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Constructing liminal blends in a collaborative augmented-reality learning environment

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Abstract In vision-based augmented-reality (AR) environments, users view the physical world through a video feed or device that *augments* the display with a graphical or informational overlay. Our goal in this manuscript is to ask *how* and *why* these new technologies create opportunities for learning. We suggest that AR is uniquely positioned to support learning through its ability to support students in developing "conceptual blends"—which we propose extend beyond cognitive spaces to include the layering of multiple ideas and physical materials, often supplied by different conversation participants. We document one case study and trace how the narrative structure of a board game, the physical floor materials (e.g. linoleum), a student's first-person embodied experiences, the third-person live camera feed, and the augmented-reality symbols become integrated in the activity. As a result, students' conceptualization of force and friction become fused with a diverse set of intellectual resources. We conclude by suggesting that the framework of liminal blends may inform the design of future AR learning environments and in particular help generate predictions about the ways in which the juxtaposition of certain resources may otherwise produce unexpected results.

Keywords Augmented Reality · Physics education · Elementary education · Play · Video analysis · Conceptual blends

Introduction

There is a new class of computer-supported tools to aid learning referred to as mixed reality or augmented reality (henceforth AR) (Lindgren and Johnson-Glenberg 2013). In AR environments, users view the physical world through a video feed or device that *augments* the display with a graphical or informational overlay. For example, students might see a video feed of a peer running around the classroom with an arrow symbol overlaid on the video display to indicate

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the force that set the peer in motion. Studies have shown AR to be successful at promoting learning across the grade levels and across subject domains (Enyedy et al. 2012; Klopfer 2008).

While designing new technologies that effectively promote learning is a laudable goal in and of itself, as learning scientists, our primary goal should be to discover *how and why* these new technologies work. Further, as learning scientists, we want to turn the question, “does it work?” on its head and ask what these new technologies can reveal about the basic processes of learning and instruction. Understanding the relationship between AR learning environments and learning processes can also help us to better identify those moments when AR is truly beneficial to students rather than those when it is merely a novel and exciting alternative to other activities with little added benefit. In this paper we suggest that AR is uniquely positioned to support learning through its ability to support students in developing conceptual blends (Fauconnier and Turner 1998)—which we extend beyond cognitive spaces to include the integration of multiple ideas and physical materials, often supplied by different conversation participants, in a way that allows participants to draw new inferences.

That is, unlike the cognitive linguistics theory on which conceptual blending theory is based, we do not assume that blends (or cognition for that matter) occur exclusively inside students’ heads. Instead, we theorize that cognition is distributed and that some conceptual blends are constructed publicly in interaction and anchored by the material world. The goal of this manuscript is to outline and illustrate a new theory of conceptual blends specifically focused on explaining collaborative sense making in AR learning environments. We call this theory *liminal blends* to highlight that an important aspect of learning within AR environments is the way that students build up layers of meaning by using their bodies and their own subjective perspective to make sense of symbolic augmentation and science content. When the bodies and motions of students are blended with physical and symbolic objects, it creates an in-between space from which students can reason and generate new inferences. Liminal blends theory draws on and attempts to integrate a number of seemingly disparate theoretical traditions including cognitive linguistics, conversation analysis, and distributed cognition. To a lesser extent, this manuscript is a methodological paper in that we seek to define a distributed unit of analysis to describe collaborative sense making and outline our method for tracing the various intellectual resources that are publically blended together to create a liminal blend.

Learning physics through play: An example augmented reality system

In the Learning Physics through Play (LPP) project, we designed an AR system that uses sociodramatic play as a form of scientific modeling. In a prior article (Enyedy et al. 2012), we provided empirical evidence that the LPP curriculum helped 1st and 2nd graders learn the core concepts of force and motion. There are two key components to the LPP system: 1) an augmented-reality system that uses computer vision to record and display the students’ physical actions and locations, and 2) software that translates this motion into a physics engine and generates a visual display based on the sensing data. We tracked students’ physical motion in a $12' \times 12'$ carpeted area at the front of the classroom to create a *modeling space*. In this space, young children make predictions by pretending to be objects in motion and they see (simultaneously) their physical motion projected onto a large screen next to them in the form of an animated ball (see Fig. 1). For example, a student attempting to act out how a ball given a large force rolls first across pavement and then through sand might walk quickly at first (in interaction with imagined pavement) and then more slowly (in interaction with imagined sand).

After making predictions by directly modeling motion with their bodies, students in the LPP project seamlessly transition into a physics microworld, comparing their predictions to what happens in the ideal Newtonian simulation. Like other microworlds, LPP allows students

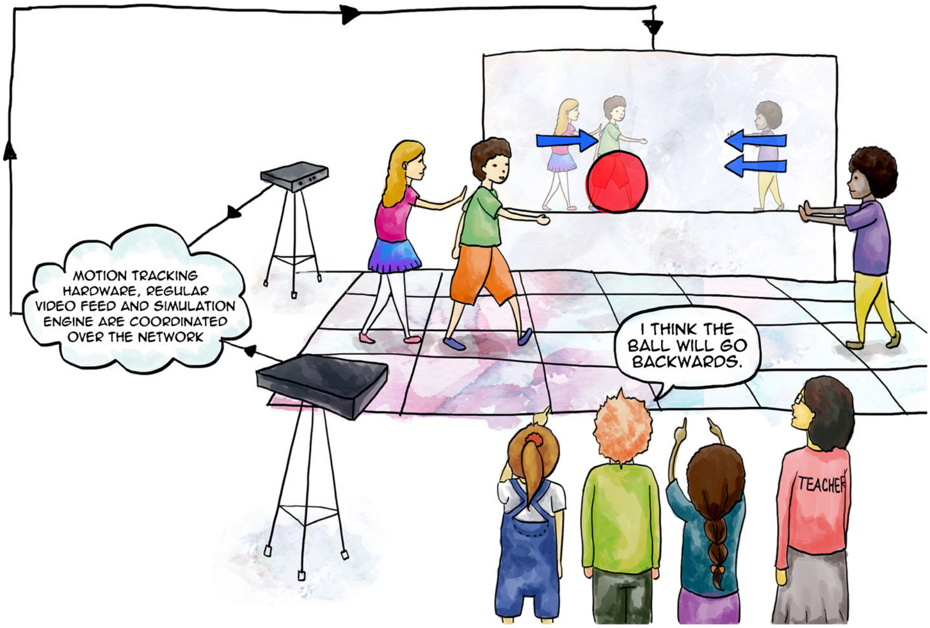

Fig. 1 In this microworld, students predict with their bodies the effects of force and friction and then compare their prediction with the visual, Newtonian simulation of a ball experiencing that same amount of force and friction

to see and manipulate a situation in ways impossible in the real world (e.g., turning off friction). We call students' initial activities in the AR system *play-as-modeling* because students are oriented toward using multiple experiences and resources to model motion as a set of rules. Much like in pretend play, one's activity is governed by and oriented toward articulating the rules of the imaginary situation (Sidnell 2011). During these play-as-modeling activities, students wear geometric patterns mounted on cards or hats that the computer can track by matching the patterns. With today's technology these hats are no longer necessary.

An important part of our pedagogical design was that the students developed all the images of objects, invisible forces, and the background art used in the LPP system during earlier lessons. Inventing these representations contributed to the understanding of the target concepts and helped students create a personally meaningful context for the activities. Moreover, students refined their symbols collectively through a process called progressive symbolization—a process of choosing what to represent and how, and then testing and refining how productive that representation was at generating predictions or helping to solve problems. In this way the activities slowly transitioned students from play-as-modeling to reasoning from symbols and concepts in a way that more closely resembles what is commonly recognized as scientific modeling.

In this project, the vast majority of first and second-grade students significantly improved their understanding of physics (see Enyedy et al. 2012 for full details). In our previously reported pilot study we used a pre-/ post-test design. Descriptive statistics were obtained on student gains. For the 43 students, the average pre-test score went up from 5.42 (SD01.38) to 8.54 (SD02.17) out of 16 on the post-test. Using a paired-samples *t*-test we determined that post-test scores were significantly higher than the pre-test scores, t(42)09.11, $p<.001$. The effect size of the gain was large, d01.99, indicating that the pre-test to post-test change was close to two standard deviations. To examine the effect size in more detail a Wilcoxon signed rank test was computed. Results indicated that 39 (91 %) of the students showed a pre to post-test gain (Z05.29, $p<.001$), with 36 (84 %) of the students increasing performance greater than one standard deviation. We also reported correlational analyses that examined the relation between grade level, age at the start of the study, gender, pre-test and post- test scores. Results indicated that there was no correlation between any of the demographic variables and the assessment scores. In sum, although we cannot make any claims that attribute the gains solely to the AR environment, students demonstrated significant improvement on all of the key measures. Furthermore, our analyses of students' interactions within the AR environment indicate that they expressed, confronted, and revised many common misconceptions as they engaged in classroom activities within the LPP environment. Furthermore, the depth at which these children learned these concepts was unusual for this age group. The teachers in the school were unwilling even to attempt to teach some of the concepts without the use of the AR environment.

