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16

Embodiment and Embodied Design

Dor Abrahamson and Robb Lindgren

Picture this. A preverbal infant climbs onto a rocking horse and straddles its center. She gently tilts her weight back and forth, sensing as she tips downward and then back up again. This child cannot articulate her observations in simple words, let alone in scientific jargon. Does 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? 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!

Embodiment theory rejects this commonly held view and argues instead that all school subjects, even mathematics, are embodied. An embodied theoretical approach to the learning sciences rejects the Platonic notion of mathematical and scientific objects as ideal entities whose mere shadows we mortals might hope to apprehend. Furthermore, this approach argues for a change in how we think about what it means to know and learn STEM content. Conceptions of knowledge are *epistemologies* (see Chapter 2, this volume), and most school curricula today implicitly assume the epistemological position that STEM knowledge consists of abstracted sign systems that are constituted in inscriptional forms. Although these are clearly pivotal to STEM practice, we instead argue for a different conceptualization of STEM knowledge: It is the situated, spatial-dynamical, kinesiological, and somatic phenomenology of the person who is engaging in mathematical or scientific activity.

Whereas embodiment theory rejects the notion of STEM concepts as entities that exist irrespective of the organisms who apprehend them, it does not deny our capacity to reason about these entities as if they exist. Philosophical scholarship refers to the nature of these entities as *ontologies*. Embodiment theory conceptualizes the ontology of STEM concepts as cultural–historical forms that enable us to engage in organized activity structures. When we discuss or reason about STEM concepts, we partake in an elaborate human practice that uses the various sign systems we have negotiated over the millennia to coordinate, enhance, and document our discourse, reflection, deliberation, planning, and action. These sign systems include spoken language and other meaning-making (*semiotic*) resources, such as diagrams, tables, graphs, and symbolic notations. Yet whereas these sign systems allow us to extend and distribute our cognitive activity over media, people, and time, such as in manipulating elements of a complex algebraic expression, the meanings of these signs—what these signs refer to, when experts think about them deeply—are ultimately grounded in their multimodal experience. A pedagogical challenge, as such, is to present curricular content for students is such a way that they can ground it in their multimodal experience.

An embodied theoretical perspective explains STEM learning as coming to participate in the cultural–historical practices of collective reference to multimodal phenomenology. Coming to participate in these practices consists of developing several intertwined capacities: *epistemic*, that is, developing ways of introspecting on one's own embodied knowledge; *semiotic*, that is, developing fluency with the sign systems of the domain; and *discursive*, that is, developing empathetic attention to how others are thinking and engaging in collaborative argumentation. As such, embodiment implies for the learning sciences a vast research program of radically re-thinking the charge of STEM education as designing and facilitating guided opportunities for students first to experience new multimodal perceptions grounded in situated experiences and then negotiate between these perceptions and the sign systems that evolved through the historical necessities of civilization to augment on the limited capacity our cognitive architecture. These negotiations, we will argue, are complexified by inherent ontological tensions between actions and symbols.

The objective of this chapter is to outline on embodiment theory, 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 reasoning about events and artifacts (Goodwin, 1994). In many fields, particularly STEM, these professional habits can be difficult to acquire, because they introduce analytic perspectives that depart from naturalistic ways of being in the world, such as thinking about the experience of time as something that can be expressed by a fraction (Bamberger & diSessa, 2003; 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. We think that students have trouble learning STEM content because they are receiving pedagogies that remove the body from the content. And for that reason, they are learning only abstracted procedures, rather than the embodied forms of reasoning that are associated with professional STEM practice and knowing. First, we discuss two types of knowing, the intuitive and the analytic, and we argue that analytic knowledge is grounded in meanings that emerge from intuitive interactions with the physical world. Second, we claim that even beyond initial learning in the disciplines, all ongoing processes of sensemaking, 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, virtual, 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 Types of Knowing

When we are immersed in any perceptuomotor activity, we engage a cognitive and motor system that is highly sophisticated yet typically demands little if any reflection. However, when we stop to think and talk *about* perception and action, we engage a different type of knowing, whose activity differs from the bodily experiences it refers to. Understanding the differences between these two types of knowing – 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 (cf. Piaget: see Chapter 2, this volume; see metacognition chapter, this volume).

Through structured reflection, the flow of 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 thesis of two types of knowing 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 (real) and scientific (ideal) forms (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 types of konwing 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 (e.g., Sklar et al., 2012).

