Boundary Interactions: Resolving Interdisciplinary Collaboration Challenges Using Digitized Embodied Performances

Virginia J. Flood, University of California, Berkeley, flood@berkeley.edu
Michael Neff, University of California, Davis, mpneff@ucdavis.edu
Dor Abrahamson, University of California, Berkeley, dor@berkeley.edu

Abstract: Little is known about the collaborative learning processes of interdisciplinary teams designing technology-enabled immersive learning systems. In this conceptual paper, we reflect on the role of digitally captured embodied performances as boundary objects within our heterogeneous two-team collective of learning scientists and computer scientists as we design an embodied, animated virtual tutor embedded in a physically immersive mathematics learning system. Beyond just a communicative resource, we demonstrate how these digitized, embodied performances constitute a powerful mode for both inter- and intra-team learning and innovation. Our work illustrates the utility of mobilizing the material conditions of learning.

Keywords: Interdisciplinary collaboration, embodied interaction design, mathematics education

Introduction

In the past decade, technology-enabled embodied interaction learning environments (TEELEs) have shown great promise for supporting collaborative learning in a variety of domains, and their design is a growing enterprise (Lindgren & Johnson-Glenberg, 2013). Designing systems that enable physically immersive and responsive pedagogical activities requires interdisciplinary collaboration between computer-science teams and learning-sciences teams. However, little is known about how these collaborating teams learn and design together.

Previous organizational studies (e.g., Engeström, 2001) and social studies of science (e.g., Hall, Stevens, & Torralba, 2002) have offered valuable insight into the nature of collaborative, interdisciplinary work "in the wild," however the computer supported collaborative processes of interdisciplinary teams designing learning systems for embodied interaction has not yet been an area of investigation. In general, many have lamented the lack of discussion and reflection on the learning processes of designers as design occurs, as opposed to much-elided (and perhaps much-edited) versions that accompany reports of finished products (Sengers, Boehner, David, & Kaye, 2005).

Here, we present our reflection-in-action (Schön, 1983) as a two-team collective of computer scientists and learning scientists building a virtual, animated pedagogical avatar (Johnson, Rickel, & Lester, 2000) with naturalistic, context-oriented, and user-responsive hand-gesture capabilities sourced from authentic human tutor behavior. Rather than focus on our learning outcomes, we explore how our design process (Koschmann & O'Malley, 2013) has been shaped by task objectives, coordination demands, and emergent material/digital design artifacts. Early on, our collaboration faced an impasse: how could the learning-sciences team (LS-team) communicate the embodied, multimodal instructional techniques that human tutors deploy for the computer science team (CS-team) to generate in a virtual tutor? Although human motion is notoriously difficult to codify, the computer-science team required a comprehensive representational scheme that would be conducive to their task of algorithmic proceduralization. To overcome this impasse, we devised a representation system using digitized, embodied physical performances. This system circumvents the bottleneck of codified inscription by capturing body motion directly.

We argue these material-turned-electronic embodied performances were key resources that occasioned both inter- and intra-team discovery and innovation. The performances acted as *boundary objects*—shared artifacts with interpretive flexibility that simultaneously supported the distinct purposes, meanings, and processes of two diverse stakeholders and could thus mediate their collaboration even in the absence of full consensus (Star, 2010). This paper details our emergent methodology in order to demonstrate how these digitized embodied performances enabled communication, analysis, and reflection on embodied interaction within and across our interdisciplinary teams.

Project background and objectives

Our collaborative project aims to integrate an animated, embodied pedagogical agent with a technology-enabled embodied-learning device for mathematics. The original device was designed to provide an interactive context for users to ground fundamental notions of proportionality in perceptuomotor activity. Learners discover strategies for achieving a non-symbolic goal state: they are required to make a computer screen green by using hand-held remotes to operate virtual cursors (Figure 1a). Unbeknownst to learners, the system generates green feedback only when their hand heights match a particular concealed ratio (e.g., 1:2) that the tutor manipulates (Howison, Trninic, Reinholz, & Abrahamson, 2011). In the original version, learners working in pairs or independently were guided through the discovery of techniques for keeping the screen green by a human tutor as they progressively enlist available mathematical artifacts (e.g., a Cartesian grid) to enact and symbolize their strategies (Figure 1a).