To date we have been able to illustrate what learning looked like in this environment using qualitative analyses that focus on how our two design principles—the role of play and the role of progressive symbolization—contributed to these gains. However, what is needed, and what the liminal blends framework provides, is a microgenetic account of learning that allows us to pinpoint the details of how the affordances of AR relate to cognition and learning. The liminal blends framework offers a theory and methodology that addresses how multiple children co-construct meaning from within AR environments that require the student to align multiple sources of concurrent information. Liminal blends, as a distributed unit of analysis, allows us as analysts to trace how children stretch their understanding of a concept like friction across their bodies, material artifacts, and the contributions from multiple students.

Theoretical framework

If we look at a learner within an AR learning environment such as LPP, it accentuates what is always the case but often goes unnoticed—that the student has access to a vast number of resources for sense making. These include the observable world, physical objects that can be manipulated, other students in the space, and the teacher. Because the world is also viewed through the AR software, the student also has ready access to a simulated or imagined world replete with additional words and symbols, which are visually aligned with select aspects of the observable world. As the students talk, move, interact, and make use of physical objects in the space, the environment changes continually, and the number of potential resources that must be coordinated expands at a dizzying rate! Our goal in developing the theory of liminal blends is to provide an explanation for how students experience this vast array of resources and yet seem to bring these resources together in a coherent manner that allows for seamless sense making within the space and learning about the real world. In doing so, our goal is to develop a coherent theoretical account that explains both the successful moments of clarity and learning, and the moments when students are confused by the confluence of information resources at their fingertips.

Our theory and method is grounded in a sociocultural framework of distributed cognition (Cole and Engeström 1993). From this perspective, cognition is distributed: 1) within a person; 2) between an individual and the cultural world; 3) across individuals; and 4) across time. Learning involves a process through which individual actions shape the social world, and yet at the same time the social world shapes the individuals. Our goal in building on distributed cognition is to highlight the process through which students experience, select, and make use of the resources available to them throughout the distributed cognitive system. To accomplish this, we draw upon and synthesize theoretical accounts that work at multiple levels of analysis so that we can explain how students engage with the intellectual resources that span these analytic levels. Below we provide an account for how resources are experienced at the four levels of distributed cognition as well as how they are coordinated across levels.

Distributed within the person: Conceptual blends

As Cole and Engeström (1993) point out, mental resources are spread throughout the brain and need to be drawn together for cognition and learning. This is even more poignant in an AR environment where previously distal ideas need to be aligned, such as students' direct observations of the world, and symbol systems that scientists use to reason about the world. We find conceptual blending theory (Turner 2014) to be quite powerful in helping to explicate this task of aligning resources.

Conceptual blending is an extension of mental spaces theory (Fauconnier 1994), and provides a general model for the integration of concepts and the creative construction of meaning (Oakley and Hougaard 2008; Turner 2014). In theory, a conceptual blend is created by coordinating multiple, distinct conceptual spaces, or source domains, and projecting them into a hybrid conceptual space that has emergent properties not found in the source domains (Fauconnier and Turner 1998). For example, consider the following riddle (from Fauconnier and Turner 1998) about a monk who wakes up early one morning at the base of a mountain, hikes up a path on the mountain, meditates at the summit of the mountain, and then sleeps overnight at the summit. The next morning, the monk hikes back down the same path to the base of the mountain. The question: Is there a place on the path the monk occupies at the same time on both days? You can solve the riddle by imagining the monk walking up the mountain at the same time that you imagine the monk walking down the mountain (and since the monks cross paths, you can infer that they do occupy one location at the same time on the two days). Even though a single individual could not ascend and descend a mountain simultaneously, the conceptual blend creates a fictive space in which the monk's separate journeys (space 1 and space 2) play out at the same time (in the blend) and the solution materializes.

The process of conceptual blending is hypothesized to involve three operations. The first operation is ***composition***, where the different source domains (e.g., the monk on day 1 and the monk on day 2) are evoked and elements from one source domain are explicitly mapped to another (e.g., both monks enter the blend, but only one mountain and one sun enter the blend). The second phase is ***completion***, where an inference or a computation is made from the emergent properties of the blend (e.g., the monks must cross paths on the journey). Often, completion is thought to involve filling in the blend by matching it to memories or frames stored in long-term memory (Coulson and Oakley 2000). The third phase is ***elaboration***. Closely related to completion, elaboration involves extending the blend by continuing to bring in new elements, running the blend as a simulation, and extending it to new situations (e.g., what might the monks say to each other as they cross paths?). In our analysis, and for education more generally (where blends are not fully formed but developed over time), elaboration is perhaps the most important part of blending, as it is here that blends bring together disparate resources to produce new insights. Completion can thus be thought of as problem solving while elaboration refers to those moments when solving a problem leads to new insights and the development of new psychological tools.

While this theoretical framework provides a powerful framework for examining how conceptual resources might be aligned, it appears to do so in a vacuum, ignoring how the individual is also situated within a sociocultural context. Therefore, we suggest that an important aspect of this process is placing the blend in relation to a goal and then using the blend as a tool to achieve that goal. As many have noted about representations and other mental structures, a structure in the absence of activity is meaningless (Greeno and Hall 1997) and computation assumes that there is a reason for making the computation. Hence, for us, completion and by extension elaboration are fundamentally about putting the blend to use (e.g., placing the monks from space 1 and 2 together in order to determine if they do pass each other).

Another potential difficulty in using the original model of conceptual blends to inform educational research is that, consistent with the norms of cognitive linguistics, conceptual blending theory began as an individualistic account of mental computations (Fauconnier and Turner 1998). For example, the person tussling with the monk riddle and producing the blend was understood to be working without seeing a picture of the monk or the mountain, without walking on the mountain, and without working with others. The earliest blending researchers ignored any gestures, drawings, or imagined content that materialized during the problem-solving phase.

Our goal in incorporating conceptual blending theory into a larger distribution-cognition framework is to explore how these individual mental processes for building on various resources intersect with the material and social world.

Distributed within the cultural world: Materially anchored blends

In blending theory, the earliest attempts to handle the integration between external and internal space occur in studies of American Sign Language and gesture. These studies begin to recognize that blends stretch across the mental, embodied, and external spaces of the setting. For example, Liddell (1998), in introducing the term *grounded* blend, shows that external body movements and external manipulations of objects (including deictic points toward external objects) in real space become blended with internal concepts from memory in narrative space. Liddell (1998) illustrates this by describing a signer who, while describing a scene from Garfield, the cartoon about a lazy cat, uses his own head to show how Garfield moves in the cartoon. Internal conceptions of Garfield become blended with the visible appearance of the speaker's head movements. The speaker is understood to be modeling how Garfield acts, and important new information absent from the verbal channel emerges in the blend, such as Garfield's gaze direction and his interlocutor's height. In short, the appearance of the speaker's face plays a role in the interaction, giving immediate form to Garfield and adding information about Garfield's movements that never manifest in talk. The blend allows the depiction of Garfield's actions to stretch across the private imagination and the public movements of the body.

Others have considered the relationship between observable physical materials and conceptual content (Dudis 2004; Hutchins 2005; Parrill and Sweetser 2004; Parill 2012; Williams 2008). Hutchins (2005), for example, extends this work to a number of empirical cases in which the computations in the blend are performed in the material world. These 'materially anchored blends' re-envision the composition phase as the construction of material objects that superimpose structures on top of one another. For example, in a historical case from nautical navigation, Hutchins (1995) shows how the 32 points of the compass rose, which represent cardinal directions, are superimposed with solar time (e.g., a 24-hour clock), dividing 24 h into 32 45-minute periods. Because 45 min is a good approximation of lunar time, and thus also a good approximation of how much the tides change, this blended structure was used to compute at what time high tide would occur at a given port. The blend in this case is external, and the computation is done by manipulating the representational state of the material world. Other examples of materially anchored blends include a lecture on recursion explored through hand movements that resemble a rat's maze (Parrill and Sweetser 2004), a story about a motorcycle rooted in one hand sequentially showing the bike and the bike rider (Dudis 2004), and a teacher explaining how to tell time by taking the conceptions of divided circles and movement along a path and visually integrating them with a physical clock (Williams 2008).

In each case, the materially anchored blend incorporates an artifact from the environment—whether the body, a compass rose, or a clock—to structure thoughts about a given domain and enable one to compute or generate new predictions. In a blend, material entities take on new meanings distinct from their traditional application. In the above examples, the blend makes it so that a computer scientist's hands can become a rat in a maze, and a compass designed to measure cardinal directions can become an indicator of high tide at a given time. These new meanings and computational uses are emergent features in the blend, and only occur when experiences from one domain connect with content from another. As such, the material objects in the blend no longer exist as independent entities but as fusions with the other concepts.

