Educ Psychol Rev (2015) 27:391–404
DOI 10.1007/s10648-015-9327-1

REVIEW ARTICLE

Enactive Metaphors: Learning Through Full-Body Engagement

Shaun Gallagher[1,2] **· Robb Lindgren**[3]

Published online: 16 July 2015

Abstract Building on both cognitive semantics and enactivist approaches to cognition, we explore the concept of enactive metaphor and its implications for learning. Enactive approaches to cognition involve the idea that online sensory-motor and affective processes shape the way the perceiver-thinker experiences the world and interacts with others. Specifically, we argue for an approach to learning through whole-body engagement in a way that employs enactive metaphors. We summarize recent empirical studies that show enactive metaphors and whole-body involvement in virtual and mixed reality environments support and improve learning.

Keywords Metaphor · Enactive cognition · Simulation · Pretense · Learning

Metaphors in Action

Some metaphors sit on a page and wait for the reader to find them. We might call them sitting metaphors, and a good example is the idea of a sitting metaphor itself (metaphors don't *literally sit* on a page). We can encounter sitting metaphors, for example, when we are literally sitting, reading a book or an electronic screen. We ingest the metaphor, and if it is a good one, doing its job, it will make us think or support our thinking process and perhaps help us along to understanding. It may exercise our imagination. As such, metaphors have always been important in learning experiences. A good metaphor will lead us somewhere, open up an insight, show us something that we could not see before, and this has obvious relevance to education.

✉ Shaun Gallagher
s.gallagher@memphis.edu

Robb Lindgren
robblind@illinois.edu

1 Department of Philosophy, University of Memphis, 331 Clement Hall, Memphis, TN 38152, USA

2 Faculty of Law, Humanities and Arts, University of Wollongong, Wollongong, Australia

3 Department of Curriculum, College of Education, University of Illinois Urbana-Champaign, 394 Education Building, 1310 S. 6th St., Champaign, IL 61820, USA

Metaphors do things, but only when we engage with them in some fashion. This engagement can be implicit and internal, as when we encounter a sitting metaphor and allow it to shape our thinking. Engagement with metaphors, however, can also be explicit and active, to various degrees on a scale that is defined at one end by passive consumption of sitting metaphors and on the other end by what have been called "enactive" metaphors (Winner et al. 1979).

The term enactive here signifies not a different kind of metaphor per se but a different kind of engagement with metaphor. Specifically, we can say that an enactive metaphor is one that we enact—that is, one that we put into action or one that we bring into existence through our action. [1] The fact that we are enacting a metaphor (rather than, for example, a plan or a design or a solution) means that the action involved can be a kind of play-acting or pretense (the kind of acting one finds in a theater or in the pretend play of a child). To enact a metaphor means to act it out. As in acting, this is an embodied process.

In this paper, in addition to developing the concept of enactive metaphor, we review empirical evidence showing that enactive metaphors are important for learning. Specifically, the evidence shows that in some cases, enactive engagement with a metaphor, in a fully embodied way, benefits the learning process more so than passive encounters with sitting metaphors (see Enactive Metaphors in Learning Interventions). Our primary aim, then, is to show the relevance of the notion of enactive metaphor, and more generally, the enactivist approach, to educational contexts. After introducing the notion of enactive cognition (Enactive Cognition), we discuss the concept of enactive metaphor by contrasting it with an analysis of metaphor found in cognitive semantics (Enacting Metaphors). We then show how the concept of enactive metaphor can be used to understand the early informal learning context of pretend play (Metaphors and Pretend Play). In Enactive Metaphors in Learning Interventions, we review studies that show how enactive processes and metaphors are relevant in formal classroom contexts. We then extend this review to recent empirical studies of technologies that offer support for the use of enactive metaphors in science education, including a study of our own using mixed reality to support the study of physics and astronomy (Putting Metaphors to Work in Technologically Supported Learning Environments).