Cognitive psychologists maintain that new culturally mediated skills, like riding a bicycle, are first acquired consciously, deliberately and then become automatized. That means that we have appropriated the cultural artifact to the point that in practicing our new skills, we can bring to bear our natural sensorimotor capacities for solving situated problems of engaging with the environment (e.g., shifting our weight on the bicycle to regain balance). As such, learning to use a cultural artifact can give rise to new embodied experiences. We argue that meanings emerging from sensorimotor engagement with cultural artifacts are essential for understanding quantitative analyses and symbolic articulations of STEM disciplinary practice.

Summary: In much of everyday activity, meanings are tacit, contextual, modal orientations for obtaining goals under given circumstances – the intuitive mode. STEM disciplines, however, operate by concretizing, parsing, analyzing, and quantifying phenomena – the analytic mode. To learn STEM content, students must, therefore, reconcile their intuitive perceptions with the structures of disciplinary cultural practice. And yet, common instructional practice often does not occasion opportunities for students to experience STEM content as emanating from, and expanding on their intuitive interactions with natural and cultural environments.

Challenge: Can naturalistic activity thus be coopted for cultural learning? That is, 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 explicit reflection result in more substantial learning? This is a challenge about *activities*.

Abstraction as Simulated Action

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 (Goldstone, Landy, & Son, 2009; see also Nemirovsky & Borba, 2004).

It is often assumed that thinking is a type of psychological activity that is essentially detached from sensory input or action output. Research in cognitive science has found, in contrast, that "abstract concepts are perceptual, being grounded in temporally extended simulations of external and internal events" (Barsalou, 1999, p. 603). This evidence recasts thinking as 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 (see also Vygotsky, 1926/1997, p. 161). 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). Some scholars go so far as to abolish traditional conceptualizations of mental representation and rearticulate cognition in terms of agent–environment dynamics (Chemero, 2009; Clark, 2013; Gibson, 1996; Hutto & Myin, 2013; Thelen & Smith, 1994; Varela, Thompson, & Rosch, 1991).

Developmental psychologists broadly agree that bodily action plays a central role in conceptual development. Vygotsky famously 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. And yet, these developmental models vary quite a bit in their epistemological assumptions – whether abstractness is an objective quality of concepts or is a relational subjective experience of individual learners. On the one hand, 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* because we know what it means for physical objects to be gathered together in a container (Núñez, Edwards, & Matos, 1999). On the other hand, some scholars qualify that our lay notion of the “abstract” is philosophically misguided for theorizing human thought. What is abstract for me, may be concrete for you—when we understand a concept, it is necessarily concrete and embodied, not abstract (Wilensky, 1991; see also Nemirovsky, Ferrara, Ferrari, & Adamuz-Povedano, 2020).

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, discursive, and cognitive performance (Goldin-Meadow & Beilock, 2010; Kirsh, 2013; Roth, 2009). Hatano, Miyake, and Binks (1977), 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" (p. 53). Gestures mediate new ways of perceiving, doing, and thinking.

Summary: Conceptual reasoning originates in sensorimotor interaction and becomes a capacity to simulate 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? This is a challenge about *materials.*

Equipment and Breakdowns: Learning as Gearing Up with Biological, Material, Virtual, and Cognitive 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 engaging artifacts changes the mind. 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, they feel simple sensations – the stick's texture and touch against their 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, until the stick itself "vanishes" and the objects remain (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 (for neurobiological evidence from studies with macaques, see Iriki, Tanaka, & Iwamura, 1996). Yet whenever an artifact fails us, its latent structure and implicit function become visible once again (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. They found that a word that contains letters typed by the right-hand, like "milky," is perceived more negatively than a word that contains letters typed with the left hand, like "drawer."

Summary: We use artifacts to extend our perceptuomotor and epistemic capacity. In so doing, we practice 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 guide learners through an optimal process of engaging with biological, material, virtual, and epistemic equipment to accomplish learning? This is a challenge about *facilitation*.

We have articulated three challenges for educational design emerging from the embodied perspective. Broadly, we have asked how educational designers and teachers 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, followed by a section that demonstrates how these heuristics can be implemented in studies of STEM 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, 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 interact with 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 (Abrahamson, 2018; Abrahamson et al., 2020). This section offers design principles for fostering embodied learning, and the next section describes a couple of designs for STEM content that exemplify these principles, drawing on a range of learning sciences research (Abrahamson, 2014; Diénès, 1971; Lindgren, Tscholl, Wang, & Johnson, 2016, 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 that addressed activities, materials, and 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. The tasks should be designed and facilitated so as to enable students to perform confidently in ways that agree with formal models of the situations in question, even if students' claims and argumentation are initially couched in qualitative and informal language rather than quantitative and formal terminology. It is important to valorize the content and form of these intuitive judgments and actions.

