Movement Matters

How Embodied Cognition Informs Teaching and Learning

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Responsive Teaching for Embodied Learning with Technology

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There is growing consensus in science, technology, engineering, and mathematics (STEM) education that the body plays an indispensable role in teaching and learning these disciplines (e.g., Lindgren & Johnson-Glenberg, 2013; Nemirovsky et al., 2014; for a review, see Skulmowski & Rey, 2018). In response, over the last ten years there has been an influx of educational technologies that capitalize on novel human-computer interfaces to deliberately incorporate learners' bodies into the exploration of STEM phenomena. As these embodied learning technologies enter schools and museums, we still know surprisingly little about how educators can support embodied STEM learning with these designs.

Synthesized from our previous studies, we introduce strategies for supporting STEM learning by being responsive to and productively engaging learners' embodied ideas as they use embodied learning technologies. These strategies include (1) attending to learners' embodied action and perception, (2) encouraging the multimodal expression of learners' embodied ideas, (3) repeating and reformulating learners' multimodally expressed embodied ideas, and (4) co-constructing multimodally expressed embodied ideas with learners. We explore these *embodied responsive teaching* strategies (Flood et al., 2020) in the context of two embodied learning technologies for mathematics—the Mathematics Imagery Trainer for Proportion and the Mathematics Imagery Trainer for Parabolas—and demonstrate how they give rise to students' mathematical discoveries.

Technology-Enabled Embodied Learning Experiences for STEM Education

Embodied STEM learning technologies present users with perceptuomotor challenges that invite them to engage in movements, which can lead to new mathematical or scientific insights (Abrahamson et al., 2014; Lindgren &

Johnson-Glenberg, 2013; Nemirovsky et al., 2014). Using computer vision and other advances (see Johnson-Glenberg, chapter 15 in this volume), these systems track and interpret learners' bodily actions, guiding participation by providing feedback about learners' movement and location. Some designs track learners' hand and arm movements, and others track whole bodies in motion (Abrahamson & Lindgren, 2014). To date, technologies have been developed for exploring a wide variety of STEM phenomena. For example, in science education there are designs that allow learners to use their bodies to predict the orbits of meteors (Lindgren & Johnson-Glenberg, 2013), to become the moving particles of different phases of matter (DeLiema et al., 2016), and to experience the impact of changing terrain on animal locomotion (Lyons et al., 2012). In mathematics education, embodied learning technologies support embodied finger-based counting (Jackiw & Sinclair, 2017), the exploration of parametric functions (Nemirovsky et al., 2014), and learners' investigation of ratio and proportion (Abrahamson et al., 2014), among many others.

When learners use embodied learning technologies, they experience new ways of moving and perceiving that constitute *embodied ideas.* These perceptuomotor experiences—the patterns learners notice and the repertoires of movement they develop—are forms of embodied knowledge that are irreducible to the brain and inseparable from the body acting in the world (Abrahamson & Lindgren, 2014; Nemirovsky et al., 2014). Learners are often invited to reflect on and make sense of their embodied ideas with peers and educators, and make connections between embodied experiences (e.g., the sensation of moving through space and time) and cultural forms in STEM (e.g., disciplinary definitions of speed as distance traveled per unit of time, external representations like distance versus time graphs; Abrahamson & Lindgren, 2014). The embodied insights that arise from interacting with embodied learning technologies, however, can be difficult to formulate into words and are frequently expressed *multimodally* using rich configurations of demonstrative action with the interface, gesture, bodily performances, talk, and other semiotic resources (Abrahamson et al., 2014). For educators to support learning and discovery with these technologies, they must pay attention to how learners move and perceive, and also be able to make sense of learners' multimodal expressions of their embodied experiences.

Our work has focused on the practices that experienced tutors use to support students using two different embodied learning designs for mathematics: the Mathematics Imagery Trainer for Proportion (MIT-Proportion; Abrahamson et al., 2014) and the Mathematics Imagery Trainer for Parabolas (MIT-Parabola; Shvarts & Abrahamson, 2019). Both Mathematics Imagery Trainers embody the principles of embodied design (Abrahamson, 2014), in which learners develop physical strategies for achieving a specific goal state. Guided by tutors, learners are invited to share their physical strategies and adopt mathematical artifacts to describe and quantify these strategies (e.g., a Cartesian coordinate system). Through this support, learners are able to make sophisticated mathematical discoveries and reconcile their embodied ideas with disciplinary mathematics (Abrahamson et al., 2012).