Distributed within the social world and within time: Interaction analysis

Attending to the material circumstances of conceptual blends is a productive step, but it still can be seen as locating cognition as the act of individuals. Our distributed cognition framework suggests that it is not enough to simply analyze how individuals blend both physical and mental resources into a coherent whole. Rather, we also need to recognize the rich social contexts that also frequently include other participants. From this perspective, each resource in the material world gathers its meaning against the ground of other resources in the setting (Streeck 2009). These meanings are forged through social interaction, when participants make successive changes to public space by layering talk, the body, and the physical environment to establish a *semiotic ecology* that organizes their activity (Enyedy 2005; Goodwin 2013). Each interaction builds upon the recent history of co-participants' actions, which are often supported by a longer history of material structures and cultural conventions available in the community. The gradual overlay of resources on top of each other, or their *lamination* in interaction (Goodwin 2013), is what establishes the evolving semiotic ecology and what gives meaning to each resource. For example, through environmentally coupled gestures (Goodwin 2007), individuals use their body to gesture on or around other visible resources within their setting, creating communication that stretches across both embodied and material resources.

The notion of lamination highlights that communication builds up layers of semiotic fields, such as linguistic, prosodic, embodied, and material resources. Participants in interaction (and also observers) can see in public view how resources become laminated over time. As such, the study of lamination in interaction focuses on cognition in action distributed across people and resources. In moments of conceptual blending—such as the experience of a student moving around as if she were an inanimate ball in a physics simulation—we can examine how the lamination of talk, body movements, and physical resources create and modify the blend.

Bringing it all together: Liminal blends

As students combine resources from these many different spaces—from within their own minds, the material world, and the social world, new possibilities emerge, which allow students to look at the world in a fundamentally new way. In these cases, there is often a "blurring" that takes place as participants appear to move fluidly between spaces, referring to the physical world in one moment, and the symbolized symbolic world in the next as they connect the two through their embodied and culturally embedded interaction.

This process of laminating talk and action in order to blur the division between physical and conceptual resources has been referred to as *semiotic fusion* (Nemirovsky et al. 1998). For example, Nemirovsky and Monk (2000) describe a student who worked to make sense of a race depicted as a graph of distance over time. To do so, the student grappled with the visual display of the graph, her own visual and tactile interactions with the graph, and an imagined simulation of bears caught up in a foot race. Through talk, gesture and embodied activity, these disparate intellectual resources were fused together in the meaning-making process, "in ways that do not distinguish between symbols and referents" (Nemirovsky, et al. 1998, p. 141). While it might appear odd to move fluidly between discussing one's own motion and that of an imaginary bear, when properly aligned this movement between conceptually distinguished spaces is evidence of how the two disparate systems are being used for sense making. This observation led Nemirovsky et al., to note that the systems appear fused—and not confused—over successive laminations, which further demonstrates one way in which learning is intimately tied to the transformation of talk, action, and the physical environment (Danish 2014; Enyedy 2005; Goodwin 2013; Hall 1996).

This kind of fusion is not limited to young students, however. Ochs et al. (1994; 1996) noticed a similar pattern in professional scientists, leading them to coin the term *liminal worlds* to describe cases where "the distinction between the scientist as subject and the physical world as object is blurred" (Ochs et al. 1996, p. 347). In a study of professional physicists trying to understand emergent theories of the atomic structure of condensed matter, Ochs and colleagues (1996) found that scientists were, "taking on the perspective of (empathizing with) some object being analyzed and by involving themselves in graphic (re)enactments of the physical events" (p. 360). For example, in trying to describe a finding related to atomic spin, a scientist used first-person pronouns (e.g., "I") to describe a series of atomic transitions that were depicted as a graph on the chalkboard, saying things such as, "when I come down I'm in the domain state," (p. 331). Ochs et al. described these linguistic constructs where the participants moved between a normative scientific description of a phenomenon to a more personal first-person description as liminal worlds, because they were episodes in which the referent atomic world and the visual displays of an external graph were blended together with subjective reasoning from a first-person perspective. These liminal worlds, which we consider to be a special case of materially anchored conceptual blends, created a qualitatively different set of resources from which to reason and were found to be productive in modeling and theory building.

This leads us to view the constitution of liminal worlds as the product of successive distributed acts of semiotic fusion. ***Liminal blends*** are not markers of students becoming confused about who or what they are, but rather, play experiences in which discarding one's identity and immersing in a new role paves routes for learning (Steen and Owens 2001). In other words, the fusion between the subjectivity of the student and the virtual and real objects in augmented reality creates new opportunities for learning. The LPP environment deliberately fostered the constitution of liminal worlds in which one's subjective understanding (and the resources that come with moving the body) is integrated with the more formal and symbolic world of traditional computer simulations, and where students are supported in moving fluidly between the two. The blend carries with it emergent properties that afford the production of new inferences. In our classroom exercise, a student moving her own body along a physical path can blend her journey with that of the image of a ball moving along a different but visually similar path (see Fig. 2). In the blend, the student's body and the ball are understood to travel together—they are conceptually and visually coupled. This coupling permits students to compare the outcomes of each movement and gradually refine their understanding of the model.

Methods

Our analysis is broadly grounded in the tradition of cognitive ethnography (Williams 2006). The cognitive-ethnography method seeks to study more than just the resources valued and used by a community. The approach aims to document how communities interact with those resources on a moment-to-moment basis to enact processes of knowing.

Data sources

Video recordings of a single lesson of second-grade students engaged in learning about friction were used to inductively examine how the conceptual blending framework applied to our data. The full unit dealt with a range of physics concepts, including force and motion, but we focus in this paper on the deceptively simple concept of friction. First, there is never a time when the body does not experience friction. With friction ever-present in the interaction between our bodies and physical materials, this makes reasoning about the effects of high friction, low friction, and especially, no friction, potentially challenging. Second, it is intuitive for students to associate low friction environments, such as an ice rink, with moving quickly. The way our

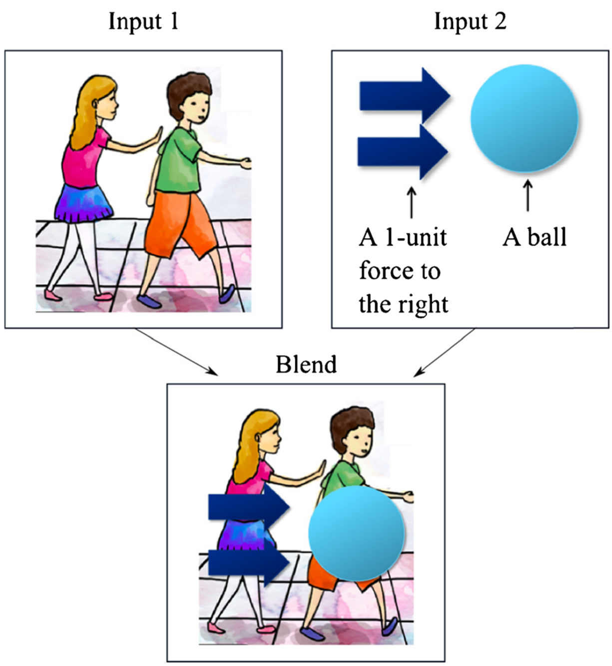

Fig. 2 A conceptual blend in which the space of the moving body is blended with the space of a simulation of a moving ball, creating a blended space that fuses the body and the ball

bodies move on ice versus in mud (relative to, say, a baseline of moving on pavement) can tempt students to associate low friction environments with increases in speed. For many students, the experience of slowing down *more slowly* on some surfaces over others can become conflated with speeding up. Furthermore, the body is not a single point of mass, but an assembly of multiple, connected vectors, and that assembly is then modified with tools (such as ice skates) and different activity structures (such as walking from carpet onto ice at an ice rink). Each of these dimensions complicates the story of how students draw on their own kinesthetic experiences to reason about friction. In short, the goal of developing early elementary school students' understanding of friction while also building meaningfully on personal experience is challenging but important.

The LPP activity itself brings together students, teachers, physical materials, abstract symbols, and live video in an AR simulation focused on modeling an object's trajectory through different types of friction. The class session occurred within a larger 15-week unit on basic physics. In this analysis, we attempt to trace what resources were mapped together in the blend (composition), what inferences or computations were made about the speed of a ball under different conditions in the blend (completion), and how the participants modified the blend in subsequent stages through collaborative activity (elaboration). The focal student chosen for this analysis, Marissa (a pseudonym), was fairly typical of the class in that her post-test answers on the topic of friction showed that she understood the mechanism for friction, but had difficulty in conceptualizing low or no-friction environments. This was typical of our results for the intervention as a whole. In Enyedy et al. (2012), we reported that only 16 of 43 (37 %) of the students received significantly higher scores on a question that addressed friction during the post-test than on the pre-test ($Z=2.38$, $p=0.02$). For example, when asked why friction slows and stops an object, Marissa explained: "Because the grass has a hard friction…It's bumpy and it sticks up to the ball, have to fight to get over it." However a little further into the question Marissa talks about what happens when the ball rolls onto ice: "It will go faster. Because it's just smooth surface." In this way, Marissa fits the profile of many of the students in the class in showing a promising but incomplete understanding of friction.

