18 Embodiment and Embodied Design

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Picture this. A preverbal infant straddles the center of a seesaw. She gently tilts her weight back and forth from one side to the other, sensing as each side tips downward and then back up again. This child cannot articulate her observations in simple words, let alone in scientific jargon. Can she learn anything from this experience? If so, what is she learning, and what role might such learning play in her future interactions in the world? Of course, this is a nonverbal bodily experience, and any learning that occurs must be bodily, physical learning. But does this nonverbal bodily experience have anything to do with the sort of learning that takes place in schools – learning verbal and abstract concepts? In this chapter, we argue that the body has everything to do with learning, even learning of abstract concepts.

Take mathematics, for example. Mathematical practice is thought to be about producing and manipulating arbitrary symbolic inscriptions that bear abstract, universal truisms untainted by human corporeality. Mathematics is thought to epitomize our species' collective historical achievement of transcending and, perhaps, escaping the mundane, material condition of having a body governed by haphazard terrestrial circumstance. Surely mathematics is disembodied!

We reject this commonly held view and argue instead that all school subjects, even mathematics, are embodied. An embodied perspective rejects the Platonic notion of mathematical objects as ideal entities whose mere shadows we mortals might hope to apprehend. Furthermore, this perspective promotes an epistemological conceptualization of mathematics, and in fact all STEM content, as grounded not in its sign systems and inscriptional forms (which clearly are pivotal to its practice) but in the situated, spatial-dynamical, and somatic phenomenology of the person who is engaging in activity society marks as "mathematical." We argue even more strongly that fundamental STEM knowledge is itself shaped by the embodied nature of the human mind.

The objective of this chapter is to outline the embodiment approach, explain how it contributes to our understanding of learning, and propose and exemplify how this understanding informs the design of STEM learning environments.

Principles of Embodiment

When we engage in professional practice, we apply particular ways of looking at and discussing situations (Goodwin, 1994). In many fields, particularly science, technology, engineering, and math (STEM), these professional habits can be difficult to acquire, because they introduce analytic perspectives that depart from naturalistic ways of being in the world (Bamberger & diSessa, 2003). And furthermore, in the STEM disciplines, to participate in professional practice one must develop fluency with dedicated semiotic systems that use unfamiliar symbolic notations (Harnad, 1990).

We believe that the embodiment approach can help educators to create learning environments that lead learners toward these disciplinary perspectives. Drawing on a broad range of learning sciences resources, this section spells out three principles that we have found helpful in making sense of and responding to students' persistent difficulty with STEM content. First, we discuss two epistemic systems, the primitive and the formal, and we argue that deep understanding of formal analysis is grounded in meanings from unmediated interactions with the physical world. Second, we claim that even beyond initial learning phases in the disciplines, all ongoing processes of sense making, problem solving, and even manipulating symbolic notation continue to be embodied – they all activate naturalistic perceptuomotor schemes that come from being corporeal agents operating in spatial-dynamical realities. Third, we argue for the pervasive role of equipment – biological, material, epistemic – in supporting and shaping cognitive activity.

Each of these three subsections culminates with a summary and a challenge for the design of STEM learning environments.

Rhyme and Reason: Learning as Coordinating Two Cognitive Systems

When we are immersed in any perceptuomotor activity, we engage a cognitive and motor system that is highly sophisticated yet demands little if any reflection. However, when we stop to think and talk *about* perception and action, we engage a different type of cognitive system, whose activity differs from the bodily experiences it refers to. Understanding the differences between these two epistemic modes – the immediate "doing" and mediated "thinking" – is important for the theory and practice of embodied learning, because educators seek to guide learners from immersive action to structured reflection.

Through structured reflection, the flow of absorbed experience is better understood. As Dewey put it, "Events turn into objects, things with a meaning … [that can] be infinitely combined and re-arranged in imagination … [and therefore] infinitely more amenable to management, more permanent and more accommodating" (Dewey, 1958, p. 167). When we make our unconscious, tacit knowledge explicit, it is as though we cast a conceptual screen

between ourselves and experience (Polanyi, 1958, p. 197). This *dual-system thesis* has parallels in the foundational literature of the learning sciences; for example, cognitive developmental psychologist Jean Piaget famously differentiated between perceptual and conceptual knowledge (Piaget & Inhelder, 1969, p. 46) and cultural-historical psychologist Lev Vygotsky juxtaposed spontaneous and scientific concepts (Vygotsky, 1962, chapter 6).