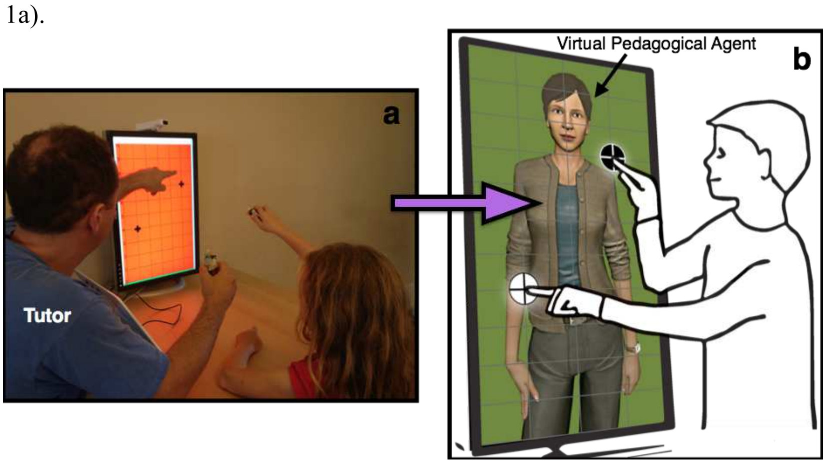

Figure 1. Multimodal tutorial tactics (a) will be emulated by a virtual pedagogical agent (character mesh by Hartholt et al., 2013) in the forthcoming design (b) of an embodied learning device for mathematics

Human tutors engage in complex forms of embodied interaction with children and the device to encourage exploration, highlight desirable patterns of activity, perform demonstrations, and foster learners' reflection on physical and symbolic aspects of their strategies (Flood, Schneider, & Abrahamson, 2014). These multimodal tutorial tactics enlist a rich array of bodily activity. Through gesture, tutors point out salient features in the virtual environment, rehearse past activity, and depict mathematical concepts. Tutors also use their body to model strategies for interacting with the device and often collaborate with the student to co-enact strategies. For example, in Figure 1a the tutor operates one remote while a student operates another to make predictions together.

Our project's goal is to design the virtual tutor so that it is capable of emulating the multimodal tutorial tactics the human tutor uses to support students' interaction with the device. The forthcoming design will feature an agent that faces the user through the screen and will have a touchscreen interface (Figure 1b). The LS-team's role in the design process has been to determine the relevant aspects of human–tutor embodied interaction the virtual tutor should enact, whereas the CS-team's role is to create a system that can generate these movements, adjusting them to the current interaction context and triggering them appropriately based on the child's progress. The joint design task provides each team a means to respectively contribute to different scientific communities (knowledge systems): For the CS-team, the project is a means to explore issues related to virtual agents and computer animation, whereas, for the LS-team, the project is a means to investigate and optimize embodied, multimodal instruction (both virtual and human) for mathematics learning. Thus, our two research teams can be seen as different stakeholders in a united design team facing an ill-structured design problem that neither group could solve alone (Star, 1989).

Design artifacts as boundary objects in interdisciplinary research teams

Fischer and colleagues (Fischer, 2000; Fischer & Ostwald, 2005) propose that heterogeneous design teams such as ours be seen as communities of interest, characterized by a *symmetry of ignorance* (Rittel, 1984), wherein neither team possesses the full breadth of knowledge to solve the problem independently, and thus both groups are equally important for the problem's resolution. Each side approaches the other's discipline with similar levels of naiveté. Fischer argues this symmetry of ignorance presents a powerful advantage in design: the process of negotiating different perspectives can disclose hidden aspects of design problems invisible to either group on their own, thus creating opportunities for learning (Fischer, 2000; Fischer & Ostwald, 2005).

A key to productive, creative interdisciplinary collaboration is in devising viable systems for communication (Mamykina, Candy, & Edmonds, 2002) that allow the two groups to negotiate and reach shared understandings (Resnick, 1991) despite their differences. Communication barriers, however, are inevitable when different communities of practice come together with their different knowledge bases and specialized languages (Fischer & Ostwald, 2005). Fischer argues that productive forms of negotiation arise via collaborative interactions with co-developed *externalizations* (from Bruner 1996) that serve as boundary objects (Star & Griesemer, 1989). As boundary objects, these hybrid externalizations afford shared reference (Stahl, 2006), thus mobilizing process pragmatics, even as the teams maintain non-overlapping interpretations of the objects' significance (Akkerman & Bakker, 2011; Star & Griesemer, 1989; Star, 1989, 2010).

