evolving technologies make it increasingly easy and affordable to support embodied activity in formal and informal learning environments alike. Although the field has provided robust insights into how we might support individual embodied learning, LEAF offers a holistic framework that can allow researchers to understand how to support the design of collaborative learning environments by attending to both dimensions of learning. Additionally, our goal in developing LEAF is to help ensure that these technologies are taken up by educators in ways that build on what the learning sciences know about embodied cognition and learning, and support learning in truly robust and deep ways.

Looking forward, we believe this framework can serve as both a springboard for further theoretical development, and as a powerful design heuristic for planning new tools and activities that leverage the body for learning. Theoretically, we demonstrated the importance of each mediator in the two dimensions of individual and collective, but much work remains to document all of the different ways that these mediators might be realized, and thus all of the unique ways that embodied cognition might be understood. For example, our initial forays into contrasting the STEP: Particles activities with the STEP: Bees activities suggest that there are additional nuances to be explored in how different content areas may benefit from distinct forms of embodied activity, both individual and collective (Danish et al. 2019). We look forward to exploring these nuances, and hope that others will join us.

We also believe that the design heuristic reified in the questions of Table 1 can provide a powerful tool for designing and iteratively refining new forms of embodied learning activity. By focusing on the classroom as a site for collective embodied learning, we hope to support the continued adaptation of embodied learning research into this important formal context, which provides unique challenges given the number of participants that must be supported. At the same time, we believe that continuing to explore the different mediators in design implementations can help to inform both the embodied learning design space, and feedback on the underlying theories.

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References

Alibali, M. W., & Nathan, M. J. (2012). Embodiment in mathematics teaching and learning: Evidence from learners' and teachers' gestures. *Journal of the Learning Sciences, 21*(2), 247–286.

Baker, M., Hansen, T., Joiner, R., & Traum, D. (1999). The role of grounding in collaborative learning tasks. *Collaborative Learning: Cognitive and Computational Approaches, 31*, 63.

Barsalou, L. W. (2003). Situated simulation in the human conceptual system. *Language & Cognitive Processes, 18*(5–6), 513–562.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology, 59*, 617–645.

Barsalou, L. W. (2010). Grounded cognition: Past, present, and future. *Topics in Cognitive Science, 2*(4), 716–724.

Cole, M. (1996). *Cultural psychology : A once and future discipline*. Cambridge: Belknap Press of Harvard University Press.

Cooley, C. H. (1902). Looking-glass self. The production of reality: Essays and readings on social interaction, 6. Chicago

Colella, V. (2000). Participatory simulations: Building collaborative understanding through immersive dynamic modeling. *Journal of the Learning Sciences, 9*(4), 471–500.

Damşa, C. (2014). The multi-layered nature of small-group learning: Productive interactions in object-oriented collaboration. *International Journal of Computer-Supported Collaborative Learning, 9*(3), 247–281.

Danish, J. A. (2014). Applying an activity theory Lens to designing instruction for learning about the structure, behavior, and function of a honeybee system. *Journal of the Learning Sciences, 23*(2), 1–49.

Danish, J. A., & Gresalfi, M. (2018). Cognitive and sociocultural perspective on learning: Tensions and synergy in the learning sciences. In F. Fischer, C. E. Hmelo-Silver, S. R. Goldman, & P. Reimann (Eds.), *International Handbook of the Learning Sciences*. New York: Routledge.

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. A., Enyedy, N., Saleh, A., Humburg, M., DeLiema, D., Dahn, M., & Lee, C. (2017a). *STEP-Bees: Coordinating embodied interaction with peers, teachers, and computer simulation to support learning.* Paper presented at the annual conference of the American Educational Research Association, San Antonio, TX.

Danish, J. A., Humburg, M., Saleh, A., Lee, C., Dahn, M., Kiefert, D., & Enyedy, N. (2017b). *A Socio-Cultural Framework for Embodied Cognition*. Paper presented at the Jean Piaget society, San Francisco, CA.

Danish, J. A., Enyedy, N., Humburg, M., Saleh, A., Dahn, M., Lee, C., ... Georgen, C. (2018). *STEP-Bees and the Role of Collective Embodiment in Supporting Learning Within a System*. Paper presented at the international conference of the learning sciences, London, England.