Enactive Cognition

The concept of enactive cognition has become an important one in recent cognitive science. We can trace its origins to the work by Varela, Thompson, and Rosch, *The Embodied Mind* (1991), which draws on phenomenological resources, especially the work of Merleau-Ponty (1962). It could have easily drawn on the work of John Dewey and other pragmatists. Indeed, long before Varela et al. (1991), Dewey (1896) clearly characterized what has become known as enactivism. We begin in perception, he suggests,

[1] It is possible that some metaphors cannot be acted out and can only remain properly propositional. For example, "I feel like a million bucks." Others can only work by acting them out; for example, if I pick up a banana and pretend it is a phone. This is, we suggest, a difference in what a concept may afford in regard to metaphor—a difference in what we can do, given the human body and the particular environment, rather than a difference in metaphor kind. This difference in affordance does not seem to depend on the level of abstractness of the concept. Some abstract concepts, like energy or mass, may be difficult to act out; others, like gravity, may be easier (see Enactive Metaphors in Learning Interventions).

> not with a sensory stimulus, but with a sensorimotor coordination . . . it is the movement which is primary, and the sensation which is secondary, the movement of body, head and eye muscles determining the quality of what is experienced. (Dewey 1896, p. 358)

The idea of enactivism is that online bodily processes, not only sensory-motor processes but also affective processes as well (Gallagher and Bower 2014), shape the way the perceiver-thinker experiences and considers the world and interacts with others. Varela offered the metaphor of "laying down a path in walking" to capture the sense of enactive cognition. The path (or our understanding) is not preestablished; we construct it as we go and specifically through bodily processes, such as walking, moving, gesturing, reaching, grasping, and interacting with others.

The enactive approach to embodied cognition can be characterized by the following background assumptions (Di Paolo et al. 2010; Dominey et al. 2015; Thompson and Varela 2001; Varela et al. 1991).

1. Cognition is not simply a brain event. It emerges from processes distributed across brain-body-environment.
2. The world (meaning, intentionality) is not pregiven or predefined but is structured by cognition and action.
3. Cognitive system processes acquire meaning in part by their role in the context of action, rather than through a representational mapping or replicating an internal model of the world.
4. In contrast to classical cognitive science, which attempts to explain cognition by focusing on internal mechanisms (so-called methodological individualism), the enactivist approach emphasizes the extended, intersubjective, and socially situated nature of cognitive systems.
5. The enactivist approach has strong links to dynamical systems theory, emphasizing the relevance of dynamic coupling and dynamic coordination across brain-body-environment.
6. Enactivism aims to ground higher and more complex cognitive functions not only in sensorimotor coordination but also in affective and autonomic aspects of the full body.
7. Higher-order cognitive functions, such as reflective thinking or deliberation, are exercises of skillful know-how and are usually coupled with situated and embodied actions.

As with any philosophical position, there is no unanimity in the enactivist camp. There are variations of enactivism. One variation emphasizes the idea that sensory-motor contingencies structure our perceptions of the world (Noë 2004). This idea builds on the Gibsonian notion of affordances (Gibson 1977). On this view, we perceive the world in terms of what we can do, that is, in terms of its pragmatic meaning. I do not first perceive something as what it is and then add a pragmatic meaning to it. Rather, the pragmatic significance is built into perception. I perceive the chair, for example, as something that affords sitting. A chair affords sitting not only because of its shape but also because of my human shape—because my joints bend at certain points and to certain angles. If my body were different—if, for example, I were shaped and sized like an elephant—then the chair would not afford sitting for me. Indeed, a different shape and/or size, and a different set of sensory-motor capabilities could redefine my possibilities for movement and action, and thereby redefine how I see the world. Enactivists cite empirical evidence to show that because one can (or cannot) move in a certain way, because one can do (or not do) certain things, and because one has certain skills defined by a set of sensory-motor contingencies, one's perception of the world is shaped by a basic pragmatic significance (see, e.g., Gallagher 2005; Jeannerod 1997; Noë 2004).