The MIT-Proportion provides an interactive context for learners to use bimanual movement to explore ideas related to ratio and proportion. To operate the MIT-Proportion, users lift and lower two independent, handheld Nintendo Wii remotes that move cursors vertically up and down a computer screen (figure 12.1a and b). The screen turns green when the cursor heights embody a set, concealed ratio (e.g., 1:2 depicted in figure 12.1b, shown in light grey). When the cursor heights do not fulfill the ratio, the screen turns red (figure 12.1a,

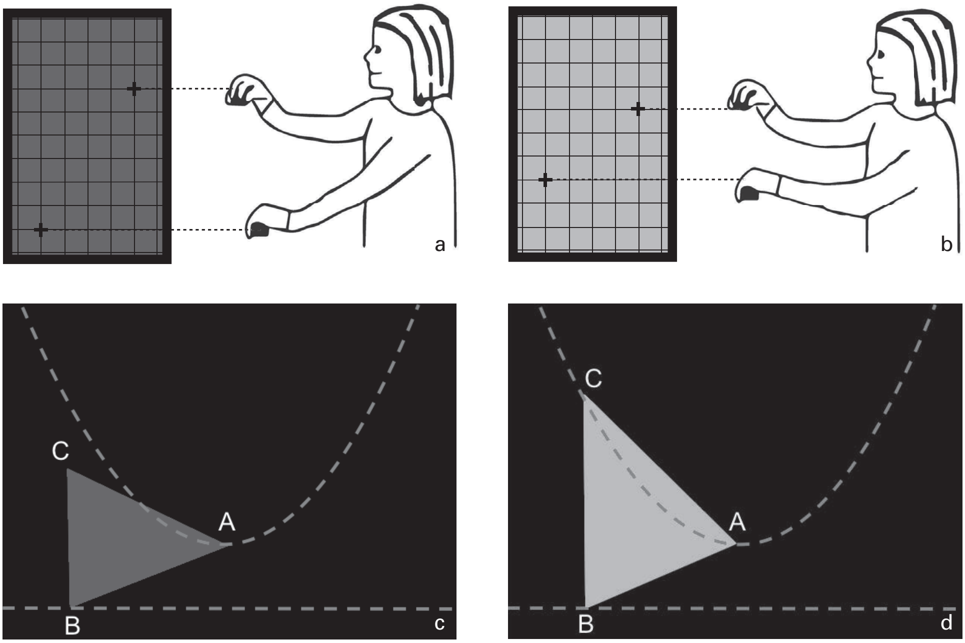


Figure 12.1
(*Top*) When the Mathematics Imagery Trainer for Proportion (MIT-P) is set to a 1:2 ratio, the screen is green only when the right-hand remote is twice as high as the left-hand remote (b, shown in light grey); otherwise the screen is red (a, shown in dark grey). (*Bottom*) In the Mathematics Imagery Trainer for Parabolas, point C is manipulated, point A is fixed (the "focus" of the parabola), and point B runs along a horizontal line (the "directrix" of the parabola). The triangle turns green when point C lies on a parabola (d, shown in light grey); otherwise, it is red (c, shown in dark grey). Lines and letters are inserted for this diagram but do not appear for students.

shown in dark grey). Learners are asked if they can figure out how to turn the screen green and how to keep it green by continuously moving the cursors from the bottom of the screen to the top. By developing and exploring different methods for "making green," learners discover many dynamic patterns and make connections between their physical strategies and challenging mathematical ideas like ratio, proportion, speed, covariation, multiplicative relations, and iterative addition, among others (Abrahamson et al., 2014).

The MIT-Parabola (Shvarts & Abrahamson, 2019), on the other hand, creates an interactive experience for learners to discover the definition of parabolas and explore their properties. Learners move their fingers on a touchpad to manipulate a triangle on a screen, moving its vertex (point C in figure 12.1c and d), and are instructed to try and keep the triangle green. In order to keep the triangle green (figure 12.1d, shown in light grey), unbeknownst to students, they must keep point C positioned so that it is equidistant from a fixed point A (the "focus" of the parabola) and from a point B, which moves along the horizontal line (the "directrix" of the parabola). It also means that the triangle will remain isosceles (two sides of equal length) as the vertex is moved. When point C is not equidistant from point B and A, the triangle turns red (figure 12.1c shown in dark grey). Moving point C to keep the triangle green means that point C (the vertex of the triangle) will move along the path of a concealed parabola that has been preset into the system. Learners are asked to determine strategies for keeping the triangle green as they move point C. Using the design, learners explore a parabola curve as a set of isosceles triangles' vertexes and express the formula of the emerging curve.