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, whether human or artificially intelligent agents). Students should have opportunities to find purpose, goals, and meaning in these environments, much as they do when playfully navigating the complex material structures of natural and cultural environments, for example climbing trees, building with toy blocks, or playing "house."

The learning environment should be designed so that relevant motor actions – ranging from the movement of a single finger or the saccade of an eye 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 manually and whole-bodily engage with 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 already knows. Tasks might suddenly require that tools be used in new ways, or 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 to take actions and move their bodies in ways that simulate the core mechanisms and spatial relations – to enact *functional metaphors* (Gallagher & Lindgren, 2015) for the target knowledge domain. Physical cueing and situated real-time feedback should be implemented to reinforce these new coordinations and elicit the kinds of movement that lead to desired conceptual insights.

Instructors should work to help students' perceptuomotor schemas develop toward those of experts. This typically involves perceiving a situation in new ways, becoming attuned to hidden aspects of the environment (Abrahamson, 2009; Shvarts & Abrahamson, 2019). Effective pedagogical practices include cueing where and how to engage a situation, physical demonstration, co-production, and hands-on coaching, as well as using media technologies to simulate audiovisual and even dynamical physical experiences that convey expert perspectives (Abrahamson & Sánchez–García, 2016).

Embodied designs will more effectively lead to learning if activity conditions prompt students to articulate their strategies for interacting with materials in the environment, thus fostering metacognition (Winne & Azevedo, this volume). 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, to compare alternative strategies, and to make requests for particular settings of the variable conditions as well as additional tools. In working with activity partners, students may need to coordinate the co-enactment of joint actions, which often requires aligning perceptual attention.

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

The Mathematics Imagery Trainer: Emergent Sensorimotor Perceptual Structures Become Signified via Disciplinary Practice as Enacting New Concepts

As an example of creating embodied design for mathematics education, we discuss a research project centered on an activity for students to learn a concept that is central to K–12 STEM curriculum, proportions (Harel & Confrey, 1994). A premise of this project was that students would understand proportionality, which is a multiplicative concept, by experiencing how it differs from ways of reasoning that rely only on the arithmetic operations of adding and subtracting.

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 both 1:2 and 2:4 are the same.

Some curricula attempt to ground the analytic idea of proportional equivalence by invoking intuitive perceptual sensations of identical flavor or color resulting from mixing liquid quantities of appropriate measures. However, for a variety of logistical, legal, and medical reasons, these sensations are usually not experienced directly in the classroom but rather are left to children's imaginations. Moreover, the numerical cases are dictated rather than determined, the and, once mixed, the liquid substances cannot be easily calibrated let alone unmixed. Consequently, a proportion is not directly experienced, and procedures for manipulating proportions are not explored, discovered, calculated, explained, challenged, shared, or elaborated.

A proposed design solution is an activity whose focal ***material*** is the Mathematics Imagery Trainer for Proportion (MIT-P; see Figure 16.1). This 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 ***activity*** goal presented to the student is to move their two hands up and down keeping the screen green. This design principle is called *dynamical conservation* (Abrahamson, 2014), because the learner needs to discover an action pattern (law of progression) that keeps constant a property of the system.

Figure 16.1. 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 make the screen green (a "success"). The four-panel figure shows a typical learner sequence – while exploring, the student: (a) positions her hands "incorrectly" (red feedback); (b) stumbles on a "correct" position (green); (c) raises her hands *maintaining a constant interval between them* (red); and (d) corrects position (green). Compare 1b and 1d and note the different intervals between the cursors. (Art: Virginia J. Flood, PhD)