Analysis

The video of the interaction was first described narratively and a time index of different events within the lesson was compiled. This allowed us to search rapidly through the corpus at need, and also helped the entire team to become more familiar with the general flow of activity. We initially analyzed the data to explore how our design principles supported student learning. This process and the results were described in greater detail in Enyedy et al. (2012). Throughout this process, the team was concurrently discussing and revising our understanding and the utility of the cognitive theory of conceptual blending. We began to identify what we thought of as the limits of conceptual blends and began our own formulation of the framework of liminal blends. We refined our theoretical framework through repeated consideration of the data at hand, but we had not yet systematically analyzed our data from the perspective of publicly co-constructed liminal blends.

Once we had refined and clarified our general theoretical framework, we analyzed the data in two passes. Our first pass was guided by the idea that students would need to develop blends, and that the key conceptual blends would include the three stages described above—composition, completion and elaboration. This process included identifying candidate compositions, completions, and elaborations, as well as iteratively refining our theoretical account of what constituted each type of blend in interaction. This was an important consensusbuilding process given that the initial conceptual blending theory was grounded in cognitive linguistics and the authors who developed these ideas did not present rich interactional data. Transitioning from hypothetical mental accounts to descriptions of rich and messy classroom interaction required us to refine our understanding until we felt confident as a team that we were in fact considering occurrences of composition, completion, and elaboration *in interaction*.

Next, we identified specific blending episodes for further analysis based on the fact that they were sustained over a continued period of time, and appeared related to key conceptual-learning opportunities. We wanted to begin with analyzing blends related to learning of key and important concepts so that we would be able to explain why the AR system was successful. We then completed an interaction analysis (Jordan and Henderson 1995) of the candidate episodes in an effort to recreate the experience from the participants' perspective. This interaction analysis was also partially guided by our assumption of distributed cognition in that we explored students' resources at the four levels identified above. We assumed that students would draw from their own prior experience and understanding, from the material environment, from the social patterns, and that they would adapt their understanding as interaction unfolded. As we identified candidate resources—or "source domains" to use a term from conceptual blending—we used the interaction itself to determine which sources the participants appeared to include in the blend. That is, if the participants did not invoke a source domain through their talk or action, we as analysts did not make the additional inference to include it. For example, at one point we believed that Marissa was drawing on her memories of slipping to initially come up with her answer. However, discussions of her slipping on linoleum at home came up much later in the activity. Without evidence that she was explicitly referring to these memories, we excluded them as a resource for her initial blend and completion. Finally, we gave special attention to the completion and elaboration episodes in our attempts to construct an understanding of what work the blend was doing for the participants and what about the situation afforded blending in the first place.

As we consider our work here to be initial theory building, we have not yet gone back to test our insights against a larger corpus of data. The validity of our findings at this stage stems from our efforts to test alternative hypotheses against the blending explanation we have constructed. We are not arguing that liminal blends is the only lens that can be used to explain learning in this case. We are arguing instead that it is a productive lens both to explain how learning was organized and to inform our efforts to design and structure learning in the complex environments afforded by augmented and mixed reality.

Findings

Composing the liminal blend

At the outset of the activity, the instructors and students work together to create a framework for the activity—identifying a shared interactional account of the environment to serve as a basis for their ongoing efforts to create a liminal blend. Their activity takes shape within a life-sized board-game environment—a long strip of paper spread out on the floor and marked off into several squares—in which one student advances when she encounters force symbols positioned on the board and reacts when she encounters the friction of different surfaces placed on the board-game squares. The imaginary context of this life-sized game is a mail sorting machine that moves envelopes along a track sometimes speed them up and sometimes slowing them down to stamp or sort them. The children had recently visited the post office and were fascinated by the machine and so the teachers incorporated it into our instructional activities. The students play by making embodied prediction—they walk off what they think will happen to the envelope on the game board—which is then compared with that of a simulated ball (which stood in for the envelope) that moved according to the classical laws of physics. In this way, the students take turns 'playing' the role of the ball, combining their individual understanding of how balls move with the material elements that make up the game board. At the same time, an overhead camera records the play space and projects an augmented video feed on a white board mounted to the wall. In addition, a computer tracks patterns positioned on the floor of the life-sized board game, converts them into student-designed symbols, and overlays those symbols on the video feed. That is, the student, force cards, and friction cards on the carpet space in turn appear in the video space as a black ball, forward-facing red arrows, and backward-facing red arrows (see Fig. 3). In this way, if the student looks toward the projected display, she will see herself from a bird's-eye-view with a ball and arrows floating above and beside her (respectively); the body is visually coupled with the symbols.

In this first section, we demonstrate *composition*, how disparate resources from distinct spaces in the classroom become mapped together to create the life-sized board-game environment. That is, we show how the discourse between students and instructors, in addition to the material anchors—despite being spread out over time and space in the classroom—fuse together or join side-by-side into a board-game blend. The initial composition phase lays the groundwork on which students complete and elaborate the blend, drawing inferences about force, friction, and speed.

Composing the material space The first space established in the activity is the *material space*. The space is collaboratively constructed by the students and the teacher, and presents the material anchors for the rest of the activity. The episode begins when students sitting in the center of the carpet shuffle their bodies to the carpet's edge to make room for a 10-foot long, rectangular sheet of white paper, which the researchers unravel slowly in front of the students. The white paper contains a drawing of a straight pathway of a dozen 10″×10″ squares, as would appear on a traditional board game, only life size. Researcher 1 places each of three separate pieces of floor material—linoleum, carpet, and an outdoor welcome mat—on its own square and asks the students:

Researcher 1: What have we added here? What are these things? (*pointing to each floor material)*
(1.0)

Fig. 3 First, the researchers unroll the paper game board. After placing the floor materials on the game board, Researcher 1 points to the linoleum and then to the mat (pictured, right)

Sam: Carpet?
(researcher 1 raises her hand as multiple students also raise their hands to be called on)
(3.5)
(researcher 1 points to student 2)
Matt: Friction.
Researcher 1: We've added friction, yeah! And they're (1.0) what do you notice about them? (0.8) Are they all the same? (*waving hands over the floor materials).*
(1.5)
Zoe? (*pointing at Zoe)*
Zoe: They're different.
Researcher 1: Yeah! (*nodding)*

Together the students and the researcher have highlighted different aspects of the world and different ways to refer to them. For example, Sam referred to carpet squares literally as carpet while the other student, Matt, referred to it more figuratively as friction. By doing so, Matt integrates the shared social understanding of the environment with the material environment that Sam had previously highlighted. This sets the state for all of the students to treat the carpet as both a piece of carpet and an item that creates friction as part of their collectively produced blend. It is important to note that this composition process is distributed across multiple participants. In later stages individuals may complete blends, but in our data they are always working from a jointly composed base such as this one.

Next, the researcher helps the students assign meaning to the entities in each square, and for some, adds new symbols to represent those ideas. For example, each square contains words that describe the number of forces associated with each square, and Researcher 1 then notifies students that they will need to place on the carpet cardboard patterns that correspond to the amount of force and friction on each game square. Researcher 1 explains that these patterns are "for the computer," but they also have symbols, such as arrows, that can be made meaningful to the students. A few minutes later in the activity, a student chimes in noting that the 3 floor materials go "big, medium, small, and…rough, medium, smooth," referring in order to the mat, carpet, and linoleum. In summary, the material space offers multiple material anchors to be used as inputs for the blend: cardboard patterns, a paper game board, students' own bodies, and floor materials. The material space is established interactionally between the researcher and the students through a process of first orienting attention collectively toward the physical materials and second applying concepts and descriptions to the materials that are aligned with the target science content.

Composing the narrative space of playing a game Researcher 1 helps to establish the narrative structure that governs the relations between the material elements in floor space. This narrative structure helps to organize the social world, providing both the rules that the students must follow in their interactions, and an interpretive frame for them to use as they work with the material elements of the game. Researcher 1, sitting down with the students on the carpet, draws an analogy to a game the students played a few weeks earlier, the "mail machine," in which students moved a piece of mail along the game board. Researcher 1 makes a sweeping gesture from the start to the finish of the current paper board game, showing the exact spatial trajectory of the game board piece on top of the new paper game board. Researcher 1 then shuffles on the carpet toward the start of the board game, positioning herself in front of the linoleum square:

Researcher 1: Well, what happens when you're going along (*waves hand from start of board toward middle of board)* and you—and you (*shuffles body next to the linoleum square and angles it toward the finish)* (0.8) in our case we

> don't have any friction until we hit these friction squares (*touches blank square ahead of linoleum then moves hand to tap linoleum square).* So (1.0) if we hit a friction—if we hit this floor (*rubbing the linoleum square with the tips of the fingers)* (0.5) you're not sure what's going to happen.