Responsive Teaching: Attending to and Engaging with the Disciplinary Substance of Learners' Ideas

To facilitate learners' discoveries and their connections between embodied experiences and disciplinary ways of organizing these experiences, educators must attend to and engage with learners' embodied ideas. In STEM education, the collection of practices that educators use to attend to and engage with learners' ideas is known as *responsive teaching* (Robertson et al., 2016; see also *teacher noticing,* Sherin et al., 2011). Responsive teaching involves (1) drawing out, attending to, and engaging with aspects of learners' ideas that have potential disciplinary value or substance and (2) engaging in ongoing *proximal formative assessment* (Erickson, 2007) (i.e., continuously monitoring students' ideas to adapt instructional support in the moment) (Ball, 1993; Coffey et al., 2011; Pierson, 2008). Students learn more in STEM classrooms where teachers are responsive to learners' ideas (Pierson, 2008; Robertson et al., 2016; Saxe et al., 1999).

A number of specific responsive teaching strategies have been identified in STEM classroom settings. These strategies include eliciting, probing, summarizing, expanding, reformulating, reflecting on, offering interpretations of, clarifying, or highlighting parts of the thinking learners share (Jacobs & Empson, 2016; Lineback, 2015; Pierson, 2008). These classroom-based studies, however, have primarily examined educators' *verbal* forms of responsiveness to students' *verbally* expressed ideas and written work. Few studies of responsive teaching have focused on investigating responsive teaching as an *embodied* phenomenon (e.g., Flood et al., 2015; Flood, 2021), or have examined how educators might specifically adapt these practices to support learners' embodied exploration of STEM with technology. Our recent research on teaching with embodied learning technologies (Flood, 2018; Flood et al., 2020; Shvarts & Abrahamson, 2019) has begun to characterize and document some of the specialized ways that educators can elicit, attend to, and engage with children's multimodally expressed embodied ideas, which we bring together and discuss in this chapter.

Theoretical Approach: Social Interaction as an Arena for Embodied Learning

To understand how responsive teaching strategies create opportunities for mathematical learning through technology-supported embodied experiences, we draw from sociocultural theory, ethnomethodology, and conversation analysis (EMCA; Mondada, 2019), and Goodwin's co-operative action framework (CoAF; Goodwin, 2018).[1] Sociocultural theorist Lev Vygotsky distinguished between children's *spontaneous* interpretations of their experience (e.g., initial patterns and physical strategies within the MIT-Proportion employed to "make green") and *academic* ways of organizing those experiences (e.g., the use of multiplication to predict a series of proportional hand positions to "make green"). Vygotsky believed that social interactions with more culturally competent others are what allow spontaneous and academic ways of organizing the world to grow together and reciprocally shape one another (Vygotsky, 1986). However, Vygotsky did not provide many details about the mechanisms within social interactions between adults and children that make these reciprocal connections possible (Wertsch, 1985).

EMCA and CoAF help us better appreciate how social interactions make these connections possible. EMCA attempts to understand the fine details of the practices people use to build, repair, and maintain a sense of shared meaning moment-by-moment in their interactions with one another (Schegloff, 1991). CoAF (Goodwin, 2018) enriches EMCA by using audiovisual recordings to illuminate the embodied ways in which participants dialogically take up and transform each other's multimodal contributions (e.g., gesture, facial expression, prosody, talk, and so on) to negotiate meanings. Each multimodal utterance a participant contributes is a *substrate* that can be broken down, reused, and reshaped (Goodwin, 2018) in the process of co-constructing new, mutually intelligible ideas from old ones. Together, these approaches help us appreciate meaning-making—where different interpretations of the world (e.g., spontaneous and academic) are brought together—as an *emergent, non-deterministic process* (De Jaegher et al., 2016) that is distributed across different people, their bodies, and the sociomaterial environment in which they are embedded.

In the case of embodied learning technologies, technology-guided bodily actions and experiences comprise a substrate (Goodwin, 2018) that can be cultivated into robust, disciplinary understandings of mathematics through social processes of reflection, negotiation, and signification that occur between educators and learners. By examining these interactions in fine detail, our investigations have been able to reveal a number of practices for attending to and engaging with learners' embodied ideas that facilitate students' mathematical discovery.