In particular, design artifacts (e.g., prototypes, plans) frequently serve as boundary objects (Bergman, Lyytinen, & Mark, 2007), providing a means to index unshared domain-specific terms and conceptualizations to publically shared elements of the perceptual field (Koschmann, LeBaron, Goodwin, & Feltovich, 2011). Sharing specific referents in joint perceptual fields—even while retaining distinct subjective senses and languages for these referents—allows participating researchers operating from within different knowledge systems to productively engage in practices that require cooperation. For example, this implicit "looseness" in co-reference to objects in the joint perceptual field has been implicated as crucial in enabling initial pedagogical discourse around conceptual content between instructors and learners (Newman, Griffin, & Cole, 1989).

Whereas past studies have discussed the role of static design artifacts such as physical models (e.g., Arias & Fischer, 2000) or diagrammatic plans (e.g., Henderson, 1991) as boundary objects, we extend this literature to the interesting case of dynamic, embodied performances.

Embodied interaction performances as boundary objects

The problem: Embodied interaction does not translate well

Our project has forced us to contend with the complexity of representing human physical activity. In particular, communicating about embodied interaction presents a formidable task. The LS-team needed to catalog a complex range of tutors' embodied activity and then convey this information to the CS-team for simulation. By analyzing a video corpus of human tutor interactions from a previous design research study, the LS-team identified 75 distinct variations of embodied interaction for the virtual tutor to perform. The CS-team needed to understand both the set of gestures required for the learning domain and the variation space for each gesture (i.e., all the different ways a certain gesture might be performed) as a prerequisite for designing the technology that would emulate these gestures artificially. Secondly, the CS-team needed to be able to accurately produce animation of this full movement range, which imposed both algorithm-design and data requirements.

One potential route was for the LS-team to supply the CS-team with a set of clips from the video corpus where human tutors interacted with students as they worked with the existing version of the system. However, this option proved impracticable given that key physical-layout features were going to change for the new configuration: The virtual tutor would now be the mirror image of the student, rather than sitting side by side as human tutors had done (see Figure 1a vs. Figure 1b). Thus, the raw video clips were inappropriate for direct emulation by the CS team because they were over-laden with incorrect contextual information and could not furnish optimal versions of the interactions for reproduction.

A serious problem was taking shape: how could we represent and catalogue precise choreographies of embodied interaction? Inscribing and archiving bodily motion has remained a challenge throughout history (Conquergood, 2014). In particular, describing human movement for accurate virtual or physical dynamical reproduction (e.g., sign-language conventions [Kilma & Bellugi, 1979] or dance choreographies [Kirsh, 2013]) is a non-trivial practice that has evolved over centuries (Guest, 1998). Existing notation schemes like Labanotation (Guest, 2005) and Laban Movement Analysis (von Laban, 1971) from dance or Stokoe notation (Stokoe, 1978) and HamNoSys (Hanke, 2004) for sign language require significant amounts of training to develop fluency in use. In addition, they are specialized for movements other than co-verbal gesture. Therefore, we needed to find an alternative method for representing and cataloguing choreographies of embodied interaction.

Devising a method to communicate: An emergent methodology

The method we devised for achieving the successful communication of embodied interaction specifications between our interdisciplinary teams altogether eschewed static verbal and diagrammatic description. We created a repository of physically re-enacted embodied interaction performances we wished to simulate and used this as a dynamic, embodied, living script for an actor to follow during a motion-capture session. In effect, we devised a way to let the bodily motion itself speak out our design intentions to each other.

Using tangible props, the LS-team fashioned a material analog of the virtual environment to investigate how to adjust particular forms of video-corpus-sourced instructional embodied interaction to accommodate the virtual tutor's new physical orientation of facing opposite the student. One member of the LS-team sat behind a transparent barrier and performed different tactics for another researcher playing a student. The LS-team was able to review each case of embodied interaction that they wished to reproduce by playing the corpus video and then directly recreating it in the material "virtual" environment (Figure 2a and 2b). This role playing and interacting with physical materials, a form of bodystorming (Schleicher, Privet, Jones, & Kachur, 2010) or experience prototyping (Buchenau & Suri, 2000), allowed for the emergence of authentic ways of redesigning particular tactics based on the natural constraints and affordances (Gibson, 1979) of the material and social space we built. Generating this information would likely be impossible through speculation, as the exact details of our interactions with the environment—such as in gesturing and object manipulations—typically escape our explicit conscious awareness (Schleicher et al., 2010).