Kahneman (2003) distinguished between effortless intuition and deliberate reasoning, the former being rapid, heuristic, and relatively resistant to modification, the latter being slower yet more accurate and amenable to change. Notably, the two systems are permeable, so that deliberate reasoning over time can become more effortless and rapid (Dreyfus & Dreyfus, 1999; Fischbein, 1987). Even working with symbolic notation can become intuitive; recent studies suggest that simple verbal and arithmetic operations can be performed unconsciously (Sklar et al., 2012).

Cognitive psychologists suggest that new knowledge is first acquired in the conscious, deliberate mode and then becomes intuitive. But embodied activities fall into the intuitive, unreflected mode. We argue that meanings experienced in the intuitive holistic mode can lead to quantitative analyses and symbolic articulation typical of disciplinary practice.

Summary: In much of everyday activity, meanings are tacit, contextual, schematized orientations toward obtaining goals under given circumstances – the intuitive mode. STEM disciplines, however, concretize, parse, analyze, and quantify these naturalistic interactions – the analytic mode. To understand STEM content, students must reconcile their unmediated perceptions and actions with the mediated structures of disciplinary practice.

Challenge: Can learning environments be designed to foster grounded learning, in which students sustain a tacit sense of meaning from corporeal activity even as they are guided to rethink this activity formally? And would this result in more significant learning outcomes?

Abstraction as Simulated Action: Learning Is Moving in New Ways

In this section, we argue that manipulating symbolic notation is cognitively quite similar to physically moving objects in space. David Landy contrived an elegant experimental design that demonstrated that the colloquial notion of "manipulating symbols," such as "moving +2 across the equal sign so it becomes -2," is not just a metaphorical form of speech – in our "mind's eye" we literally move those symbols across the equal sign, so that we arrive later at our destination if the moving symbol must brave a counter current (Goldstone, Landy, & Son, 2009).

Many people believe that thinking is a type of psychological activity that is essentially detached from sensory input or action output. Many cognitive science studies have found, in contrast, that "Abstract concepts are perceptual, being grounded in temporally extended simulations of external

and internal events" (Barsalou, 1999, p. 603). And if so, thinking is always the evocation and dynamical manipulation of perceptions of the physical world. Melser (2004) argued that thinking is a form of covert, truncated action – "truncated" in that the mental faculties related to planning and executing external physical actions are engaged, but the musculature is not. Empirical evidence from neuroimaging supports these claims, finding that "rational thought … directly uses sensory-motor bodily mechanisms.… [It] is an exploitation of the normal operations of our bodies" (Gallese & Lakoff, 2005, p. 473). For example, when we imagine, we activate by and large the same parts of the brain as in actual seeing (Kosslyn, 2005). And when we hear the verbs *lick*, *pick*, and *kick*, we covertly activate the motor system that controls the mouth, the hands, and the legs, respectively (Hauk, Johnsrude, & Pulvermüller, 2004). These findings have led some scholars to go so far as to abolish traditional conceptualizations of mental representation and rearticulate cognition in terms of agent-environment dynamics (Chemero, 2009; Clark, 2013; Hutto & Myin, 2013; Thelen & Smith, 1994; Varela, Thompson, & Rosch, 1991).

Developmental psychologists broadly agree that bodily action plays a central role in conceptual development. Famously, Vygotsky stated that, "The word was not the beginning – action was there first" (Vygotsky, 1962). Piaget argued that the same action-oriented mental processes at play in coping with concrete situations are also involved when people learn mathematical or scientific ideas, such as the notions of "square" or "gravity." He asserted that "the roots of logical thought are not to be found in language alone.… But … more generally in the coordination of actions, which are the basis of reflective abstraction" (Piaget, 1968, p. 18).