In this description, the researcher stops her hand at the first friction material, the sheet of linoleum, and raises the question, "What's going to happen?" Afterward, Researcher 1 describes how the students will "move through" the game board and again gestures a smooth sweeping motion from the start to the finish to illustrate the sequential process of engaging the entire board (see Fig. 4). A student named Marissa is selected as the first game player and she asks Researcher 1 multiple times, "Where am I going to stand?" and Researcher 1 explains, "The beginning is over here," while walking to the start of the game board. In each of these verbal and gestural turns, the instructor and the students start to map the narrative of a board game onto the physical board game paper and the physical floor materials. In effect, the mapping takes a hypothetical board game movement and specifies it in the material conditions of the classroom floor. The grid on the paper could have been used for numerous mathematical activities, but it has been clearly demarcated as a board game in this space, giving a specific indicator of how students should move their bodies in the activity.

This creates a material layout of squares and symbols through which Marisssa will become a living game piece, what Hutchins (2005) refers to as a "trajector" because it adds directionality to the blended space. Taken together, the material space and the narrative space have become laminated together (see Fig. 5), giving Marissa the chance to see movement on the paper as the number of squares one can advance per turn. We refer to this as a pre-blend because while it has many of the qualities of a blend (i.e., multiple source domains explicitly mapped to one another) it has not yet been completed. No one has yet used this potential blend to do any intellectual work. It is clear that the researcher intends for the children to engage in a particular way with these resources and this intent guides the time and effort that the group is expending to publicly compose this pre-blend. The composition of this pre-blend will subsequently be used to establish the conditions for the liminal world. The student will be making an embodied prediction from the first-person viewpoint. At this stage, however, students only know that they will be comparing their own embodied predictions to that of a computer.

Composing augmented reality space As the activity unfolds, students quickly orient toward a live video feed from a camera mounted directly above the carpet space and pointing downward. The camera feed is projected onto the white board. That is, if students look toward the white board, they can see live video of the carpet (and themselves moving around it) from a

Fig. 4 Researcher 1 displays the direction of movement from the blank square to the linoleum square

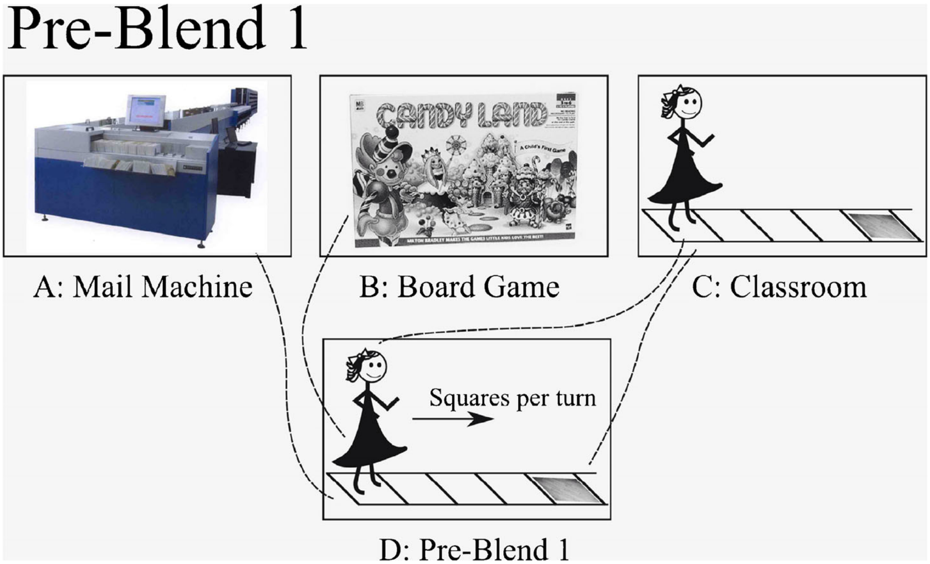

Fig. 5 In Pre-Blend 1, Marissa recognizes that movement on the gridded paper involves enacting the "squares per turn" approach taken in board games

bird's eye perspective (students see the tops of their heads in the video). The students, in fact, frequently look at the overhead video feed while they are moving on the carpet, creating a mapping between their own first-person perspective and the camera's third-person perspective—incidentally the same perspective one takes when looking down at a physical game board (Fig. 6). The overhead feed space is also critical to facilitating the liminal world as it provides the link for students to connect their own bodies and their position within the material environment to the visual symbols within the virtual environment, the space we turn to next.

As noted earlier, Researcher 1 explains that cardboard symbols on the floor space will track the forces and friction encountered in the game board and that these symbols are "for the computer." Just after Marissa takes her first steps in the game, Researcher 2 walks over to Marissa and initiates the mapping between Marissa and the ball (see Fig. 7).

Researcher 2:	Marissa, do you want to hold the ball while you walk? (*hands over a cardboard square that corresponds to the "ball" seen in the projected display)*
Marissa:	(*grabs the cardboard square and looks at the projected symbol)* (4.5)
Researcher 1:	Okay, so she landed here, so we put a force of two here (1.0) like, right next to it (*leans down and touches the square on which Marissa is standing)*—there you go.
Sophia:	(*walks over to Marissa and places the cardboard friction square at Marissa's feet)* (0.8)
Researcher 1:	Nice! (1.0) Let's put it right here, so that it (*bends down to move the cardboard friction square)*
Sophia:	(*places the cardboard friction square so that the arrows/forces are pointing toward the origin of the game board*)

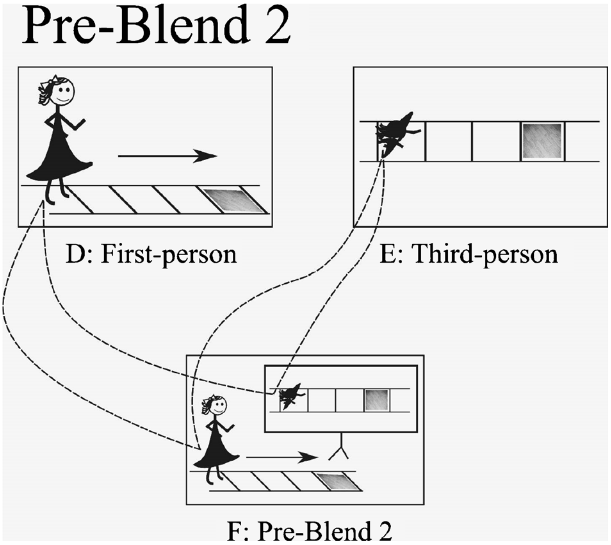

Fig. 6 In Pre-Blend 2, Marissa connects her experience of moving on the floor to her experience of seeing the third-person display of her own figure on the screen. In the blend, the figure that appears in the overhead view (the top of Marissa's head) is the same entity as the figure walking on the carpet (Marissa herself)

Marissa: No, it's [going the other way.]
Researcher 1: [there you go]
Figure out which way it goes.
Marissa: It's going the other way.
Sophia: (*rotates the cardboard square 180°)*
(4.5)
Researcher 1: Okay, ummm (1.0) (*the corresponding projected symbol for friction now also rotates 180°)*. There we go. Alright, thanks Sofia!
Marissa: (*moves the cardboard square for the ball and watches it move on the projected image)*

In this exchange, Researcher 2 hands Marissa the cardboard pattern for the ball and asks, "Marissa, do you want to hold the ball while you walk?" At the same time, Sophia retrieves a different cardboard sheet that represents two forces and lays it next to Marissa on the floor. These cardboard pieces appear immediately as colored symbols in the augmented reality view, floating on

Fig. 7 Researcher 2 hands the cardboard symbol for the "ball" to Marissa. Seen from a bird's eye view, Marissa moves the cardboard symbol while watching the image of the ball move on screen

top of the carpet. The ball symbol appears on screen as a black ball and the two force cards appear on screen as two horizontal red arrows. This interaction laminates Marissa's first-person experience of her body, the top-down video image of her body, and the animation of a ball into one cohesive whole.

With all of the components of the liminal world introduced, Marissa can begin to think of her pathway through the board game as fused with that of the ball. Even though the image of the ball and Marrisa's body are in separate physical locations in the classroom, the spaces are visually, temporally, and conceptually yoked in the video feed. In this way, the new video symbol input space is fused with the existing infrastructure. The projected symbols for the ball and the forces are mapped directly onto Marissa and the paper board game. Marissa then insists that the red arrows symbolizing the forces are pointing in the direction of the spatial trajectory of the game narrative. In summary, the material space, the augmented video space, and the symbolic space have all been successfully integrated in the pre-blend (see Fig. 8).

Completing the blend of narrative, game board, and sensory experience

The activity begins with Marissa and Researcher 1 standing at the start of the game board. After Marissa draws a "force of 2" card, she takes two steps forward and pauses at the second square. Marissa's small steps may be a trivial completion of the very complicated blend that has been collaboratively constructed, but it shows that the blend has utility for the activity at hand. It has been put to use and therefore completed. Marissa successfully coordinates 2 arrows with the concept of force, force with motion, herself as the ball that is in motion, and finally motion translated in terms of squares per turns in the game board world. All this allows her to rather effortlessly take the appropriate action of taking two deliberate steps on the long piece of paper rolled out on the floor.