Intercorporeal Attunement: Attending to Learners' Embodied Action and Perception

A fundamental aspect of responsive teaching involves making sense of learners' ideas and monitoring these ideas for the seeds of productive disciplinary understandings that can be used to bridge learners' intuitions with more formal concepts and practices (Robertson et al., 2016). Educators must be able to recognize these seeds, even if they initially represent incomplete or incorrect ideas from a mathematical or scientific perspective. Previous studies have examined how educators attend to the ideas that learners share through verbal explanation and inscription (e.g., Pierson, 2008), but very few studies have attempted to understand how educators monitor and make sense of learners' embodied ideas when they are using embodied learning technologies. Educators must continuously attend to not only what learners say but also to learner's movements, their idiosyncratic forms of perception, and their interpretations of their embodied experiences (Abrahamson et al., 2014; Flood, 2018; Shvarts

& Abrahamson, 2019). This *intercorporeal attunement* (Sheets-Johnstone, 2000) allows tutors to reframe learners' attention to perceptuomotor activity at consequential moments so tutors can suggest cultural forms (e.g., disciplinary mathematical ways of describing phenomena) as helpful ways for learners to coordinate their activity and organize their interpretations of embodied experiences (Shvarts & Abrahamson, in press; Flood, 2018).

Using dual eye-tracking, Shvarts and Abrahamson (2019) illustrate a form of intercorporeal attunement, in which tight spatial *coupling* of tutors' and students' perceptuoaction systems dynamically emerge as they work with embodied learning technologies together. In one example a student, Ada,[2] is working with a tutor moving the vertex of the MIT-Parabola triangle searching for positions that turn the triangle green. At first, both Ada and the tutor's gaze follow the path of the triangle (figure 12.2a). A little later, however, Ada develops a specialized way of organizing her movements: instead of watching the path the triangle takes through space, she begins to keep her gaze along the median of the triangle (an imaginary segment that extends from the triangle's vertex to the opposite side, splitting it in half) as she is moving the vertex (figure 12.2c). Notably, the tutor is able to anticipate Ada's perceptuomotor switch. Before Ada begins attending to the median, the tutor herself begins attending to the median (figure 12.2b).

Coupling with students' performances makes it possible for tutors to detect when effective perceptuomotor strategies have emerged and allows tutors to distinguish critical moments for intervention. In this example, attending to the median is a helpful perceptuomotor strategy for dynamically maintaining an isosceles triangle (two sides of equal length), which will keep the triangle green as the vertex is moved. This will also result in the vertex being moved along the path of the "secret" parabola. After anticipating Ada's switch, the

Figure 12.2
(a) Ada and the tutor's eye movements (Ada in white, the tutor in grey) synchronously follow the movement of the triangle as Ada moves the vertex. Later (b) the tutor attends to the median of the triangle before (c) Ada begins attending to the median of the triangle. In (a) the triangle is red (shown in dark grey) and in (b) and (c) the triangle is green (shown in light grey).

tutor asks Ada to reflect on her strategy to keep the triangle green, reframing Ada's attention in this moment toward cultural forms of perceiving and expressing the strategy. In response, Ada is able to articulate the isosceles quality of the triangle she is manipulating.

When educators recognize the disciplinary potential in learners' ways of moving, perceiving, and interpreting embodied experiences, opportunities arise to connect learners' embodied ideas with mathematical ways of organizing those ideas. Coupled as an intercorporeal system with students and the device, tutors seem to be able to vicariously experience learners' perceptuomotor experiences from the learners' point of view (Shvarts & Abrahamson, in press).

Goodwin (2018) has argued that skilled actors (e.g., senior surgeons) are able to inhabit the actions of the newcomers with whom they work, perceiving as newcomers and being in a state of bodily readiness to anticipate what moves the newcomers will make next. However, such intercorporeal attunements are not always readily achieved and can require additional interactional work. In the next sections, we describe three additional practices educators use to elicit and engage with learners' multimodally expressed embodied ideas in order to help lead users of embodied learning technologies towards new discoveries.

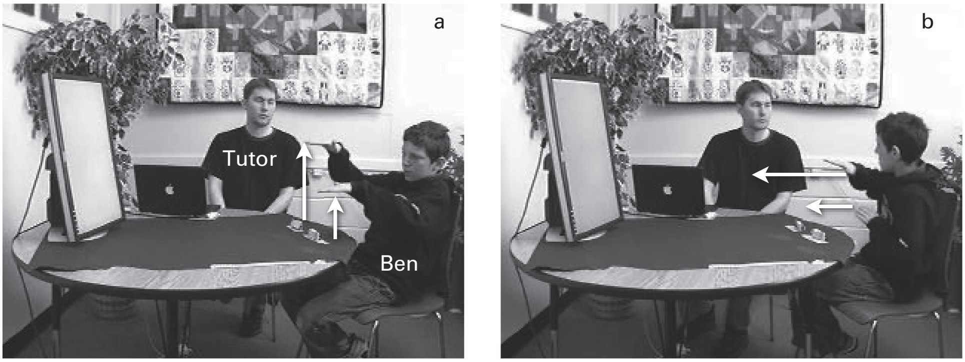
Encouraging the Multimodal Expression of Learners' Embodied Ideas