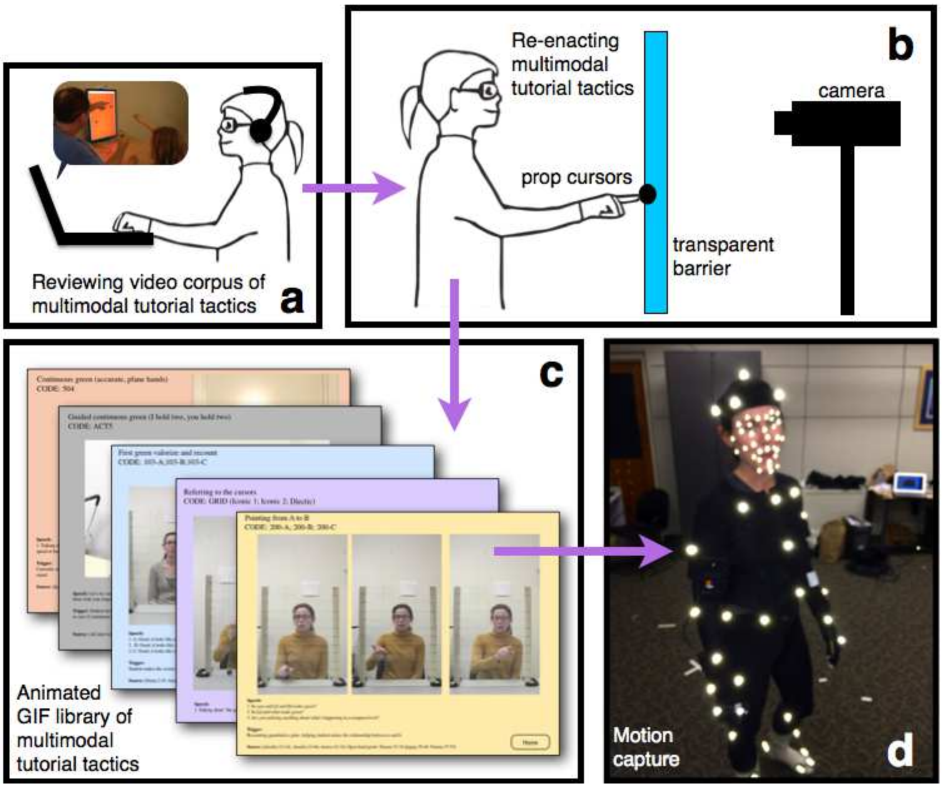

Figure 2. By directly watching human tutor interaction (a), the LS-team re-designed it for the new virtual environment with material props (b). These video-recorded re-enacted performances were converted into animated GIFs and organized into a library (c) which facilitated a motion capture session with the CS-Team (d).

The LS-team video-recorded each prop-supported embodied performance of the choreography of every multimodal tutorial tactic of interest. Next, the LS-team converted each clip of embodied interaction into animated Graphic Interchange Format (GIF) files, a format for short, looping "moving pictures" most recently popularized by the blogging platform Tumblr (Uhlin, 2014). The GIFs of multimodal tutorial tactics were organized by pedagogical function (e.g., gestural techniques for highlighting co-variation) to create a comprehensive library of digitized, animated embodied performances (Figure 2c). See http://goo.gl/8ImYYX for an example slide from the multimodal tutorial tactic library.

The animated GIF library of multimodal tutorial tactics was essential for helping the CS-team initially understand the problem space. In addition, this library also served as a living, moving script of embodied interaction to guide a member of the LS-team's physical performance of the tactics for a motion-capture session with the CS-team (Figure 2d). Because motion capture requires extensive calibration and set-up time, the entire set of embodied interaction had to be captured in a single session. Each GIF of embodied interaction from the library could be quickly watched, learned, and performed for capture. The library served as a direct choreographic resource and afforded accurate physical reproduction of 75 distinct motions in a single session.

For the CS-team, the motion capture performance was a product as well as a process of communication. The data generated is a direct input to their second task of building a system that synthesizes larger families of gestures. For the LS-team, the motion-capture performance became a way to communicate tacit professional expertise, which, we venture, is a form of felt know-how that is ultimately inarticulate (Dreyfus & Dreyfus, 1986; Polanyi, 1958; Ryle, 1984) and never fully translatable to words.