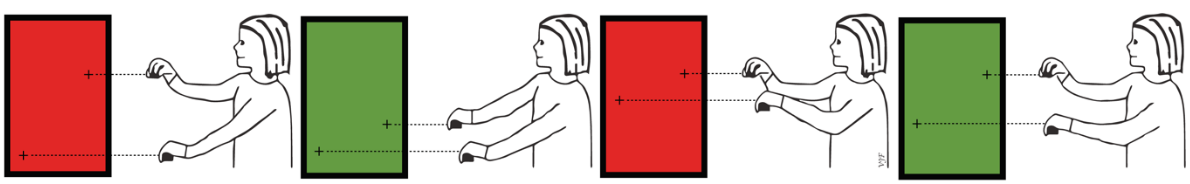
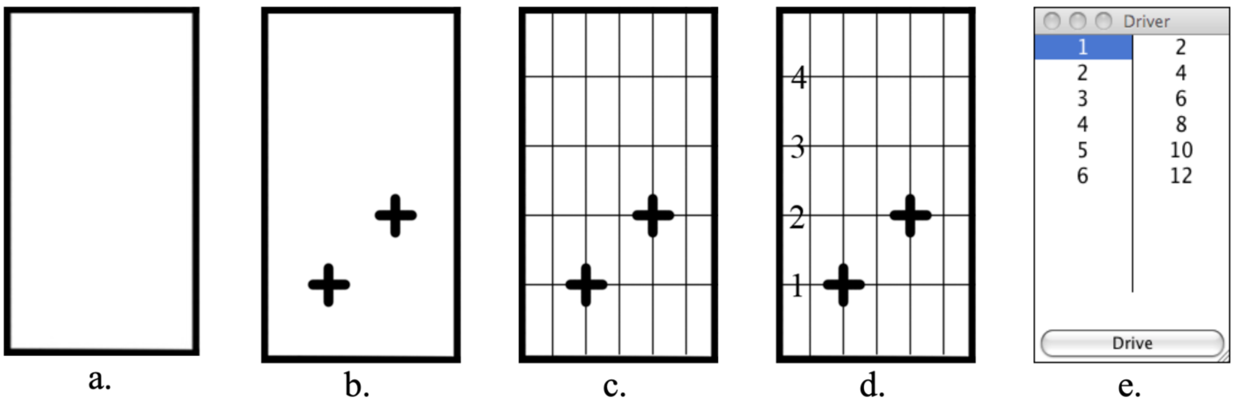


Figure 16.2. The Mathematical Imagery Trainer for Proportion (MIT-P): schematic representation of the display configuration sequence used in the activity, beginning with (a) a blank screen, and then featuring a set of symbolical objects incrementally overlaid onto the display: (b) a pair of cursors that “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.



Over several empirical studies with elementary and middle-school students, our participants figured out how to maintain a green screen. So doing, they moved their hands simultaneously in a dynamic form that experts perceive as a proportional progression. The students, however, who could yet model their hand movements as proportional, explained that they kept the screen green by attending to the spatial interval between their hands as it related to their hands’ elevation above the desk. They said, “The higher I go, the bigger the distance.” This is what we mean by inferences and assertions that are mathematically correctly even if couched naively in qualitative forms using informal language. Such perceptuomotor ways of thinking and talking should be encouraged and celebrated, because they carry the embodied ways of knowing that are soon to ground the disciplinary analysis of the same situation.

The activity ***facilitation*** then calls to overlay frames of reference onto the interaction space (see Figure 16.2). Students tended to adopt these new materials to enhance their performance. And in so doing, students began to talk more mathematically. For example, students utilized the grid (Figure 16.2c) to enact their “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.” This is called the principle of *functional parity* (Abrahamson, 2014), because students adopted a mathematically advanced form through recognizing its compatibility with their own form. Later, when numerals were introduced (Figure 16.2d), students suddenly realized the multiplicative relation between the left- and right-hand values and stated, “On the right it’s double what’s on the left.” As such, the students articulated mathematically what it is that stays the same across equivalent ratios. When we asked students to reason about relations among their various strategies, including their intuitive–interactive and formal–analytic methods for moving their hands in green, they were able to explain connections between their additive and multiplicative conceptualizations of proportion (Abrahamson, Lee, Negrete, & Gutiérrez, 2014).

Empirical research using eye-tracking methods supports the thesis that when students engaged in solving our motor-control problems, they spontaneously generated new sensorimotor perceptual structures to coordinate the positioning of their two hands (Duijzer, Shayan, Bakker, van der Schaaf, & Abrahamson, 2017). Several tablet variations on this design are now available (e.g., Abrahamson, 2012). The design genre has been implemented for other mathematical topics, including parabolas, trigonometry, and area (for a review, see Abrahamson, 2019) and adapted for inclusive classrooms with students of different sensorial abilities (Abrahamson, Flood, Siu, & Miele, 2019).