Like Piaget, many contemporary cognitive scientists have proposed models to explain how abstract concepts emerge from concrete sensorimotor experiences. Notably, the cognitive semantics theory of conceptual metaphor posits that all human reasoning is grounded in *image schemas*, "patterns of our bodily orientations, movements, and interaction … [that] are imaginatively developed to structure our abstract inferences" (Lakoff & Johnson, 1980, p. 90). For example, we can make sense of the mathematical construct of a *set* only because we know what it means for physical objects to be gathered together in a container (Núñez, Edwards, & Matos, 1999).

Several psychologists have studied how people gesture while they speak and solve problems, and these studies have provided further evidence that thinking is embodied. For example, examining how people move their hands as they speak about artifacts they have just learned to manipulate helps us understand how actual interactions develop into simulated actions that impact future physical and cognitive performance (Goldin-Meadow & Beilock, 2010; Kirsh, 2013). Hatano, Miyake, and Binks, who studied abacus experts' mental arithmetic, concluded that "abacus operation tends to interiorize into mental operation through a transition stage wherein the

mental operation is not completely independent from the motor system and abacus-simulating finger movement gives important support" (Hatano, Miyake, & Binks, 1977, p. 53). Gestures mediate new ways of looking and thinking.

Summary: Conceptual reasoning originates in physical interaction and becomes internalized as simulated actions.

Challenge: How do we select, create, and facilitate physical interactions that give rise to conceptual reasoning and thinking that is aligned with desired educational learning outcomes?

Equipment and Breakdowns: Learning as Gearing Up with Biological, Material, and Epistemic Tools

The relation between human cognition and technological artifacts has long fascinated scholars. How are these two entities, the mental and the material, the animate and the inanimate, somehow synthesized in human neurobiology? What might it mean to experience conceptual change by manipulating an artifact that is external to the brain (Sfard & McClain, 2002)? After engaging in such an activity, do we retain any useful residual knowledge that we can then apply even in the *absence* of the artifacts (Salomon, Perkins, & Globerson, 1991)?

There is evidence that learners do so; Polanyi offers the following example. Imagine a blind person using a stick to negotiate through a physical space. When the person holds the stick for the first time, the person feels simple sensations – its texture and touch against his fingers and palm. But as one learns to use the stick for feeling one's way, the simple sensation is transformed – gradually, one feels the point of the stick touching the objects being explored (Polanyi, 1958, pp. 13–14).

This example demonstrates that artifacts affect cognition via the incremental adaptation we experience as we develop the skill of operating through these artifacts. As we "instrumentalize" the artifact, we necessarily "instrument" ourselves (Vérillon & Rabardel, 1995). That is, as we figure out how to apply the artifact to the world according to our needs, we develop the skill of controlling and interpreting the world through the mediating artifact. And whenever an artifact fails us, its latent structure and implicit function become transparent (Koschmann, Kuuti, & Hickman, 1998).

There is substantial evidence that thought and action persist in the absence of the artifacts that shaped them. This residual effect of artifact-mediated activity is perhaps most strikingly demonstrated in cases where prosaic structural elements of semiotic media surreptitiously colonize the meanings of signs. For example, Jasmin and Casasanto (2012) have shown that the historical QWERTY configuration of keyboards implicitly paints our affective perception of words in accord with their composition of right-hand side (positive) and left-hand side (negative) characters.

Summary: We use artifacts to extend our perceptuomotor and epistemic capacity. In so doing, we internalize physical and mental habits of interacting with the world via the artifacts' mediating structure. When these somatic, manipulatable, or cognitive artifacts fail to deliver desired effects, we consciously reflect on, recalibrate, or modify our modes of engaging the world. That is, we learn.

Challenge: How do we take learners through an optimal process of engaging with biological, material, and epistemic equipment to accomplish learning?

The embodied perspective, exemplified by the studies reviewed in this section, appears to be gaining a foothold in learning sciences discourse; leading journals and conferences have dedicated special issues and symposia to this perspective (Abrahamson, 2012; Hall & Nemirovsky, 2012; Kiverstein & Clark, 2009; Marshall, Antle, Hoven, & Rogers, 2013; Nemirovsky & Borba, 2004). We have articulated three challenges for educational design emerging from this perspective. Broadly, we have asked how educational designers might help learners ground classroom content knowledge, particularly in STEM disciplines, in their tacit knowledge, and what role action and equipment may play in this process. The next section offers some current responses to these challenges in the form of heuristic guidelines for educational design as well as two examples of their implementation in studies of STEM content learning.