Enactivists suggest that this way of thinking about cognition involves rethinking the concept of mind at its most basic level (Varela et al. 1991). Cognition, as embodied and enactive, is not exclusively the result of neural processes in the head. It is something accomplished in a dynamic set of interactions between brain and body, and between body and environment. The correct physical unit of analysis for understanding cognition is not the neuron, or the neural representation, or the brain, but the brain-body-environment in their dynamic interplay (Gallagher 2005).

These insights build on initial principles expressed in Varela et al. (1991) and developed by a number of others (e.g., Di Paolo 2009; Gallagher 2005; Gallagher and Varela 2003; Noë 2004; Thompson 2007). The enactivists have not only fleshed out the basic ideas of sensory-motor contingencies and the cognitive system as a dynamic embodied system but also emphasized affective and intersubjective aspects. It is not difficult to understand that we may perceive and think about the world differently if we are angry or depressed rather than happy or satisfied. Even hunger can shape, and perhaps distort, cognitive processes. Danziger et al. (2011), for example, show that the rational application of legal reasons does not sufficiently explain the decisions of judges. They show that judges are ≈65 % more lenient in the first hours after a meal break than in the hours just preceding a meal break. Thus, whether the judge is hungry or satiated may play an important role in leniency or strictness in his or her rulings.

Likewise, intersubjective and social relations can generate different ways of understanding the world. Our interactions with others, from infancy onwards, shape our perceptions and actions. Joint attention and joint action can have cognitive results that extend well beyond what any one particular individual can accomplish. The idea that two (or more) heads (or bodies) are better than one can be shown empirically in experiments that test memory and problem-solving skills (e.g., Sutton 2006; Sutton and Williamson 2014). In addition, the dynamics of conversation can be shown to facilitate cognition in a way that enhances understanding (Kendon 1990). De Jaegher and Di Paolo (2007) refer to this kind of intersubjective enhancement as "participatory sense-making" and suggest that our cognitive life is shaped by our interactions with others, in play, conversation, work, love relations, and fellowship, as well as in competitive and negative situations. Our enactive engagements with others create new possibilities or reinforce old constraints, initiate, or transform social and cultural practices, and define aspects of life in social and cultural institutions that transcend purely physical survival (Gallagher 2013a).

Referencing this background on enactivist approaches to cognition, in the next section, we appeal to the notion of metaphor found in cognitive semantics in order to explicate the concept of enactive metaphor. And, in the sections that follow, we show the relevance of this concept to learning contexts.

Enacting Metaphors

The well-known work of Lakoff and Johnson (1980, 1999) demonstrates the role of embodiment in the formation of metaphors that lead to the development of abstract concepts. They argue that basic bodily movements (moving forward, moving back), spatial situations (being inside, being outside), anatomy, vestibular function and posture (having a left hand and a right hand, maintaining balance, the upright posture), and so forth contribute to basic metaphors that scale up to higher-order cognition. "Image-schemas" are structures that recur in our everyday bodily experience. Examples include containment, paths, forces, balance, and the relations of up-down, front-back, and part-whole. We experience our body as a container when we eat; we experience paths when we walk, forces when we are pushed upon, balance when we stand upright, and so on. These image-schemas carry and transform basic bodily experiences into metaphoric concepts. The image-schema of "containment," for example, "a schema consisting of a boundary distinguishing an interior from an exterior" (Lakoff 1987, p. 271), and involving movements in and out, allows us to conceptualize a number of abstract concepts.

> You wake *out* of a deep sleep and peer *out* from beneath the covers into your room. You gradually emerge *out* of your stupor, pull yourself *out* from under the covers, climb *into* your robe, stretch *out* your limbs, and walk *in* a daze *out* of your bedroom and *into* the bathroom. You look *in* the mirror and see your face staring *out* at you. (Johnson 1987, pp. 30–31)