Danish, J. A., Enyedy, N., Humburg, M., Davis, B., & Tu, X. (2019). *Collective embodied activity and how different concepts map to social exploration*. Paper presented at the International Conference on Computer Supported Collaborative Learning, Lyon France.

Davidsen, J., & Ryberg, T. (2017). "This is the size of one meter": Children's bodily-material collaboration. *International Journal of Computer-Supported Collaborative Learning, 12*(1), 65–90. https://doi.org/10.1007/s11412-017-9248-8.

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 Science, 120*(9/10), 611–639. https://doi.org/10.1108/ils-08-2019-0081.

DeLiema, D., Enyedy, N., Danish, J., Lee, C., Illum, R., Dahn, M., ... Mahoney, C. (2016). *Blending play and inquiry in augmented reality: A comparison of playing a video game to playing within a participatory model.* Paper presented at the International Conference of the Learning Sciences.

DeLiema, D., Enyedy, N., & Danish, J. A. (2019). Roles, rules, and keys: How different play configurations shape collaborative science inquiry. *Journal of the Learning Sciences, 28*(4–5), 513–555. https://doi.org/10.1080/10508406.2019.1675071.

Eckert, P. (1989). Jocks and burnouts: Social categories and identity in the high school: Teachers College Press.

Engeström, Y. (1987). *Learning by expanding: An activity - theoretical approach to developmental research.* Orienta-Konsultit Oy: Helsinki.

Engeström, Y. (1999). Activity theory and individual and social transformation. In Y. Engeström, R. Miettinen, & R.-L. Punamäki (Eds.), *Perspectives on activity theory.* New York: Cambridge University Press.

Engeström, Y., & Sannino, A. (2010). Studies of expansive learning: Foundations, findings and future challenges. *Educational Research Review, 5*(1), 1–24. https://doi.org/10.1016/j.edurev.2009.12.002.

Engeström, Y., Miettinen, R., & Punamäki, R.-L. (1999). *Perspectives on activity theory.* New York: Cambridge University Press.

Enyedy, N. (2003). Knowledge construction and collective practice: At the intersection of learning, talk, and social configurations in a computer-mediated mathematics classroom. *The Journal of the Learning Sciences, 12*(3), 361–408.

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*, 1-32.

Enyedy, N., Danish, J. A., & DeLiema, D. (2015). Liminal blends: How students blend symbols, experiences, and their own bodies together in order to co-construct meaning in a collaborative augmented-reality learning environment. *International Journal of Computer Supported Collaborative Learning.*

Flood, V. J., Neff, M., & Abrahamson, D. (2015). Boundary interactions: Resolving interdisciplinary challenges using digitized embodied performances. In O. Lindwall, P. Häkkinen, T. Koschman, P. Tchounikine, & S. Ludvigsen (Eds.), *Exploring the material conditions of learning: The computer supported collaborative learning (CSCL) conference* (Vol. 1). Gothenburg: International Society of the Learning Science.

Gallagher, S., & Lindgren, R. (2015). Enactive metaphors: Learning through full-body engagement. *Educational Psychology Review, 27*(3), 391–404.

Georgen, C. (2019). *"Can't nobody floss like this!": Exploring embodied science learning in the third space.* Paper presented at the a wide Lens: Combining embodied, enactive, extended, and embedded learning in collaborative settings, 13th international conference on computer supported collaborative learning (CSCL) 2019, Lyon, France.

Goldin-Meadow, S., & Alibali, M. W. (2013). Gesture's role in speaking, learning, and creating language. *Annual Review of Psychology, 64*, 257.

Goldin-Meadow, S., & Beilock, S. L. (2010). Action's influence on thought: The case of gesture. *Perspectives on Psychological Science, 5*(6), 664–674.

Goodwin, C. (2000). Action and embodiment within situated human interaction. *Journal of Pragmatics, 32*, 1489–1522.

Goodwin, C. (2017). *Co-operative action*. Cambridge: Cambridge University Press.