Embodied Design: From Theory to Practice

When we apply an embodiment theory of cognition in the creation of learning environments, we are engaging in embodied design. The phrase *embodied design* was first coined by Thomas van Rompay, then a cognitive-psychologist-turned-industrial-designer, who used conceptual metaphor theory to tune the emotional experience evoked by public structures, such as bus stop shelters (Van Rompay, Hekkert, & Muller, 2005). Abrahamson (2009) imported the phrase into the learning sciences to describe the craft of engineering pedagogical artifacts and activities attuned to how humans naturally perceive the world, yet conducive to disciplinary reanalysis and signification. In an environment based on embodied design principles, learners could approach a problem in chemistry, biology, physics, material science, or mathematics using their natural bodily instincts and movements. This section offers design principles for fostering embodied learning and then describes a couple of designs for STEM content that exemplify these principles, drawing on a range of learning sciences research (Abrahamson, 2013; Antle, Wise, & Nielsen, 2011; Birchfield & Johnson-Glenberg, 2010; Diénès, 1971; Edwards, 1995; Howison, Trninic, Reinholz, & Abrahamson, 2011; Kamii & DeClark, 1985; Levy, 2012; Lindgren, 2012; Montessori, 1967; Papert, 1980; Pratt & Noss, 2010).

Principles for Embodied Design: Physical Experience, Guided Signification

In the previous section, we identified three challenges for pedagogical design:

- Can learning environments be designed to foster grounded learning in which students sustain a tacit sense of meaning from corporeal activity even as they are guided to rethink this activity formally? This is a question about *activities*.
- How do we select, create, and facilitate physical interactions that give rise to conceptual reasoning and thinking that is aligned with desired classroom learning outcomes? This is a question about *materials*.
- How do we take learners through an optimal process of engaging with biological, material, and epistemic equipment to accomplish learning? This is a question about *facilitation*.

We respond to these three challenges with three roughly mapped sets of proposed guidelines for embodied design.

The First Challenge: Activities

The activities most effective for learning draw on students' preexisting capacity to orient and mobilize in real or virtual three-dimensional space. Activities should require that students use their perceptual senses and kinesthetic coordination to judge properties of stimuli and perform new actions.

Initial tasks should include little to no symbolic stimuli, with a preference instead for figurative, iconic, diagrammatic, and graphical representations.

Activities should begin by engaging students in ostensibly simple tasks (making a screen green, hitting a target, etc.). The means of execution should initially be straightforward, but the overall objective may initially be opaque, with more complex objectives emerging over time.

The Second Challenge: Materials

Learning activities should be situated in an orchestrated environment that includes technological artifacts and facilitating agents (e.g., tutors, museum docents, or teachers). Students should have opportunities to find purpose and meaning in these environments, much as they do when navigating the complex material structures of the unmediated world.

The learning environment should be designed so that somatic actions – ranging from the movement of a single finger to the leaping of one's entire body – become coupled with the environment via action-feedback loops.

In the case of computer-based environments, such as augmented reality, virtual worlds, and simulations, students should experience firsthand the manipulation of virtual objects on a screen, tabletop, floor, and so forth.

Breakdowns of the action-environment couplings should be gradually introduced by presenting objectives that cannot be met using solutions and

configurations that the learner has already mastered. Tasks might suddenly require that tools be used in new ways or that new tools or frames of reference be used; or the materials themselves might shift to demand novel motor configurations. Students should gradually develop new perceptuomotor schemas that enable them to effectively control objects in service of the more sophisticated task objective.

The Third Challenge: Facilitation

Patterns of movement and body engagement that optimally facilitate conceptual development will not always occur naturally. Students will often need scaffolding (see Reiser & Tabak, Chapter 3, this volume) to take actions and move their bodies in ways that simulate the core mechanisms and spatial relations – to enact *functional metaphors* for the target knowledge domain. Physical cueing and situated real-time feedback should be implemented to reinforce these metaphors and elicit the kinds of movement that lead to desired conceptual insights.