In terms of social groups, you are either *in* (part of the *in*-crowd or *in*-group) or you are simply "*out* of it." Balance is metaphorically transformed into an understanding of justice. When we project an embodied experience of moving along a path onto an abstract concept like "life," life is understood as movement along a path, a journey, involving detours, rough patches, and so on. For Lakoff and Johnson, thinking and speaking are metaphoric in so far as information from one domain (the source domain, e.g., journey) gets mapped onto a second domain (the target domain, e.g., life) such that we understand the target domain in terms of the source. One metaphorical structure leads to the next. *Time is money*, so time can be spent or wasted. Or, to follow Fauconnier and Turner's (2002) semantic blending theory, one metaphorical/conceptual space can "blend" with another to form a new space (also see Lakoff and Turner 1989). In this regard, higher-order cognition is composed of structures that combine and blend metaphor-based categories that can ultimately be traced to embodied experiences and practices.

The cognitive semantics of image-schemas, metaphors, and blending gives us a way to conceptualize how embodied perception and action can scale up into the more sophisticated and intellectual aspects of cognition. One could argue that the processes involved in this scaling up are enactive processes that depend on all of the embodied, affective, and intersubjective aspects discussed in the previous section. Some proponents of the cognitive semantics approach to metaphor downplay differences between the use of metaphors in linguistic practices in contrast to more action-oriented practices (such as pretend play—see the following section). There is "no formal difference between metaphor as revealed by linguistic expressions and metaphor as revealed by other forms of human action, including the production and use of material culture" (Ortman 2000, p. 616). As Malafouris (2013) points out, however, this claim fails to acknowledge the important affordance differences actually involved in using artifacts (material mediation) versus linguistic mediation. His "material engagement theory" emphasizes the affordances that are based on the different properties of things versus words, texts, or propositions. Accordingly, he suggests that "materially enacted metaphors" (e.g., picking up a banana and pretending to use it like a telephone) are different from proposition-based metaphors (e.g., producing a statement like "Time is money" or "I feel like a million dollars").

Pursuing this critical perspective, our aim in this paper is to show the relevance of action-based enactive metaphors for learning and to focus on how we can put metaphors to work in actual learning situations. We want to show how we can enact metaphors in concrete learning situations, where *enacting metaphors* means that we take them on in a fully embodied way in specific contexts. In this respect, we build on both enactivism and cognitive semantics, to see how these approaches apply in educational contexts.

Metaphors and Pretend Play

One obvious place to look for processes that involve enacting metaphors is in pretend play, which is one of the earliest informal learning contexts. Pretend play has traditionally been defined as "symbolic play" involving linguistic capabilities (Huttenlocher and Higgins 1978) and internal representational and intellectualist meta-representational capacities (Leslie 1987). It is possible, however, to take a less intellectualistic or cognitivist, and a more enactivist approach to pretend play. Gregory Currie (2004), for example, moves towards such an understanding of pretense when he focuses on the perceptual ability to *see-in*, i.e., the ability to see resemblances or affordances *in* the objects (e.g., see 2004, p. 220). He remains close to the traditional cognitivist line, however, since he does not take *seeing-in* as sufficient for pretense and thus requires further representational, offline processing.

Following a more enactive view, Rucinska (2014) suggests that the ability to *see-in*, combined with embodied actions, is sufficient for constituting some basic types of pretend play. Sensorimotor skills take over the role of any *offline* imaginative or representationalist capacities and provide support for *online* action-oriented capacities based on direct perception, where the seeing of affordances motivates action.

For example, 18-month-old infants, with presumably limited linguistic and conceptual capacities relative to adult cognition, are capable of basic object-substitution pretense, as in the example of pretending that a banana is a phone (e.g., Sainsbury 2009). It seems unlikely, however, that the infant is engaging in a manipulation of propositions, symbols, or offline representations in order to affect the pretense. In this case of pretend play, the infant literally manipulates the banana—grasps it and puts it to her ear. In doing so, specifically, *in the doing itself*, she treats the banana metaphorically. The metaphor at stake, however, is not sitting someplace in her head; it is in her hand and in the movement that she makes with the banana. She constitutes the metaphor by her action. She, in effect, enacts a metaphor that builds on an affordance presented by the shape of the banana, and on her previous experiences with phones.