The GRASP Project: Cueing Student Gestures to Elicit Science Explanations

A second example of embodied design, in the area of science education, comes from a research project on the use of augmented reality to scaffold students' mechanistic explanations of science phenomena (also see the chapter on augmented reality in this volume by Schneider & Radu). Argumentation and the articulation of causal relationships often do not occur spontaneously in student discourse in science classrooms (Berland & McNeill, 2010; see Andriessen & Baker, this volume), nor does the active engagement of student bodies in the construction of scientific explanations. However, studies have shown that physical activity, such as gesturing, can support students' scientific reasoning (Flood, Amar, Nemirovsky, Harrer, Bruce, & Wittmann, 2015; Singer, Radinsky, & Goldman, 2008), and, further, that explicitly prompting students to gesture can lead to stronger mechanistic explanations in science (Lindgren, Wallon, Brown, Mathayas, & Kimball, 2016). The challenge is how to encourage gesturing in ways that are not overly-prescriptive and didactic, while still ensuring a focus on causal elements of the phenomena students sought to explain.

The GestuRe Augmented Simulations for supporting exPlanations (GRASP) project uses augmented reality technology to merge dynamic visualizations of science phenomena with students' hand gestures, situating students as actively involved in creating representations of the causal factors that underlie physical processes such as the changing of seasons on Earth or thermal conduction. Augmented reality falls within the spectrum of XR or "extended reality" environments that use computer graphics to enhance human experiences beyond what can be achieved in the real world. AR is used in the GRASP simulations to allow students' free-form hand gestures to interface with dynamic simulations. For example, in Figure 16.3, a student performs a gesture above a motion sensing device to show the angle at which light rays from the sun are hitting the surface of the Earth at a specific geographic location. This angle reflects a particular spatial configuration of the Earth and the Sun, and in turn indicates the current season at that location (e.g., a near perpendicular light ray would indicate that it is summer at that location).

Consistent with the ***activities*** guidelines for embodied design, students are initially prompted to use the gesture-augmented GRASP environment to perform simple simulation tasks. For example, in the seasons simulation, a student is first asked to place the Earth in an orientation showing summer for the northern hemisphere (e.g., June) (Figure 16.4). Students are able to move the Earth by making hand gestures that represent the angle that light rays hit the surface of the Earth at a particular location for the desired time of year (e.g., a mostly perpendicular orientation in the summer). Performing the gestures that move the Earth back and forth between June and December is not difficult, but for most students it is not initially intuitive why they must angle their hands rather than dragging or pushing the Earth to the desired orientation. The reason is that in making a physical representation of the light rays at a certain angle, they enact the causal mechanism behind the changing of the seasons: a smaller angle leads to lower density of light and cooler overall temperatures.

Figure 16.3. A student using a hand gesture to represent the angle at which light rays are hitting the Earth in the GRASP seasons simulation.

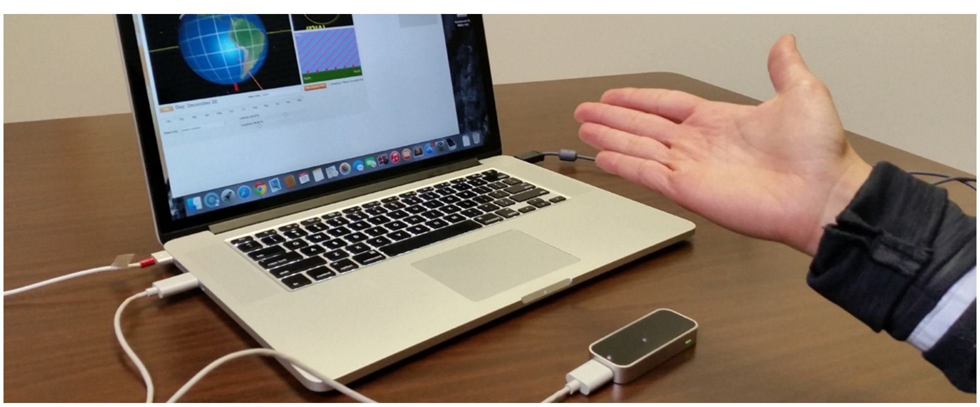
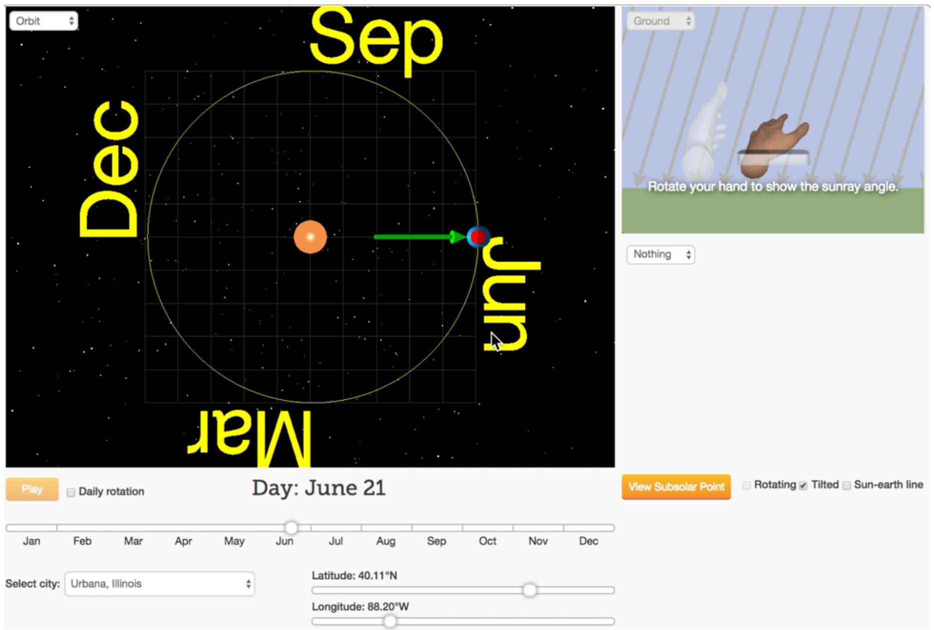