Graesser, A. C., Fiore, S. M., Greiff, S., Andrews-Todd, J., Foltz, P. W., & Hesse, F. W. (2018). Advancing the science of collaborative problem solving. *Psychological Science in the Public Interest, 19*(2), 59–92.

Greeno, J. G., & Engeström, Y. (2014). Learning in activity. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (2nd ed.). Cambridge: Cambridge University Press.

Griffin, P., & Cole, M. (1984). Current activity for the future: The Zo-ped. *New Directions for Child Development, 23*, 45–64.

Gutiérrez, K. D., & Jurow, A. S. (2016). Social design experiments: Toward equity by design. *Journal of the Learning Sciences, 25*(4), 565–598. https://doi.org/10.1080/10508406.2016.1204548.

Gutiérrez, K. D., & Rogoff, B. (2003). Cultural ways of learning: Individual traits or repertoires of practice. *Educational Researcher, 32*(5), 19–25.

Hall, R., & Stevens, R. (2015). Developing approaches to interaction analysis of knowledge in use. In A. A. di Sessa, M. Levin, & N. J. S. Brown (Eds.), *Knowledge and interaction: A synthetic agenda for the learning sciences*. New York: Routledge.

Hmelo-Silver, C. E., & Azevedo, R. (2006). Understanding complex systems: Some Core challenges. *Journal of the Learning Sciences, 15*(1), 53–62.

Hod, Y., & Sagy, O. (2019). Conceptualizing the designs of authentic computer-supported collaborative learning environments in schools. *International Journal of Computer-Supported Collaborative Learning, 14*(2), 143–164. https://doi.org/10.1007/s11412-019-09300-7.

Howison, M., Trninic, D., Reinholz, D., & Abrahamson, D. (2011). *The mathematical imagery trainer: From embodied interaction to conceptual learning*. Paper presented at the Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.

Humburg, M., & Danish, J. (2019). *Using Annotations to Unpack Embodied Models of States of Matter in Early Elementary Science*. Paper presented at the annual meeting of the American Educational Research Association, Toronto, CA.

Humburg, M., Danish, J. A., Tu, X., Georgen, C., Davis, B., & Enyedy, N. (2020). Using Scientific Annotation Tools to Support Collaborative Embodied Learning in Elementary School Classrooms. *[Manuscript submitted for publication]. Learning Sciences, Indiana University.*

Järvelä, S., Kirschner, P. A., Hadwin, A., Järvenoja, H., Malmberg, J., Miller, M., & Laru, J. (2016). Socially shared regulation of learning in CSCL: Understanding and prompting individual-and group-level shared regulatory activities. *International Journal of Computer-Supported Collaborative Learning, 11*(3), 263–280.

Jeong, H., & Hmelo-Silver, C. E. (2016). Seven affordances of computer-supported collaborative learning: How to support collaborative learning? How can technologies help? *Educational Psychologist, 51*(2), 247–265.

John-Steiner, V., & Mahn, H. (1996). Sociocultural approaches to learning and development: A Vygotskian framework. *Educational Psychologist, 31*(3–4), 191–206.

Jordan, B., & Henderson, A. (1995). Interaction analysis: Foundations and practice. *Journal of the Learning Sciences, 4*(1), 39–103.

Lakoff, G., & Johnson, M. (2003). Metaphors we live by. 1980. Chicago: U of Chicago P. Chicago

Lee, C. D. (2017). Toward a framework for culturally responsive design in multimedia computer environments: Cultural modeling as a case. In *Culture, technology, and development* (pp. 42-61): Psychology Press.

Lindgren, R. (2015). Getting into the cue: Embracing technology-facilitated body movements as a starting point for learning. In V. Lee (Ed.), *Learning technologies and the body: Integration and implementation in formal and informal learning environments* (Vol. 135). New York: Routledge.

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. https://doi.org/10.3102/0013189x13511661.

Lindgren, R., Morphew, J., Kang, J., & Junokas, M. (2019). An embodied Cyberlearning platform for gestural interaction with cross-cutting science concepts. *Mind, Brain, and Education, 13*(1), 53–61. https://doi.org/10.1111/mbe.12191.