As part of responsive teaching, educators try to provide opportunities for learners to share and reflect on their reasoning (Robertson et al., 2016). Doing so makes it possible for learners to clarify and elaborate their ideas and also allows educators to better understand learners' ideas so they can effectively adapt their support in the moment (proximal formative assessment; Erickson, 2007).

Learners, however, often know more than they can express in words, and sometimes the words they use to describe their ideas can mislead (Crowder, 1996; Flood et al., 2015; Roth & Lawless, 2002). Both in and outside of embodied learning environments, nonverbal aspects of learners' explanations can contain discrepant, "mismatched" information when compared with verbal aspects (e.g., Alibali & Goldin-Meadow, 1993). In technology-enabled embodied learning environments, embodied ideas—drawing on tactile and kinesthetic experiences, and containing complex, dynamic spatial information—are especially challenging for children to articulate. In addition, learners themselves may often still be making sense of and organizing their experiences as they try to express them multimodally (Crowder, 1996). As a result, a key approach for being responsive to learners' embodied ideas involves finding ways to elicit these ideas in modalities beyond speech and being on the lookout for ways gesture is nonredundant to or mismatched with speech (Flood et al., 2015).

We present an example from previous work (Flood et al., 2020) to illustrate this embodied responsive technique. Ben, a middle school student, is working with two tutors to try to determine how to turn the MIT-Proportion's screen green. Unbeknownst to Ben, the MIT-Proportion is set to a 1:2 ratio. Ben shares a theory for producing green feedback that is difficult to interpret. He says, "My right hand is sort of the pinpoint sort of thing, so . . . , and then to keep it green you have to even them out, I would say." The tutor is responsive to Ben's ambiguous but potentially promising idea for how to make green, and he explicitly encourages Ben to use his hands, stretched out flat without the remotes, to explain what he means.

When encouraged to gesture, Ben is able to provide a physically accurate demonstration of how his hands need to move to make the screen: his right hand rises approximately twice as fast and ends up twice as high (figure 12.3a). Verbally, however, Ben describes his hands as "even apaced" and "going at the same pace." The tutor is responsive to this mismatch between Ben's gestured demonstration and encourages him to elaborate. In response, Ben uses his hands again, but this time he evokes the analogy of two cars traveling a horizontal trajectory where one is going "twenty" and one is going "fifty." He describes this as going "the same speed limit" (figure 12.3b).



"you keep them going even apaced"

"If you wanted to do this with a car, it would sort of be the same speed limit"

Figure 12.3
After being encouraged to use gesture to explain his idea, (a) Ben uses his hands to show how the remotes must move "even apaced" although he moves his hands at different speeds. When asked to elaborate, (b) he describes his hands as being like cars moving at the "same speed limit" going "twenty" and "fifty." Underlined speech corresponds with gesture.

By only paying attention to Ben's initial verbal explanations ("even them out," "same pace") it would be easy to conclude that Ben believed (incorrectly) that the remotes have to go the same speed to make green. However, by encouraging Ben to use his hands to explain his idea further, the tutors created an opportunity to better understand Ben's embodied idea and let it evolve. With his continuing multimodal explanation, Ben explores a disciplinarily valuable idea: the remotes have to move at two *different* yet *constant* speeds. By eliciting and probing Ben's gesture, the tutors were able to make sense of the apparent mismatch between Ben's speech ("even apaced," "same pace," "same speed limit") and his gesture. Instead of correcting Ben, the tutors adjusted their instruction in the moment and made space for Ben to pursue the idea. Ben's new productive car analogy emerged from his exploration and reflection on his own gestured movements. These gestures, elicited by the tutors, became a *substrate* from which Ben could build.

Encouraging students to "explain an idea in your own *hands*" provides productive opportunities for reflection on embodied ideas: Through this reflection, learners are able to reformulate and elaborate their initial utterances in ways that demonstrate new clarity or specificity, and sometimes they are able to make new discoveries/realizations like Ben's car analogy.