The blend is now publicly available for others to comment on, elaborate, or re-mix. In this episode, Marissa and Researcher 1 discuss Marissa's speed after she lands on the second square, which contains a symbol for 1 force.

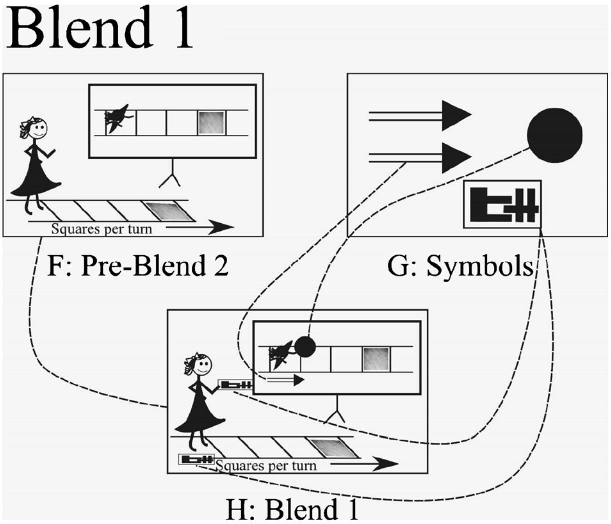

Fig. 8 In Blend 1, Marissa experiences the gridded paper as a game board, herself as the game piece, the overhead view as a display of her own movement, and the symbols as linked to her own movements

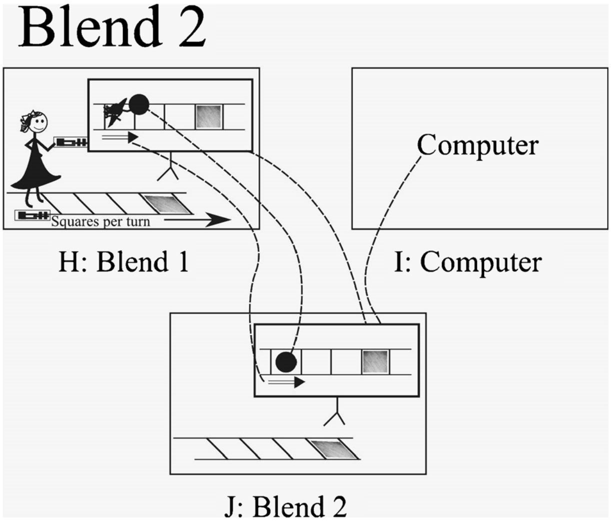

Fig. 9 In Blend 2, the computer (and its embedded physics engine) controls the movement of symbols in the display space, and Marissa, previously linked to those symbols, can compare her own journey with the journey of the symbols in the computer simulation

Researcher 1: Well what [speed] did you start with? (*pointing at Marissa*)
Marissa: (*Turning her shoulders to look back at the start square*) Two (*Turning now to look at Researcher 1*)
(0.8)
Three
Researcher 1: So you're going two and then you're going th[ree]
Marissa: [thr]ee

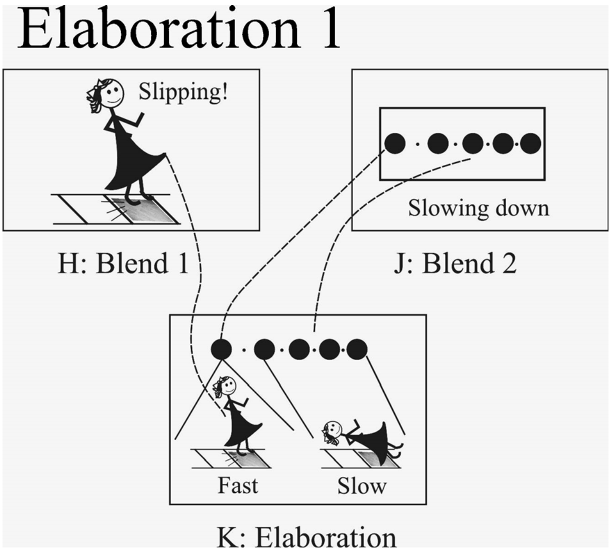

Fig. 10 Marissa elaborates the blend again to account for both her initial ideas and the results of the computer simulation

Researcher 1: Because
(1.0)
Marissa: (*Turning her shoulders again to look back at the start square*) I st—I had two.
Researcher 1: (*Pointing to the start square*) You had two (*and then pointing to the second square*) and then you landed on a
(0.5)
Marissa: Three
(0.8)
Researcher 1: (*Leaning in to take a closer look at the second square*)
[A three?]
Marissa: [A one]

Researcher 1 and Marissa's discussion of speed involves mathematics rooted both in the physical resources in the room and in the narrative structure of the game board. Marissa has a chance to provide a description of her speed within the context of the blend, which incorporates both the narrative structure and the material floor spaces. There is a 2-force symbol that advanced Marissa from the first square and there is a 1-force symbol on Marissa's current square. In the blend, Marissa can combine these two moments in the journey—the initial 2-force and the 1-force—to tally the total forces accrued.

Importantly, the numerical total represents units of force tied historically to specific events in the narrative, both conceptually and physically. That is to say, the force of 1 is only meaningful for this calculation when we account for the fact that Marissa is already moving at a speed of 2, according to the "rules" of the game. Thus the position of the single force along the board is key to giving it meaning. This is similar to Fauconnier and Turner's (1998) note that, "In the blend, but not in the original inputs, it is possible for an element to be simultaneously a number and a geometric point" (p. 147). Marissa's reasoning, in this context, appears to build on the idea of forces in the sense of an impetus to change speed, the integers and arithmetic rules that allow her to combine forces (adding 1 to her existing speed of 2), the historical moments in the game which indicate her speed when each force is encountered, and specific spaces on the game-board which dictate when, in the game narrative, she will encounter each. Speed is thus constructed within the history of the game board narrative and in terms of the physical semiotic structures of the game board.

It is also important to note that despite Marissa's physical traversal of the board, the concept of "speed" that she discusses with the researchers is an abstraction particular to the blend. Speed in this local context means the number of squares you move in a turn, which roughly corresponds to a formal understanding of speed as the distance travelled in a fixed time. Speed, however, does not refer to the actual speed with which Marissa moves her body between squares. In order to emphasize this last point, we note that Marissa moves between squares at a constant speed, taking cautious steps one at a time even after she has acknowledged that she has "sped up" in game terms. The representation of speed is therefore housed in force cards, in the geography of the board game, and in the location of Marissa's body along a trajectory within the board. While this abstraction of speed in space and symbols is powerful in helping Marissa reason about the relationship between force, friction, and speed, it also has its limits as indicated in the subsequent episode when new physical experiences accentuate her immediate experience of the speed of her feet. This concrete experience of speed is also incorporated into the blend with unpredictable results for how Marissa completes the blend.

Elaborating the blend to reason about friction

After landing on the force square in the previous episode, Marissa prepares to advance three squares, where she will land on the linoleum slab used to represent a low friction surface. She walks slowly from one square to the next, and when she steps on the linoleum, Marissa, who is wearing socks, slips slightly forward with her right foot and then spends 2 s subtly twisting her feet on the linoleum. Researcher 1 initiates a dialogue with a question about what will happen next:

Marissa: I slip? (*followed by three exaggerated motions swiveling on the linoleum back and forth in socks*)
(1.5)
Researcher 1: Ahhh, okay so we have a good—we have an interesting situation
Marissa: (*Marissa intentionally twists her feet on the linoleum; arms raise up slightly*) I'm [SLIPPING!]
Researcher 1: [Marissa is] going speed 3 and then she landed on (0.8) the linoleum. (1.5) So she says she might slip. So what's that going to do to your speed?
Marissa: Make it faster.
Researcher 1: Interesting. Okay. Does everyone agree that if she lands on the linoleum it will make her go faster?
Three voices: Yesssss.
Researcher 1: Yes? Okay what do you think Gabriella?
(1.8)
Gabriella: I think it will
Marissa: Cuz can I?
Gabriella: It will go [faster]
Marissa: [cuz] because—because if there's a 3 and I'm going very fast (steps back one square and faces forward) I would land on this and I would slide (walks forward and slides her feet forward in a controlled way on the linoleum; then returns to standing on the linoleum tile), because it's slippery.

In this episode, the experience of placing feet on actual linoleum causes the blend to be remixed and the computation to produce an unexpected answer. Marissa's initial slip, and perhaps her memories of slipping on linoleum in socks at her home (an event she later describes as "freaky" and "scary"), can be seen as a departure from the intended blend and an elaboration of the material space to include her real interactions with the physical world here and now (e.g., her slippery socks). While this physical and tactile aspect of the material space has always been potentially available to the blend, none of the participants had yet highlighted that aspect of material experience and introduced it into the material input space and thus made it available as part of the public blend. That is, Marissa's body was already blended with the experience of a board game piece, and so moved at a deliberate speed, leaving the symbols and geography to represent speed. Once she slips, however, she is dislodged from this tidy conceptual blend, and a new pathway within the conceptual integration network, one that highlights how her own body feels like it *speeds up* in response to the linoleum, is added into the mix. This elaboration of the blend leads Marissa to the conclusion that her speed will increase. This inference emerges from an interaction between blends that draw on different source inputs.