Instructors and other agents in the environment should work to help students' perceptuomotor schemas develop toward those of experts. This typically involves seeing a situation in new ways, becoming attuned to hidden aspects of the environment. Effective pedagogical practices include physical demonstration, co-production, and hands-on coaching, as well as using media technologies to present audiovisual and even haptic (i.e., touch-based) experiences that convey expert perspectives.

Embodied designs will more effectively lead to conceptual development if students are asked to articulate their strategies for interacting with materials in the environment. For example, students may be asked to describe regularities in feedback based on their actions, to elaborate on these regularities relative to the content knowledge evoked by the activity, to develop strategies for utilizing these insights so as to accomplish the task more effectively, and to make requests for particular settings of the variable conditions as well as additional tools.

Having outlined a set of guiding design principles, we now describe several studies of embodied design in mathematics and science.

The Mathematical Imagery Trainer: Concepts as Signified Operatory Schemes

As an example of creating embodied design for mathematics education, we discuss a research project centered on an activity to help students learn the concept of proportion. The concept of proportion is an essential component of early curriculum, because it is key to STEM reasoning in high school, college, and the professions as well as everyday numeracy. However, many students in middle school and beyond experience difficulty in reasoning proportionately, often engaging "additive" rather than "multiplicative" visualizations of problems. For example, students might assert that 1:2 = 2:3, because

they attend only to absolute intervals among the numerical values (i.e., 1). A premise of this project was that students would learn proportionality effectively by conceptualizing new multiplicative procedures in terms of familiar additive operations, and that they could achieve this by coordinating among complementary multiplicative and additive visualizations of a proportions situation (Fuson & Abrahamson, 2005; Harel & Confrey, 1994).

The instruction of proportion often begins with a situation that gives rise to some proportional progression. A proportional progression, such as 1:2 = 2:4 = 3:6 = *etc.*, unfolds as a repeating linked adding on the left and right sides of the ":" symbol, that is, 1:2 = (1+1):(2+2) = (1+1+1):(2+2+2) = *etc.* Students learn to produce such successions of number pairs by iterating from each ratio to the next in the form of a ratio table and using multiplication shortcuts. However, what students do not experience when they enact this procedure is the meaning of proportional *equivalence* that the "=" symbol signifies. That is, students never have a structured opportunity to enact, visualize, conceptualize, and calculate exactly what is conserved during additive expansion or multiplicative scaling. Namely, in what sense is 1:2 the same as 2:4 or 3:6? By way of contrast, the equation 2+3 = 4+1 is fairly easily understood because each of the two expressions adds up to the same total – they each denote a set of five things. In contrast, it is harder for learners to understand in what sense 1:2 and 2:4 are the same.

Some curricula attempt to ground the idea of proportional equivalence by using text and pictures to invoke familiar experiences in which two ratios, such as 1:2 and 2:4, are associated with the same perceptual sensation. For example, equivalent ratios are modeled as the identical flavor resulting from mixing two ingredients measured respectively as either 1-and-2 units or 2-and-4 of the same units, or, analogously, the identical color resulting from mixing quantities of blue and yellow paint. However, these sensations are not experienced directly in the classroom but rather are left to children's imaginations. Moreover, the numerical cases are dictated rather than determined. Consequently, a proportion is not directly experienced, and procedures for manipulating proportions are not explored, discovered, calculated, explained, challenged, shared, or elaborated.

A design solution proposed by the Embodied Design Research Laboratory (Abrahamson, Director) is the Mathematical Imagery Trainer for Proportion (MIT-P; see Figure 18.1). The device measures the heights of the user's hands above a designated datum line, calculates the ratio of these two measures, and compares it to a particular ratio on the teacher's console. If the ratio is correct, the screen is green, and otherwise it is red. The goal presented to the student is to move their two hands up and down keeping the screen green rather than red. Note that the student is thus to enact proportional progression qualitatively (without measurement or enumeration), moving their hands simultaneously in continuous space. This design principle is called *dynamical conservation* because the learner needs to discover an action pattern (law of