Learning from digitized embodied performances

The embodied performances recorded in the library and via the motion-capture session became durable, public, external representations for our interdisciplinary team to negotiate understandings of the phenomena at hand. Thus, the embodied performances played the role of external boundary objects facilitating communication and collaboration between teams. However, these collaborative and individual team interrogations of the performances also led to revelations that would likely have gone unnoticed otherwise, affording insight into issues in our respective domains as well as insight into design challenges we faced and needed to resolve together. Below, we provide specific between- and within-team examples of how we learned from the embodied performances as boundary objects.

Inter-team revelation: A collaborative design solution

Collaborative discussions about the embodied interaction performances led to a novel solution to a vexing design problem that may generalize beyond our project context. Real tutoring situations rely on the tutor's careful analysis of the student's online verbal responses. However, this is a particularly challenging task to accomplish computationally. How could the virtual tutor monitor what the child knows without eliciting and analyzing verbal responses? During reflections about the library and motion capture, we realized an alternative solution. Just as we had relied on embodied performances to communicate with each other during our project, we reasoned, the virtual tutor could potentially rely on embodied performances to communicate with the student. Namely, the agent can gauge the learner's perception of strategy by performing particular interaction techniques and then eliciting a simple yes/no evaluation from the learner as to whether the agent's embodied performance accurately reflects what the learner is attempting to do. Based on the response, the system can develop a model of the learner's perceived strategy. Instead of verbal processing, embodied re-enactment can thus be used as a tool for measuring the student's current understanding, taking advantage of the embodiment of the agent. The virtual tutor's performance would be recognizable to the learner as mimicry *because* the agent has a similar body (Núñez, Edwards, & Matos, 1999).

We suspect that this innovation in nonverbal assessment technique would be applicable for other tutoring systems with embodied virtual pedagogical agents across a broad range of domains that instruct and train particular forms of embodied interaction in complex environments (e.g., procedural training, Rickel & Johnson, 1999).

Intra-team revelations: Gaze and multi-phase gestures

During subsequent, independent analyses of the digitized embodied performances in the library, each team also revealed a new dimension of embodied interaction of interest to them.

The LS-team noticed that some of the embodied performances of multimodal tutorial tactics in the library had an unnatural quality to them, but at first they could not articulate why. After analysis and reflection on the library, they realized it was because the actor had stared into the camera for some of the performances and failed to re-enact naturalistic patterns of gaze to accompany the embodied interaction being performed (See http://goo.gl/8ImYYX "200-B" for an example of unnatural gaze). This led the LS-team to notice that their original analysis of the video corpus never explicitly attended to gaze. This is a significant omission as in natural face-to-face communication, speakers producing depictive gestures frequently look down at their own hands to direct their listeners' attention to the embodied aspect of their utterances and signal their relevance (Streeck, 2009). The team now plans to investigate the role that gaze plays in directing students to instructors' gestures as part of pedagogical tactics in order to better incorporate this phenomenon into the forthcoming design.

For the CS-team, the gesture documentation process led to discovery of the high prevalence of multi-phase gestures not observed in the team's previous work on co-verbal gesture. Multi-phase gestures consist of several segments with variable form and repetition. They require more complex representational schemes and algorithms for manipulation, ultimately allowing animated characters to create more complicated and controllable gesture forms to convey very particular ideas.

Discussion

Overall, our case supports Fischer and colleagues' assertion that the *symmetry of ignorance* existing between heterogeneously composed design teams can be advantageous for design processes by forcing teams to devise innovative communication systems that later become springboards for collaborative, creative work and opportunities to learn. The communication system we devised served as a boundary object, generating individual intra-team revelations resulting in new discipline-specific knowledge as well as collaborative inter-team revelations resulting in new interdisciplinary shared knowledge (Figure 3).

Specifically, our case study demonstrates the value of using embodied performances to communicate in an interdisciplinary team of learning scientists and computer scientists. Our interdisciplinary design-process challenges were resolved by creating a new form of design artifact, a set of embodied performances that were archived systematically in an electronic library and then re-enacted by a human actor for motion capture. These material performances mobilized our collaboration by obviating the need to painstakingly work out and establish a shared verbal/symbolical language for describing embodied interaction with the learning device. Additionally, while discussing and interacting with the archived performances, we devised a design solution for dealing with assessment nonverbally that mirrored our own communicative process. At the same time, the evolving constraints imposed by each team on the other in the course of creating and analyzing the performances occasioned each team opportunities to reflect on their own practice and make unexpected discoveries (i.e., the prevalence of multi-phase gestures for the CS-team and the importance of gaze for the LS-team). In turn, these discoveries present both teams with future opportunities to pose important domain-specific research questions that were not possible to forecast at the project's inception.