This episode is important for illustrating the complex and contextually bound nature of blends in real world learning environments. Specifically, this episode highlights how carefully designed spaces intersect with unanticipated realities to create new blends. Furthermore, those blends can produce both normative and non-normative inferences depending on how they are constructed by the participants. Thus, as designers and analysts, it is crucial to attend to how participants read and react to the unfolding interaction in their construction of blends rather than focusing solely on the intentionally supported blending spaces. Specifically, in this episode Marissa's carefully constructed game-narrative speed, which was coupled with a careful and systematic physical world speed, was suddenly disrupted by the intrusion of the feeling of "moving fast" into the blend space when her foot slipped. The importance of this embodied experience is made clear when Marissa calls out "I'm slipping!" She then goes one step further to indicate that this is not a simple distraction to be laughed at when she adjusts her predicted speed from 3 to 4, allowing the feeling of "speeding up" to trump the symbolic representation of linoleum as a "low friction" or "friction 1" surface. This may indicate the relative importance of the embodied space over the symbolic space, or may simply reflect the tenuous nature of Marissa's understanding of the computed space prior to this point—ideas that might be explored with a larger corpus of data. Regardless of the full implication, the value of the blending framework here is that it makes the cause of this contradiction and resulting non-normative inference clear, and situates it in both the designed space and the accidental event.

The elaborated blend—as a publicly co-constructed object—is now available to the rest of the class to complete in a different way, elaborate, or re-mix. This is exactly what happens next. Steve immediately disagrees with Marissa's inference and answers a question by the researcher intended for Marissa. His disagreement can be seen as a different completion of the publically constructed blend—a completion that privileges a naive causal logic that to speed up an object requires some sort of action.

Researcher 1:	Okay, is that going to make your speed go faster?
Steve:	No she's going to slow down when she slides.
Researcher 1:	Why do you think so, Steve?
Steve:	Because it's a surface that's not providing anything moving (0.5) like for example inside the mail machine things are moving.
Researcher 1:	Okay.
Steve:	That when she gets to that surface (*pointing at the linoleum*) nothing's moving her.
Researcher 1:	Nothing's moving her. And then why would she slow down (*left hand moves back and forth over a small distance*) [rather]
Steve:	[because]
Researcher 1:	than just continuing? (*left hand moves back and forth across the whole body*).
Steve:	Because um she's slowing (*stands up and takes one step forward*) down (*slows body to a stop*). (1.0) She hits this (*takes a step forward and stops*) and no forces like there is on the other cards.
Researcher 1:	Okay. (1.0) Okay. [So we] have two different opinio[ns.]
Marissa:	[But my] [my] thing—my opinion is that I think I will keep on going because (0.8) these forces give me a head start (dragging foot across two of the squares ahead of the linoleum). And I would—I would keep—well I would keep on moving because there are forces (takes a step forward to the square before the linoleum) and then once I hit that (slides right foot forward on linoleum) I would just slide (leans whole body forward and picks up back foot to demonstrate flailing during a slide).

The researcher asks Marissa a question, but Steve stands up from his seat along the perimeter and walks onto the game board with Marissa. To us, Steve's standing up and physically moving into the game-board space signifies that the blend is a public resource for interaction and reasoning. More than that, it is the intellectual currency of the classroom. If you want to make a claim you have to make that claim in and through this blend. Steve, who is wearing shoes and therefore presumably does not feel the slipperiness of the linoleum in the same way as Marissa, completes the blend in a way that privileges the logical claim which states that for an object to move, it has to be *moved* by something (i.e., a force). He says, "Because it's a surface that's not providing anything moving," and evokes their shared field trip to the post office where they saw a machine that moved envelopes along by conveyor belts and other mechanical means. Although he is bringing up their shared history, he is also clearly talking in terms of the blend when he says, "She hits this, and no forces—like there is on the other cards." While he does not explicitly deny her experience of slipping, he does not use it as a resource in his completion of the blend to make an inference.

Marissa responds by adopting some of Steve's language of forces—a vocabulary she had not yet used during this activity—but she does not change her inference or the prominent role that her immediate physical experience plays in her elaborated blend.

Comparing the computer's blend to Marissa's blend

The power of the AR simulation to provide a contrast with Marissa's embodied prediction lies in the mapping between Marissa's activity in the space and the AR microworld that is projected on the whiteboard. This mapping is repeatedly established during the activity by Researcher 1, Researcher 2, and Marissa. Researcher 1 notes early on that the cardboard symbols in floor space are "for the computer" and will appear as symbols in the augmented space. Researcher 2 both hands Marissa the flat cardboard square for the ball, asking "Marissa, do you want to hold the ball while you walk?" and asks Marissa, "Can you bring me the ball?" upon which Marissa brings over the cardboard square. The ball, in other words, becomes synonymous with the cardboard square symbol and also takes the same journey as Marissa, albeit seen from an overhead view on the classroom wall instead of on top of the white paper on the carpet.

As shown above, interaction and collaboration is used to establish a direct and public blend between Marissa, the narrative journey, and the image of the ball. In the blend, cardboard and arrow depictions of forces move Marissa and the image of the ball. The participants work to align the elements in the floor space, augmented space, and symbol space according to the narrative structure of the board game. With this blend firmly established, Researcher 2 organizes a comparison between Marissa's journey and the computer's depiction of the ball's journey:

Researcher 2:	Let's try to see if the computer agrees with her prediction. …
Researcher 2:	So the question is, when we run this, is it going to speed up or is it going to slow down when the ball hits the linoleum, right? (moves the cursor in the augmented reality space to point to the linoleum square).
	(6.0)
	So, Marissa, you said, when the ball get's here, it's gonna get faster, right?
	(0.8)
Marissa:	Where?
Researcher 2:	When it gets right here (moving the mouse up and down).
	(1.0)
Marissa:	Yeah.

If the fusion between Marissa and the ball was implicit before, the mapping now becomes public and explicit. Researcher 2 refers to "Marissa's prediction" of what happens "when the ball get's here," while pointing with the cursor to the augmented video feed space. Marissa's early movements with her own body on carpet space are collectively realized as a prediction of how the computer will show the ball moving in the AR simulation (see Figure 9). Marissa, at first, does not realize that Researcher 2 is pointing toward the AR simulation. Up until this point, the journey had been focused on the carpet space; cardboard symbols were merely "for the computer." This points to the importance of the interaction to establish the mappings and clarify the referents of acts and objects within this complicated space. Once Marissa begins to treat the spaces as integrated, she quickly agrees that her earlier embodied prediction will correspond with how the ball will interact with linoleum in the simulation. The mapping becomes so strong that when the virtual ball is seen to roll across the classroom floor Marissa physically ducks to avoid the virtual ball.

Despite that the inputs to the computer blend remain completely hidden—there is no mention of how the computer generates the simulation—the class is strongly impacted by the computer's prediction. The computer shows the ball rolling across the game board in the AR simulation and then slowing down at the linoleum (the opposite of her earlier prediction). When the computer simulation comes to an end, multiple students call out that the ball slowed down. Marissa, after agreeing that the ball did slow down on the linoleum, maps the experience back to the publicly constructed blend and her earlier slip. She introduces a caveat to her earlier prediction: "If I go on this (walking to stand on the linoleum square), I could slip (acting out the slipping with her right foot) and then I would fall and then it would make me go slower because I would slip." Marissa introduces the event of falling on the linoleum—which would slow her down—in order to match the computer's prediction of the ball's journey across the game board, but preserves her inferences that the act of slipping will cause her to speed up momentarily (see Figure 10).

Marissa and the ball have been fused to such an extent that the motion of the virtual ball in the AR simulation (and her classmates' reactions to it) invites Marissa to backtrack and revise her own prediction. Importantly, she revises her prediction by adding the event of falling rather than changing her inferences about linoleum friction. In a sense, she is creating a new, alternative blend to help explain the combination of experiences. Before moving on to the next student's prediction the teacher asks Marissa to go home and slide across a linoleum floor five times and investigate if she speeds up or slows down during her slide.

Discussion

Prior approaches to examining how AR can be used to develop innovative learning environments have largely focused on the cognitive resources of individual students, particularly the way that those resources are tied to the body and embodied activity (Lindgren and Johnson-Glenberg, 2013). However, we believe that these resources are only a small part of a far more complex and distributed cognitive architecture, one that involves individuals, the material world, other people, and a shared cultural history. Specifically, we believe that cognition is distributed 1) within the individual, 2) within the material world, 3) between individuals, and 4) across time. Building on the notion of conceptual blends, we can articulate how resources are blended together both within and across these levels. As students blend these resources, they are then able to look at the world in a whole new way, creating a *liminal world* where they can explore both the physical world that they live in, and a symbolic and scientific world that explains how that world operates. Students explore this liminal world and engage with new and newly meaningful scientific concepts that are well out of their reach in more traditional learning environments.