Revoicing and Reformulating Learners' Multimodally Expressed Embodied Ideas

In addition to eliciting students' contributions, another crucial aspect of responsive teaching is taking up and reformulating learners' ideas in order to help them extend and connect these ideas with new STEM disciplinary understandings. One way to achieve this is through the practice of *revoicing* or *recasting* learners' contributions. In revoicing, educators repeat (report or restate verbatim), reformulate (modify the content of), and/or elaborate (add new content to) ideas learners have shared (O'Connor & Michaels, 1996). This practice can serve a number of purposes, including (1) highlighting particular elements of students' ideas while backgrounding others, (2) helping students adopt disciplinarily normative language and representations, and (3) extending and reshaping the content of students' contributions to resemble disciplinarily normative concepts (Forman & Ansell, 2002; O'Connor & Michaels, 1996).

Revoicing has been studied primarily as a verbal phenomenon. Yet, when working with embodied learning technologies, learners do not just share ideas with words, but do their best to capture and represent their embodied experiences of interacting with the system, drawing on multiple modalities like full-body reenactments, gesture, and demonstrative action with the device. What

Table 12.1

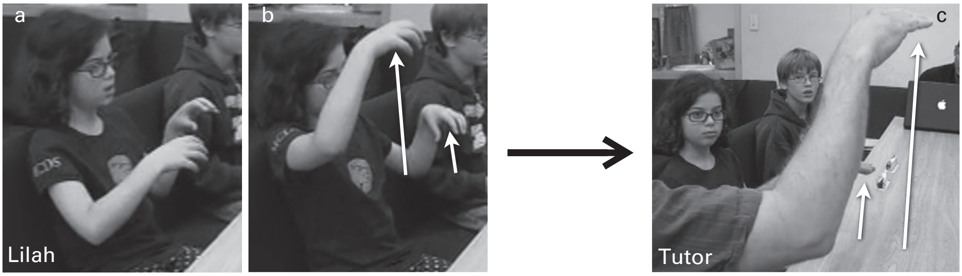
	Repeat gesture	Omit gesture	Elaborate gesture	Modify gesture
Repeat talk	▨	▨	▨	▨
Omit talk	▨		▨	
Elaborate talk	▨	▨	▨	▨
Modify talk	▨		▨	

does responsive revoicing look like in this context? When learners share ideas in multiple modalities, there are a number of different ways educators can re-“voice” what has been shared (Flood, 2018). They can repeat, elaborate, omit, or modify parts of learners’ speech or gesture (table 12.1). For example, an educator might repeat a learner’s gesture, but elaborate on their speech, adding a vocabulary word to describe what was represented in gesture (Shein, 2012). Gestures, like sentences, have different phrases or parts to them (Kendon, 2004), and educators also repeat and reformulate gestures by adding, omitting, or modifying gesture phrases (Flood, 2018).

We illustrate gesture reformulation with an example from Flood (2018) and demonstrate how revoicing gestures can help learners make connections between their multimodally expressed embodied ideas and disciplinary ideas. With the help of some tutors, Lilah and a peer are working with the MIT-Proportions with the concealed ratio setting of 1:2. The children have already reported two strategies for “making green:” (1) ensure that the right hand is always *double as high* as the left hand; or (2) move the hands with the right hand rising *double as fast* as the left hand. One of the tutors asks whether there is any connection between these strategies. Lilah volunteers an answer, and her response is composed of talk and an elaborate multipart gesture that has a variety of distinct gesture phrases (figure 12.4a and b).

As Lilah says “that one” she points to the right hand remote. Then, as she continues to speak, she holds her hands out in front of her as if holding phantom remotes. When she says “same time” she holds her hands level at chest height (figure 12.4a), and when she says “would have to go faster” and “lift higher,” she raises her hands so that the right hand travels approximately twice as fast and ends up approximately twice as high (figure 12.4b). Overall, Lilah’s embodied performance accomplishes the idea that the right hand remote is going faster because it must go higher at the same time.

One of the tutors uses gesture and speech to revoice and reformulate Lilah’s idea, treating her initial utterance as a *substrate* and reusing and transforming



“if you’re going to do it like, at the same time [a] that one would have to go faster [b] to like end at the same time [a] that one would have to [b] lift higher”

“it has more ground to cover” [c]

Figure 12.4
Lilah’s explanation of “faster” has two gestural phrases that she repeats twice: (a) she holds both her hands at the same height, and (b) then she pantomimes a motion with curled hands that would produce green feedback. (c) The tutor’s revoicing turn reformulates Lilah’s explanation by repeating only one of her gesture phrases, using flat hands, and co-timing it with a new verbal description. Underlined speech corresponds with gesture.

it (Goodwin, 2018). The tutor reenacts Lilah’s gesture moving his right hand so that it travels twice as fast as his left hand and ends up twice as high (figure 12.4c). However, he also reformulates Lilah’s gesture: He changes the shape of his hands, flattening them instead of pantomiming the operation of the remotes. He also simplifies the hand movements, omitting gesture phrases where Lilah held her hands at the same height. Finally, he also modifies Lilah’s speech, saying that the right hand has “more ground to cover” than the left, which could describe horizontal or vertical distance.