Central to this kind of pretense process is the ability to see affordances in the object. This is not a passive seeing (as Currie might take it); rather, for the enactivist, recognizing affordances is an active event. That is, seeing is a pragmatic grasping of the possibilities for action—a preparation for (or even part of) grasping with the hand (see Gallagher 2013b). To be clear and to emphasize the full scope of the enactive view, this is not just a matter of sensory-motor contingencies. As Rucinska (2014) points out, other elements enter into the pretense: imitating, responding to emotions, gesturing, smiling, giggling, context-sensitivity, and linguistic skills. The play is situated, and all of these factors bespeak *affective* and *intersubjective* dimensions that are likely to occur in the play situation.

Pretense, accordingly, involves a metaphoric transformation—it involves *acting-as-if* or *seeing* something *as* something else. More precisely, in the action, the banana (target) is a phone (source). On the overly cognitivist view, imaginative transformation is simply to "substitute one thought content for another", thus, "accessing and controlling inputs (beliefs and desires) to the acts of imaginative projection that underpin pretence" (Currie and

Ravenscroft 2002, p. 140). This interpretation relies heavily on belief-like states and thinking processes to underpin such abilities. Currie thus overly intellectualizes the process. “In pretence one acts under a supposition, for example, that the box I am sitting in is a car; in suppositional mode one can also consider an idea, draw consequences from it, consider the evidence for it, and compare it with other ideas” (2003, p. 233). It is not clear, however, that the infant is doing any of this when she actively grasps the banana as a phone or drives the box as a car.

On the enactivist view, pretend play can be characterized without appealing to higher-order cognitive or recreative imaginings. *Seeing-as* does not require thoughtfully representing the object, but rather the exercise of a basic motoric skill, which may be motivated in an intersubjective imitative process. The caregiver, for example, picks up the banana and talks into it and giggles as she does so, as she captures the infant’s attention with her facial expression. This is part of an embodied interaction that the infant immediately picks up on. The infant sees the banana as a phone not through a set of mental representations but in the caregiver’s actions, and in picking it up and imitating the caregiver—a clear instance of participatory sense-making. The infant capitalizes on the social affordances offered in such a situation. The affordance is summarized not merely in terms of one object substituting for another but in the dynamic relationship of joint attention and joint action with the caregiver.

The pretense process thus involves taking a perceptual (or social) affordance in a metaphorical direction. *Seeing* affordances *in* objects involves seeing beyond the mere physicality or physical presence of the object—it involves seeing possibilities for action or interaction, and this includes seeing objects *as if* they were involved in such actions. Rather than seeing a phone in the banana, one sees in the banana the affordance of a particular sort of action. Precisely to the extent that perception is enactive, a metaphorical dimension is always available in perception. In this respect, pretense does not have to be “a ‘higher’ mental process” (Currie 2004, p. 219). It rather stays on a perception-action level where what is seen is not so much the object (banana/phone) but the possible action (calling and talking).

This can happen, as Robert Mitchell (2002, p. 8) puts it, “within any medium – including bodily actions, gestures and sounds … – and has considerable consequence, in that it allows organisms to *experience* something *as* something else – a doll as a baby, a stick as a horse, … – which is essential for pretence.” Metaphoric meaning can extend to the entire play environment. In this regard, Vygotsky (1978) is right to suggest that what is essential for pretense is meaning. According to the enactivist approach, meaning- or sense-making already occurs in perception and action. Perception is already “charged with meaning” to the extent that it “arouses the expectation of more than it contains …” (Merleau-Ponty 1962, p. 4)—perception is charged with possibilities, anticipatory of my possible actions relative to my bodily abilities and skills.