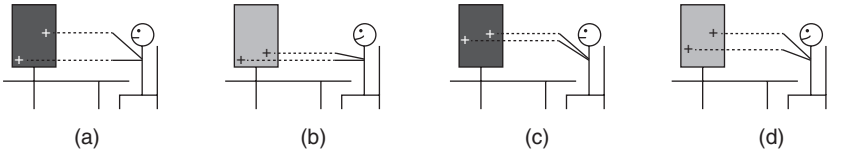

Figure 18.1. *The Mathematical Imagery Trainer for Proportion (MIT-P) set at a 1:2 ratio, so that the right hand needs to be twice as high along the monitor as the left hand in order to achieve a "success." The four-panel figure shows a paradigmatic interaction sequence – while exploring, the student: (a) positions her hands "incorrectly"; (b) stumbles on a "correct" position; (c) raises her hands maintaining a constant interval between them; and (d) corrects position. Compare 1b and 1d and note the different intervals between the cursors.*

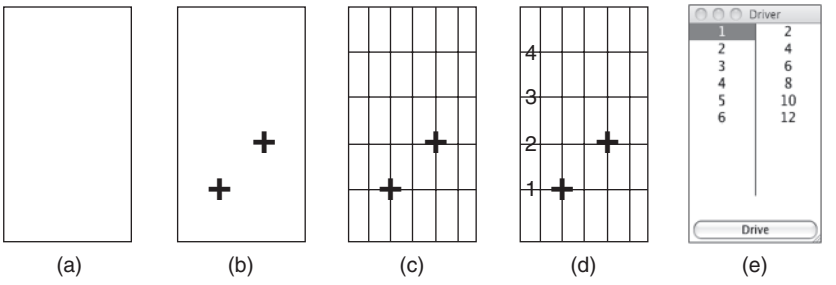

Figure 18.2. *The Mathematical Imagery Trainer for Proportion (MIT-P): schematic representation of the display configuration sequence used in the activity, beginning with (a) a blank screen, and then featuring a set of symbolical objects incrementally overlaid onto the display: (b) a pair of cursors that "mirror" the location of the user's left and right hands, respectively; (c) a grid; (d) numerals along the* y*-axis of the grid; and (e) a "driver" for controlling the cursors numerically rather than manually.*

progression) that keeps constant a property of the system. Once the student has developed and articulated the new skill, we overlay frames of reference onto the interaction space (see Figure 18.2).

We implemented the MIT-P design in the form of tutorial task-based clinical interviews, wherein 23 grade 4–6 students (ages 9 to 11) participated either individually or in pairs. When students first figured out how to maintain a green screen, they did so by manipulating the interval between their hands, in relation to their hands' elevation above the desk, articulated verbally as, "The higher I go, the bigger the distance." When we introduced mathematical artifacts into their working space (as in Figure 18.2), students tended to adopt these to enhance their performance. And in so doing, students began to talk more mathematically. For example, students utilized the grid (Figure 18.2c) to enact the "higher-bigger" strategy, and doing so led them to reconfigure their strategy into the iteration law of proportional

progression, such as "For every 1 I go on the left, I go 2 on the right." Later, when the corresponding numerals were introduced (Figure 18.2d), students suddenly realized the multiplicative relation between the left- and right-hand values and stated, "On the right its double what's on the left" (Abrahamson, Trninic, Gutiérrez, Huth, & Lee, 2011). When we asked students to reason about relations among their various strategies, they were able to explain connections between their non-multiplicative and multiplicative conceptualizations of proportion (Abrahamson, Lee, Negrete, & Gutiérrez, in press).

In a controlled experiment run with 128 students, participants who directly or vicariously engaged activities with the MIT-P outperformed a control group on conceptual items (Petrick & Martin, 2011). Several tablet variations on this design are now available (e.g., Abrahamson, 2012; Rick, 2012).