Analyzing AR learning with liminal blends

In these three episodes, we see mathematics and physics rooted in a game-board narrative, a physical game board, bodies, and augmented-reality symbols. Toward the end of the activity, the computer simulates the normative model of *the ball encountering friction* using the representations Marissa had already put into action, which leads Marissa to revise the description of *how her own body encounters friction*. The AR activity establishes a liminal world blend between Marissa and the ball that allows for a dialogue between Marissa's first-hand experiences and classical physics simulations. Importantly, the computer receives high epistemic credibility as a source of how balls move on linoleum. This finding begs for the study of interactions between social others (e.g., teachers and peers) and the cognitive spaces that people blend to produce inferences.

The liminal blend allows continuity between past and present sensory experiences and the ball's classical response to force and friction. Once the ball and Marissa become coupled in their trajectory through the game board, Marissa comes to believe that the events that the ball encounters according to the computer in the live feed space need to match how she moves through the floor space. The blend simulating the journey of Marissa/ball call for Marissa to look back at the inputs to her own blend and think about her experience in new ways. However, this integration does not happen in a vacuum. The kinesthetic experiences are read into a narrative and into semiotic infrastructure that creates two contrasting roles for the body. Is the body enacting the movement of the game-board player or an interaction with the physical surface? Is speed the mathematical total of forces or how the body responds to walking and slipping? The blend combines these inputs, making predictions based on the resources in this environment problematic. Conceptual blending, in this way, shows how resources gather meaning against the ground of other resources, and how accounts of learning need to consider integration across these resources.

Implications for future work

Returning to our two questions—why does an AR environment, like LPP, promote learning, and can we use what we learned about cognition in these circumstances to inform future design—we believe we are in a position to expand upon the design principles for AR that we derived from our earlier analysis of LPP (Enyedy et al. 2012). Those design principles were that 1) Socio-dramatic, embodied play can be used as the root activity for learning and seen as a form of participatory modeling to support inquiry, and 2) that we can use the students' own representations of the rules and abstractions within the system itself as a form of progressive symbolization and the construction of rich semiotic ecologies. The blending analysis presented here elaborates how that semiotic ecology is forged into a coherent whole, and in particular highlights the value of exploring learning within an AR environment as distributed. In order to expand upon this notion of distributed cognition that is embedded within our idea of liminal blends, we will briefly suggest a key way in which each of the levels that we have discussed might be re-thought in light of our analyses. This brings the levels together synergistically as well as explores the potential of developing liminal blends.

Rethinking individual resources

A common idea emerging from studies of embodiment in AR and mixed-reality (MR) environments is that it is important for there to be a clear congruence between the bodily motion and the concepts being studied (Lindgren & Abrahamson, forthcoming). However, such an analysis seems to ignore that the individual and their embodied activity are always necessarily situated in a rich social world. For example, many of our examples do show a metaphorical mapping between the body walking and the ball rolling. However, we have also found that this mapping does not need to be complete—we have found that students do not need to "roll" as a ball to think with their body about the motion of a ball responding to a force. Simply walking the space provided some insight. More profoundly, a motion such as high-kick walking could be assigned a symbolic function such as fast motion, rather than a literal one. The reason is that the high kick helps to convey the speed and systematicity of that motion in locally understood ways, allowing students to explore the motion not simply as motion, but as an object of scientific study that needs to obey certain rules. That is, by moving beyond the individual physical experience, we can see the necessity and value of the social context for helping students to experience the value of given physical actions.

In addition, other embodied actions that served more communicative functions (e.g., gesturing and pointing) were able to complement and elaborate the semiotic meaning assigned to the body. One of the reasons that our approach diverges in this way is that we are interested in exploring how embodiment can serve as a resource for reflection, rather than focusing solely on how embodiment supports memory and recall. By recognizing the role of reflection in this learning process, it also becomes possible to articulate when it might be beneficial to support this kind of non-congruent behavior—at those times when it increases the potential for reflection which can help students explore challenging concepts that might not be learned easily and quickly through congruent embodied behavior. In short, we find that moving beyond the superficial congruence and toward more metaphoric and conceptual mappings created through embodied modeling and play opens up important new avenues for instructional design.

We therefore suggest that it is important to consider physical actions within an AR environment not just in terms of their congruence with specific concepts, but to think about the cultural and material factors that will allow students to either notice that congruence, or make sense of that physical behavior in other valuable ways.

Rethinking material resources

An obvious assumption of AR environments is that augmentation should add real value to the reality that it is modifying (Lindgren and Johnson-Glenberg 2013). However, we see two ways that a liminal blend analysis can extend this idea. First, it is valuable to think about how the physical world can also add value to the virtual world of the AR, and not assume that this needs to be a unidirectional impact. The material world is already a rich part of a distributed cognitive system, and one that students have a long history of interacting with. In the LPP system, and in the example above, we were able to draw on this by using physical materials that invoke ideas about friction (e.g., linoleum, carpet, etc.). The entailments that these physical items brought with them were quite powerful, and helped to give meaning to the augmented elements. Second, the physical and material world plays a central role in organizing interaction, and this should be considered when designing the physical environment and activity systems within which AR systems are deployed. For example, consider the discussion above during which Steve interjects during Marisa's explanation. Steve uses the fact that he can move into the material space, which the blend occupies, and inhabit the blend. He can take on the roll of the ball, point to, or touch elements of the blend to present his own prediction about the behavior of the system. While there are certainly many physical layouts that can support both blending and AR, we have found that a shared space where students have ready access to the same set of materials helps support a social and interactional frame where they can fluidly negotiate the meaning of those materials and thus refine their shared blend in productive ways.

Rethinking interaction and time

Once we begin to focus on the value of interaction within an AR environment, a number of possibilities arise regarding how we might best design for interactions that will support students in exploring the valuable resources at their disposal. In particular, our goal in reflecting upon the organization of interaction within an AR environment is to reflect on how different interactional structures support the process of blending multiple resources with a goal of producing a liminal blend, allowing students to move effortlessly between the real and imagined world so that they can come to understand both in new ways.

Two key ideas emerged in our analysis. First, we have seen that it is valuable to consider the different role that each collaborator has vis-à-vis the physical embodied concept. For example, even though students played a number of roles in our simulation, taking on the role of the ball that was being kicked or rolled seemed to support the most robust reflection about how the ball would respond to forces. Once students understood these basic ideas, being an observer, a force, etc., was equally powerful. Future work can continue to tease out the value added by these different roles and how it relates to students' opportunities to engage with underlying concepts. The second idea for promoting collaboration in MR/AR learning environments is to conceive of the whole room as an open tool that promotes open interactions (Hutchins 1995). An open interaction is one where the students have access to each other's actions and representations as well as the opportunity to observe their peers as they create, modify, use, and negotiate their semiotic activity. Open tools and open interactions means that students can see and comment upon the embodied intellectual work of the other students, which they did rather frequently. This notion of open spaces is tightly coupled with our second point about the material space above; neither feature works independently. Rather, designers need to attend to this kind of alignment between the physical layout, social frames, and the conceptual resources that they hope students will blend together. When these elements line up effectively, students are able to create liminal worlds, and explore the resources that cut across these various conceptual and physical spaces to make sense of the world around them.

Conclusion

All learning happens in complex social spaces where students need to bring together multiple resources that are distributed between themselves, their physical embodiment, and their social spheres. This is particularly clear in collaborative AR environments where students need to go one step further and engage with two different worlds simultaneously—that which they can see and feel, and that which is augmented by advanced technologies—intended to highlight new and important aspects of the natural world. Our goal in articulating the theory of liminal blends has been to help explicate the complexity of learning within these AR environments and provide guidance about how we can both analyze and design AR environments to take into consideration the distributed nature of cognition. Ultimately, we believe that the answer is to begin by focusing on how resources need to be aligned. This is, after-all, the heart of all AR designs, which seek to align the physical world with a virtual one. The trick, however, is to move beyond that simple alignment and explore how it necessarily is situated within and builds upon a complex sociocultural world. Once we can do this, we can re-think what it means to align resources in a manner that explicitly articulates the intersection between cognition and interaction in powerful ways. This theoretical framework also highlights the inherent complexity for students in aligning perspectives through AR, and for educators in supporting them in doing so. By bringing the need for this kind of alignment to the fore, we hope to complicate conversations about when and how AR can be a useful educational tool. There are many situations where the effort required to support blends may not be warranted by the target concepts and social context of learning. Fortunately, in the case of the LPP environment, we believe that working towards developing liminal blends was invaluable for helping early elementary students begin to explore these foundational physics concepts in an intellectually honest way at an early age.

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