Not all forms of pretense, of course, are simple object-substitutions. There are also subject-substitutions or role-playing in which I pretend to be someone or something else. In this regard, as in theatrical acting, I directly enact the metaphorical transformation of myself in my actions. I am (metaphorically, not literally) that other or that object. Again, this is not something that necessarily requires higher-order cognition (although, of course, it does not rule out contributions from that domain, especially in relatively sophisticated role-playing); it can be a fully embodied transformation. Affordances that I can act upon or metaphorically transform by my actions, however, do open up new insights leading to the development of new perspectives and possibilities. As such, these processes constitute a way of learning.

Enactive Metaphors in Learning Interventions

Metaphors have a long tradition in interventions designed to examine and enhance learning in areas such as science (e.g., Christidou et al. 1997; Duit 1991; Gentner and Wolff 2000). Effective metaphors allow learners to transfer understanding of a familiar domain to a new, unfamiliar domain. For example, discussing the atmosphere as a "blanket" of gasses around the earth opens up potential insights pertaining to its protective or temperature-control characteristics (Cameron 2002). Educational metaphors, however, are typically disembodied, static models of processes that require the learner to "think through" the mappings from source to target domain. They are sitting metaphors, and while they are capable of making explicit the semantic similarities between domains, it is not always clear that these kinds of metaphors bring learners any closer to a state of knowing that would allow them to perform actions in a particular domain with an awareness or instinct for how these actions will affect the system, or to see the consequences of such actions before they happen. Enactive metaphors in educational contexts, on the other hand, present learners first with an activity—moving in a prescribed way or play-acting a specified process. Enactive metaphors have the potential to dialogically develop a stable sense of relationships by prompting the user to act out their understandings with their bodies and adapt those understandings via salient channels of feedback. In an example developed below, students can metaphorically identify with an asteroid and act out its movement in a planetary system in order to learn from their own kinesthetic feedback about the principles of gravity.

There is empirical evidence from cognitive psychology that naturally occurring bodily movements and gestures accompany higher levels of understanding. Gesture, for example, takes up some of the cognitive load and adds to or supplements processes of mathematical cognition. Studies by Goldin-Meadow and others show that children perform better (faster and more accurately) on math problems when they are allowed to use gestures, in comparison with when they are asked to sit on their hands (Alibali and DiRusso 1999; Goldin-Meadow et al. 1999, 2001). Alibali and Nathan's (2012) observation of teacher and student gestures in a mathematics classroom showed that enactive gestures frequently appear during effective instructional discourse such as using one's arms to demonstrate the slope of a line. Gesture, as a part of language, not only scaffolds our thinking processes but also adds meaningful information, both for the gesturing subject (actually supporting her thinking) and for the communicating partner (Cole et al. 2002; McNeill 1992). Gesture, using visual-spatial formatting, provides extra information that is not found in the verbal-representational format of speech alone, as evidenced, for example, in problem-solving tasks involving mental rotation (Chu and Kita 2008). Likewise, the use of gestures to enact the rotation of physical models of molecules correlates with higher accuracy on a diagram translation task (Stull et al. 2012).

In recent studies, education researchers have seeded learning interventions with enactive activities as a potential means to instigate new learning. In a seminal study of reading comprehension, for example, it was shown that having children simulate the events of a story with a set of figurines improved reading comprehension (Glenberg et al. 2004). Glenberg (2008) shows how these comprehension effects can be extended into areas like math and science when students enact an experiment that they read about in order to learn about the control-of-variables in scientific experimentation. Similar strategies can be applied to mathematics learning: Martin and Schwartz (2005), for example, show improved performance on fraction problems using physical manipulatives when the problem was given narrative framing ("Imagine you had to share these pieces equally with five people").

A number of studies have shown that enactive metaphors can be particularly effective for young learners in classrooms and similar educational settings. Shoval (2011) showed that students engaged in “mindful movement”—positioning their bodies in specified ways—when reasoning collaboratively about angles showed greater learning than students who were taught angle concepts through traditional instruction. Plummer (2009) also noted learning gains for elementary students acting out celestial trajectories with their bodies or objects representing stars and planets. Because enactive metaphors frequently rely on one’s familiarity with one’s body and how it moves, they can be leveraged to create learning situations based in “kinesthetic conflict,” such as having young children hop in a zigzag line as a way to reveal and confront student ideas about the conservation of length (Druyan 1997).