MEteor: Cueing Body Actions Aligned with Scientific Principles

A second example of embodied design, in the area of science education, comes from a research project on immersive simulation technology for strengthening middle school students' intuitions about kinematics. Students frequently struggle to acquire a formal understanding of the principles that govern how things move, and often fall back on weakly organized systems of knowledge based on their everyday interactions in the world when reasoning about physical phenomena (diSessa, 1993). One way to connect everyday experience to formal concepts is to engage students in analogical thinking and have them reflect critically on their own preconceptions (Clement, 1993). Fully immersive interactive virtual reality environments can support exploration of kinetics concepts by grounding them in the familiar domain of one's own body movements and connecting these experiences to formal representations. Several projects have sought to cultivate physics knowledge with immersive virtual worlds (Kafai & Dede, Chapter 26, this volume; also see Dede et al., 1996; Enyedy, Danish, Delacruz, & Kumar, 2012; Johnson-Glenberg, Birchfield, Megowan-Romanowicz, Tolentino, & Martinez, 2009), but these environments stop short of explicitly prompting learners to enact the movements of an idealized physical system, consistent with the first of our embodied design principles related to facilitation.

The MEteor project is designed to support movement cueing and to combine correctly performed actions with a formal framework for interpreting those actions. MEteor is a room-sized (30' x 10') mixed reality simulation game that attempts to strengthen and structure intuitions about Newton's laws and Kepler's laws by having them enact the movement of an asteroid traveling through space. Students use their whole bodies to make predictions about where the asteroid will move as it encounters planets and other objects with gravitational forces; audio and visual cues guide their movements, allowing them to adjust their predictions in real time. MEteor is a relatively short-term intervention, designed to disrupt preexisting misconceptions and

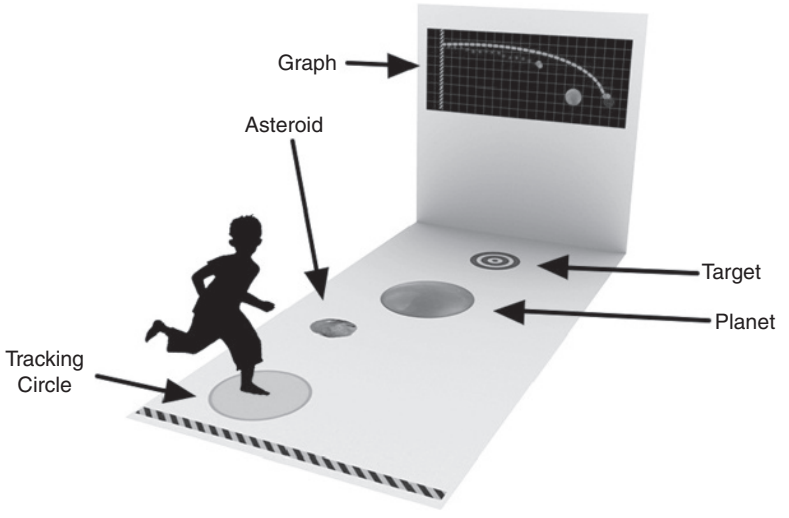

Figure 18.3. *The MEteor simulation game for whole-body metaphor-based interaction. A student launches an asteroid and must predict its motion as it interacts with other objects (e.g., planets) in space. In the scenario above the student has fallen behind the asteroid, causing her tracking circle to change color. A graph on the wall display allows the participant to review the previous trial.*

give rise to new perspectives that have the potential to be built on with formal instruction.

A MEteor user begins by walking onto a platform and linking his or her body movements to the floor-projected image of an asteroid (pronounced visual and audio effects reinforce this connection). The learner now controls the movement of the asteroid up until the point that it enters an area of space where a planet's gravity and other forces influence the asteroid's trajectory. The objective of the learner, through a series of increasingly difficult game levels, is to accurately predict the movement of the asteroid; scoring in the game is dependent on how closely the learner adheres to the correct path, and visual indicators (i.e., a color gradient surrounding the learner's feet) are in place to guide their real-time movement. Level 3 of the game, for example, requires the learner to pass their asteroid through an area of space directly behind a planet placed in the middle of the floor display. To successfully hit the target area, a learner must discover that an asteroid passing near to a planet will curve around it, and accelerate in the process. After completing a trial launch, a learner reviews their attempt via a diagrammatic representation of their movement on a wall display (see Figure 18.3). They are prompted to explain why the asteroid moved the way it did, and the instructor helps them reframe their description, typically first-person models conveyed in everyday language, in terms of gravitation force and orbit. Breakdowns occur when the learner's movement fails to align with that of

the launched asteroid or when the objective of a level is not achieved. The data visualizations on the wall display give learners the opportunity to reflect on these actions and recalibrate for the next trial.