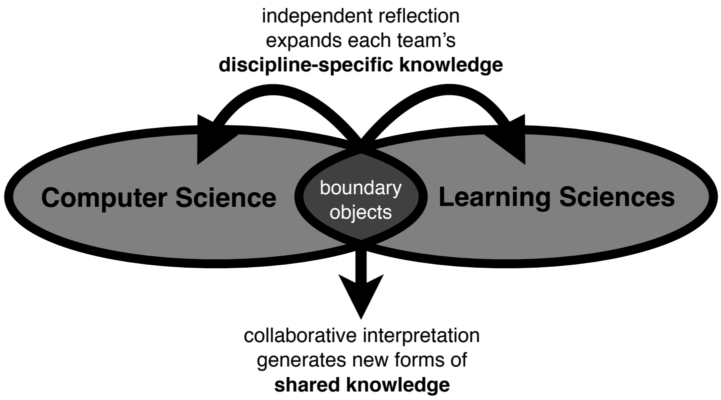

Figure 3. Interrogating embodied performances as boundary objects independently allowed each separate team to expand their discipline-specific knowledge. Collaborative interrogation of boundary objects led to the production of new, shared knowledge as a design solution emerged.

In retrospect, we believe it is not surprising that successfully conveying embodied interaction specifications ultimately required communication through bodily re-enactment. Particular mediums and modalities are simply more adept at carrying particular forms of information (Kress, Jewitt, Ogborn, & Tsatsarelis, 2001). Further, the embodied practices of pedagogical interactions (e.g., how to effectively draw a student's attention to a mathematical pattern by pointing) represent a tacit form of professional know-how that may not be possible for its practitioners to translate into propositions (Dreyfus & Dreyfus, 1986; Polanyi, 1958). Independent of verbal exposition, embodied interaction performances anchor references in pragmatically loose yet mutually appreciable visual and physical-material forms, enabling dialog between collaborating teams. Embodied performances, as boundary objects, offered us a powerful tool for building a shared understanding of the problem space.

At the same time, however, an important benefit of boundary objects is that they allow for work without need for consensus (Star & Griesemer, 1989; Star, 2010). Indeed, our library of embodied performances offered a critical advantage beyond serving as a means for shared reference, in that each team could perceive the same performances differently. Because the library preserved actual rich, dynamic *performances* of embodied interaction, a sufficient level of detail existed for both teams to comprehend their particular phenomena of interest within the record. That is, the LS-team could look at a particular performance (i.e., a particular case of embodied interaction) and understand it holistically as a pedagogical tactic, whereas the CS-team could decompose the rich sequence of activity into composite parts, and begin re-organizing the performances by morphological similarity. Different granularities or units of analysis (Star & Griesemer, 1989; Star, 2010) are simultaneously possible with the preservation-modality being bodily motion itself.

As scientists approach new frontiers together—as is the case in our current project—they often rely on explorative bodily activity to make sense of new results for which they do not yet have verbal language to describe (Becvar, Hollan, & Hutchins, 2005; Ochs, Gonzales, & Jacoby, 1996). Architects and designers similarly use their bodies to imagine uncharted territory together before pinning concepts down in words or drawings (Murphy, 2004; Sema, 2014). However, in both science and design, the body's role as an epistemic resource in the process of invention and discovery—acting as a significant methodology in and of itself—is frequently simply left out of the record of procedure as legitimate and even pivotal to the practice.

We view the case we present here as testament to avoiding such omissions: embodied performances were an essential aspect of our collaboration and learning process. However, we only arrived at this solution serendipitously after many failed attempts to communicate.

Concluding Remarks

The nature of embodied learning technology poses new, difficult, and yet-to-be discussed challenges for collaboration between computer scientists and learning scientists. In particular, we conjecture that as TEELEs are scaled up, the need for virtual agents capable of embodied interaction—including naturalistic gestures, demonstrative action, and interaction with the user—will increase. Thus we hope our findings and lessons learned will be relevant to others working in interdisciplinary teams to design physically immersive learning technologies. In addition, we think that the recommendation to embrace digitized embodied performances as a means to communicate is likely useful to a broader audience of interdisciplinary teams designing for embodied and tangible interaction across a range of applications.

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Acknowledgments
This material is based on work supported by the National Science Foundation under Award No. 1321042