Figure 16.4. A screenshot of the GRASP seasons simulation. The view on the left shows the position of the Earth relative to the Sun at a given time of year, while the smaller view on the left shows the associated angle of light rays hitting the Earth at that time.



The ***materials*** that comprise the GRASP simulations are digital visualizations designed to make unseen and hidden processes such as molecular interactions visible. Dynamic visualizations are not uncommon in contemporary science education; however, changes in the GRASP visualizations are tightly coupled with students' hand movements, such that they are able not only to *see* these changes but *feel* them, and to enact a working model that can lead to generative intuitions (e.g., the 'bumping' of one's hands can lead to insights about what happens when molecules collide). The GRASP simulations are orchestrated environments designed specifically as tools for enabling students to articulate explanations; gestures are coupled with the unobservable mechanisms behind visible phenomenon to create a dynamic digital–physical model that the student is a part of.

The GRASP simulations possess a unique form of ***facilitation*** borrowed from commercial video games, where student actions are cued by "ghost" images that solicit productive actions. In this case, semi-transparent hands appear on screen to suggest that students try a gesture and observe consequent changes to the state of the simulation. In the seasons simulation a ghost hand cues the student to angle their hand to change the direction of the incoming light rays (upper right of Figure 16.4). In the gas pressure simulation the ghost hands suggest that the student should hit their fist against the flat palm of their other hand. If this action is taken, the volume and the pressure of the container shown on screen will change so as to match the frequency of gas molecules hitting the side of the container with the frequency of the user's colliding hands. This often instigates curiosity and exploration; however, not all facilitation can be orchestrated through the interface, so the activity is also seeded with questions posed to the students, such as, "What do your hands represent?" Facilitation in embodied design requires more than simply prompting students to perform the desired action— they must also be encouraged to reflect on the meaning of those actions.

Conclusion: Learning is Moving in New Ways

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. These examples show how math and science teaching can be made more effective if hands-on activities 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 what it means to say that math and science concepts are not abstract mental entities, removed from the physical world. Rather, these concepts are grounded in deeply somatic, kinesthetic, and imagistic experiences. Interactive tasks typical of embodied design thus steer learners to discover, refine, practice, and reflect on perceptuomotor action schemes that solve local problems but can then be reframed as exemplifying new math or science concepts (Abrahamson, 2019). As such, embodied designers are educational choreographers of STEM concepts: they create movement forms that instantiate STEM concepts, they build activities for students to accomplish those movement forms, and they offer students ways of reflecting on these movement forms so as to adopt new ways of thinking.

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 (Becvar Weddle & Hollan, 2010) enskillment theory (Ingold, 2011), or ethnomethodology approach to conversation analysis (Flood, 2018), 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 disciplinary practice. 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; Engestrom & Greeno, this volume).

A child balancing on a rocking horse, 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, 2013). Even as students develop new physical action schemes as cognitive and social entryways 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.

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