In MEteor, a learner is aided in their adoption of functional metaphors through salient cueing mechanisms. If, for example, a learner begins to deviate from the correct trajectory of an object moving through space, all the available dynamic visual elements of the simulation (the color of the tracking circle, the actual position of asteroid, etc.) will change to steer the learner back on course. We predicted that the MEteor experience would result in more highly organized systems of knowledge, and data collected so far suggests that this is the case, showing that learners who engage with the full-body simulation are less likely to focus on the surface features of the simulation experience (e.g., background stars or textures of the planets) compared to participants who used a desktop version of the same simulation (Lindgren & Moshell, 2011). Participants who are given the opportunity to enact the physics concepts with their bodies seem to be more attuned to the important dynamic relationships the simulation conveys, as evidenced by their use of arrows and other representations of movement in their post-simulation diagrams. Additionally, participants using the full-body simulation appear to have a more robust understanding of the simulation space as evidenced by their superior ability to identify the conditions that would lead to a successful versus an unsuccessful launch (Lindgren & Bolling, 2013).

Conclusion and Future Directions

We have argued that all cognition is grounded in bodily experience, and our examples demonstrate specifically that math and science conceptual understandings are grounded in bodily experience. And if so, learning environments for math and science can be made more effective if they are designed to tap into bodily know-how that originates both from existing life experience and new learning experiences.

The studies reviewed in this chapter show that math and science concepts are not abstract, conceptual mental entities, removed from the physical world. Rather they are deeply somatic, kinesthetic, and imagistic. Interactive tasks typical of embodied design thus steer learners to discover, refine, and practice physical action schemes that solve local problems but can then be generalized to math or science conceptual understanding (Trninic & Abrahamson, 2012). Embodied designers design schemes that underlie reasoning in the disciplines.

The embodied turn in the theory and practice of STEM education implies that studying physical skill development (Bernstein, 1996) should bear directly on studying conceptual development (Thelen & Smith, 1994), for example by interfacing neurophysiological and clinical studies with formal

models, such as dynamic field theory (Spencer, Austin, & Schutte, 2012, p. 415). Furthermore, the essential role of teachers in guiding students' physical engagement with embodied design suggests the relevance of the fields of cognitive and social anthropology, such as studies of vocational apprenticeship or distributed cognition in the workplace (see Collins & Kapur, Chapter 6, this volume), as bearing theoretical and analytic means for researchers to make sense of how learners come to think through and with their bodies in ways that begin to approximate professional practice (e.g., Becvar Weddle & Hollan, 2010; Ingold, 2011). This marriage of motor-developmental psychology and sociocognitive anthropology bodes well for the learning sciences, as it offers powerful means of realizing the call for dialectical research at the intersection of cognition and sociocultural theory (diSessa, 2008; Greeno & Engeström, Chapter 7, this volume).

A child balancing on a seesaw, it turns out, is developing more than physical coordination – she is building an embodied sense of equivalence that may one day inform her moral reasoning about social justice (Antle, Corness, & Bevans, in press). Even as students develop new physical action schemes as cognitive and social entry into the activity structures of the disciplines, so are scholars developing new conceptualizations of education to explain how embodied knowledge transforms into a body of knowledge. In more than one sense, learning is moving in new ways.

Acknowledgments

For their superb commentary on an earlier draft, we heartily thank Shaun Gallagher, Geoff Saxe, and Katharine G. Young. For inspiring conversations and suggestions, we thank Jeanne Bamberger, Raúl Sanchez Garcia, and Cliff Smyth. We are grateful to Keith Sawyer for constructive critiques and very useful suggestions. Funding for the *Mathematical Imagery Trainer* was provided by a UC Berkeley Committee on Research Faculty Research Grant. Funding for the MEteor project was provided by the National Science Foundation (DRL-1114621). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of UC Berkeley, UI Urbana-Champaign, or NSF.

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