The tutor’s reformulation decontextualizes Lilah’s explanation in both gesture and speech to be less situated in the details of the device, and presents a more generalized disciplinary definition of “faster” as *greater distance traveled during the same amount of time.* Although some aspects of Lilah’s multimodal explanation were reformulated, the visible repetition of part of her gesture serves as bridge for Lilah to recognize the similarity between her idea and the tutor’s reformulation. After the revoicing, Lilah adopts the tutor’s reformulated version of what faster means into her explanation of how to make the screen green.

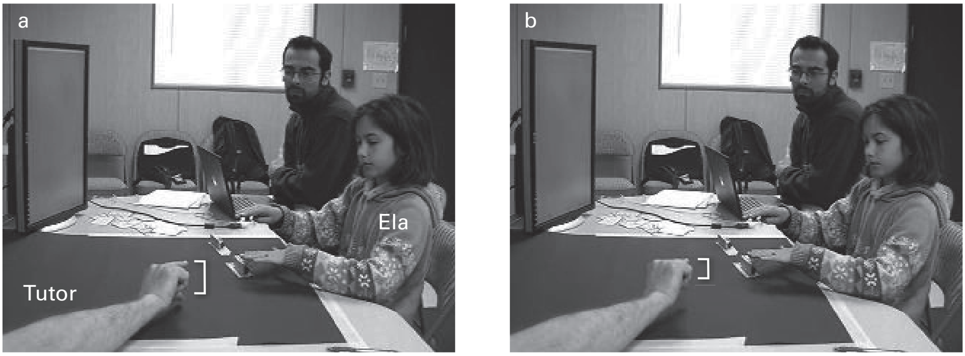
Overall, this example illustrates how reformulating learners’ multimodally expressed embodied ideas can be a powerful responsive teaching strategy for highlighting what parts of learners’ representations of embodied experiences are relevant to how scientists and mathematicians might think about representing the situation.

Co-constructing Multimodally Expressed Embodied Ideas Together

Another way that educators can take up and build on learners' ideas is by directly interacting with the gestures that learners produce when describing their embodied experiences with embodied learning technologies. Educators and learners can contribute to *the same gesture* as part of co-constructing a multimodally expressed embodied idea together. As an embodied responsive teaching strategy, educators can interact with an unfolding student gesture by (1) highlighting aspects of the gesture (Flood et al., 2015) or (2) contributing new dynamic gestural imagery to the gesture (Flood et al., 2020). By co-constructing gestures, educators can help steer and formulate ideas in productive new directions, while at the same time keeping these new directions grounded in learners' initial observations and ideas. We present an example from Flood et al. (2020) of a tutor and learner co-constructing an embodied, dynamic representation together through gesture.

Ela and two tutors are working with the MIT-Proportion set to a 2:3 ratio. After being encouraged, Ela uses her hands to gesturally demonstrate her discovery of how to make the screen green: she raises her left hand one unit; then, to locate the right hand, she raises the right hand one and a half units. With her iterative 1-to-1.5 method, Ela is able to predict a number of height pairs that go together such as 1 and 1.5 units, 2 and 3, and 3 and 4.5, but she gets stuck predicting larger numbers and cannot predict where the right hand would be if the left were on 10 units. The tutor sees an opportunity to build on Ela's multimodally expressed embodied 1-per-1.5 idea and transform it into multiplicative understanding. He instructs Ela to keep her hands outstretched but instead of iteratively raising each hand by units, he suggests she try positioning the right hand one and half *times* as high as the left hand. He instructs her to lift her left hand about six inches off the desk, and then to put her right hand at a height that is the same height as the left hand plus another half of that height (figure 12.5) so the height of the right hand is one and a half *times* as much as the left hand.

The tutor also uses his own hand to contribute additional dynamic imagery to co-construct a multimodal embodied representation with Ela when she struggles with the embodied multiplicative strategy. She gets stuck when the tutor asks her to predict where the right hand would be if the left hand is at two units.[3] As she hesitates, the tutor reaches into Ela's gesture to lend an extra hand (both literally and figuratively). He makes a pinch shape with his hands to bracket the height under Ela's left hand, which she has raised to two units (figure 12.5a), then he decreases the height between his thumb and index



Tutor: "If you take two, and take half of two, which is one, so it's. . ."