Ma, J. (2016). Designing disruptions for productive hybridity: The case of walking scale geometry. *Journal of the Learning Sciences, 25*(3), 335–371. https://doi.org/10.1080/10508406.2016.1180297.

Ma, J., & Hall, R. (2018). Learning a part together: Ensemble learning and infrastructure in a competitive high school marching band. *Instructional Science, 46*(4), 507–532.

Newen, A., De Bruin, L., & Gallagher, S. (2018). *The Oxford handbook of 4E cognition*. Oxford: Oxford University Press.

Philip, T. M., Gupta, A., Elby, A., & Turpen, C. (2018). Why ideology matters for learning: A case of ideological convergence in an engineering ethics classroom discussion on drone warfare. *Journal of the Learning Sciences, 27*(2), 183–223.

Ritella, G., & Hakkarainen, K. (2012). Instrumental genesis in technology-mediated learning: From double stimulation to expansive knowledge practices. *International Journal of Computer-Supported Collaborative Learning, 7*(2), 239–258.

Saleh, A., Danish, J. A., Enyedy, N., & Lee, C. (2015). Assessing young Children's cognition through multimodal interviews. In O. Lindwall, P. Häkkinen, T. Koschman, P. Tchounikine, & S. Ludvigsen (Eds.), *Exploring the Material Conditions of Learning: The Computer Supported Collaborative Learning (CSCL) Conference* (Vol. 1). Gothenburg: The International Society of the Learning Sciences.

Saleh, A., Danish, J., Humburg, M., & Enyedy, N. (2017). *How body-based actions support elementary students' science explanations about the particulate nature of matter*. Paper presented at the annual conference of the American Educational Research Association, San Antonio, TX.

Stahl, G. (2010). Guiding group cognition in CSCL. *International Journal of Computer-Supported Collaborative Learning, 5*(3), 255–258.

Stahl, G. (2017). Group practices: A new way of viewing CSCL. *International Journal of Computer-Supported Collaborative Learning, 12*(1), 113–126. https://doi.org/10.1007/s11412-017-9251-0.

Stahl, G., Ludvigsen, S., Law, N., & Cress, U. (2014). CSCL artifacts. *International Journal of Computer-Supported Collaborative Learning, 9*(3), 237–245.

Steier, R., Kersting, M., & Silseth, K. (2019). Imagining with improvised representations in CSCL environments. *International Journal of Computer-Supported Collaborative Learning, 14*(1), 109–136.

Tissenbaum, M., Berland, M., & Lyons, L. (2017). DCLM framework: Understanding collaboration in open-ended tabletop learning environments. *International Journal of Computer-Supported Collaborative Learning, 12*(1), 35–64.

Tu, X., Georgen, C., Danish, J. A., & Enyedy, N. (2020). *Extended embodiment: Physical and conceptual tools in a mixed-reality learning environment as supports for young learners' exploration of science concepts*. Paper to be presented the international conference of learning sciences (ICLS). Nashville, TN.

Vygotsky, L. S. (1978). *Mind in society : The development of higher psychological processes*. Cambridge: Harvard University Press.

Wertsch, J. V. (1985). *Vygotsky and the social formation of mind*. Cambridge: Harvard University Press.

Wertsch, J. V., & Penuel, W. (1998). The individual-society antinomy revisited: Productive tensions in theories of human development, communication, and education. *The handbook of education and human development: new models of learning, teaching and schooling*, 415.

Wilensky, U., & Stroup, W. (1999). *Learning through Participatory Simulations: Network-based Design for Systems Learning in Classrooms.* Paper presented at the Computer Support for Collaborative Learning (CSCL) 1999 Conference, Stanford Univ, Palo Alto, CA.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review, 9*(4), 625–636. https://doi.org/10.3758/bf03196322.

Witte, S. P., & Haas, C. (2005). Research in activity: An analysis of speed bumps as Mediational means. *Written Communication, 22*(2), 127–165. https://doi.org/10.1177/0741088305274781.

Youngquist, J., & Pataray-Ching, J. (2004). Revisiting "play": Analyzing and articulating acts of inquiry. *Early Childhood Education Journal, 31*, 171–178.

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