Figure 12.5
The tutor reaches in to Ela's gesture to co-construct a multimodally expressed embodied idea about multiplication. (a) He makes a pinch shape under Ela's left hand, and then (b) shrinks it by half and moves his hand toward Ela's right hand. Underlined speech corresponds with gesture.

finger by about half and slides his hand towards Ela's right hand (figure 12.5b), saying, "If you take two, and take half of two, which is one, so it's . . ." By contributing this dynamic imagery to Ela's gesture-in-progress, the tutor helps her find the correct one-and-a-half times position for her hand. Ela finishes the tutor's sentence, correctly answering "three." The tutor's interaction with Ela's gesture impacted her understanding, and she later applies the same shrinking pinch gesture to illustrate a new situation when she compares the relationship of the speeds of the two cursors.

Together Ela and the tutor have co-constructed a dynamic, embodied way of representing the relationship between the left- and right-hand heights, using iterative addition and then multiplication. Ela's initial gesture, demonstrating iterative addition, serves as a *substrate* that is taken up and simultaneously transformed by the tutor, allowing the tutor to instruct Ela on how to experience her gestured demonstration as a functional multiplicative relation between the heights of the left and right hand. Overall, co-constructing a gesture with learners is a useful responsive-teaching strategy to build from and elaborate learners' initial embodied ideas (e.g., Ela's additive scheme), thus connecting them with new disciplinary understandings (e.g., the functional multiplicative scheme the tutor and Ela co-construct).

Concluding Remarks

Embodied learning technologies pose unique challenges for instructional practice by embracing learners' hands and full bodies as the primary instruments of

STEM learning. Educators must find ways to responsively guide learners toward disciplinary understandings, starting with the *substrate* of learners' spontaneous, embodied experiences of perceiving and moving as they operate the devices. In this chapter, we presented four ways that educators can attend to and engage with multimodally expressed embodied ideas to support learners' mathematical discoveries as they use embodied learning technologies. Drawing on EMCA, CoAF, and sociocultural studies, our fine-grained investigations contribute to filling current gaps in our understanding of how learning can be facilitated with digital technologies that deliberately incorporate the body into STEM learning. In addition, our work has implications for instructional practice by suggesting effective multimodal discursive moves instructors can adopt to facilitate meaning-making with embodied learning technologies.

Although we have discovered these embodied responsive teaching practices in the case of mathematics, we conjecture that these practices would also have utility in other STEM learning domains. Responsive teaching that attends to and engages with learners' embodied ideas is, itself, an embodied practice that involves recruiting one's own body to make sense of learners' perceptuomotor activity, to repeat and reformulate leaners' gestures, and to co-gesture. Future research could investigate teachers' embodied learning of responsiveness (i.e., how teachers come to adopt embodied practices of attending to and interpreting learners' multimodally expressed embodied ideas). For example, the role of mirror neurons (see Butera & Aziz Zadeh, chapter 16 in this volume) could be examined. In addition, the collection of practices we have presented here are not comprehensive, and we hope our work will open up additional investigation into the embodied dimensions of responsive teaching with educational technology.

Notes

1. Sociocultural theory, developed by Lev Vygotsky, is widely used in the fields of psychology and education. It is an approach to understanding learning and development as fundamentally entwined with and emerging from social interactions embedded in particular cultures, places, and times. Ethnomethodology and conversation analysis (EMCA), on the other hand, come from sociology and investigate the systematic practices people use to create social order as part of everyday life. Ethnomethodology (which means "people's methods") originated with the sociologist Harold Garfinkel; conversation analysis, an offshoot that focuses specifically on conversational practices, was introduced by the sociologists Harvey Sacks, Gail Jefferson, and Emmanuel Schegloff. Drawing on both of these approaches, the co-operative action framework (CoAF), developed by linguistic anthropologist Charles Goodwin (who trained with Gail Jefferson), synthesizes sociocultural theory, EMCA, and semiotics to explain how meaning-making, coordinated social activities, and human artifacts are all made possible through human beings' propensity to decompose, reuse, and transform the resources others have introduced into public arenas across multiple scales of time.

2. All student names are pseudonyms.

3. This is good evidence that Ela is earnestly trying to understand Dor's proposal, since earlier predicting 3 from 2 was no problem with her original iterative strategy (raising the left hand one unit and the right unit one and half units).

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