Putting Metaphors to Work in Technologically Supported Learning Environments

New technologies have the potential to open up new frontiers of enactive metaphors by integrating learners’ perceptions and movements with vivid and immersive imagery. Current digital environments can be seductive, enabling and encouraging action in what Kirsh (2013) refers to as “enactive landscapes.” These expressive and exploratory technologies compliment educational thinking that discourage a “formalisms first” approach in favor of preceding formal instruction with inquiry and authentic activity (Nathan 2012). Lindgren et al. (2015) argues that new technologies allow for a paradigm of “body cueing” in education that strives to create an embodied foundation for new learning by prompting learners to move and engage in novel or expert-like ways. For example, a computer simulation with motion sensing capabilities might prompt a student to move their hand or body with the periodicity of a wave. Or, an augmented reality application might guide a novice archeologist to explore and navigate through an excavation site the way that an expert scientist would investigate it. Whereas acquiring expert behavior previously required having an expert on-hand to show or highlight optimal ways to move and focus one’s attention, new technologies are capable of delivering perceptual cues that elicit expert actions.

Different technologies offer a range of opportunities for supporting enactive metaphors, and some of these technologies have been available for some time. Motion sensors and other simple measurement devices have long been used in classrooms as a means for making student activity explicit and available for reflection (e.g., Solomon et al. 1991). Newer technologies such as those that provide haptic feedback (Han and Black 2011) make metaphors tangible and present; the arm acting as a lever can have the appropriate forces applied, and the body acting as an object in a magnetic or gravitational field can be pulled in accordance with their simulated distance. One class of technologies that seem to offer particular affordances for engaging learners in enactive metaphors are “mixed reality” environments that merge physical and virtual worlds (Milgram and Kishino 1994). In these environments, authentic and expressive physical activity can be augmented with digital displays that reinforce the metaphor (e.g., imagery of space, views from inside the human body, etc.) and tools for performance feedback and reflection. In essence, these mixed reality technologies allow students to become part of the system they are trying to understand, giving them an “insider” perspective on the critical mechanisms and relationships that define the domain (Lindgren and Johnson-Glenberg 2013).

There have been a handful of studies that have examined the learning effects of enactive metaphors with mixed reality and augmented reality technologies. These studies have shown learning gains for elementary school students in a participatory simulation of force and friction (Enyedy et al. 2012), for high school students participating in collaborative mixed reality games around chemistry concepts and disease transmission (Johnson-Glenberg et al. 2014), and for elementary students embodying ratio as a way to control a display screen (Abrahamson et al. 2011). Another project involving young learners involved a simulation that allowed the children to manipulate sound output with their bodies (Antle et al. 2008). One version of the simulation explicitly employed the metaphor "music is body movement" and mapped movements to sound concepts such as having higher speed movements produce higher tempo. Compared to a version of the simulation that had nonmetaphorical mappings (e.g., fast movement produces low pitch sounds), the metaphor participants showed more accurate physical demonstrations and improved verbal explanations in the posttest.

To provide a more detailed account of the use of a technology-enabled enactive metaphor, we turn to our own work with mixed reality. To examine how interactive metaphors can shape learning and engagement, we created a mixed reality environment in which middle school students could act out their predictions about how objects move in space. The project, called *MEteor* (Metaphor-Based Learning of Physics Concepts Through Whole-Body Interaction in a Mixed Reality Science Center Program), uses wall- and floor-projected dynamic imagery to create a realistic and immersive simulation of planetary astronomy (planets with gravitational properties that support orbiting satellites, etc.). Children interact with *MEteor* by using their bodies to launch an asteroid with a certain velocity and then predict where the asteroid will move based on the presence of planets and associated forces. This involves an enactive metaphor in that the child identifies with the asteroid—"I am the asteroid"—and acts out the behavior of the asteroid. In using *Meteor*, the children are guided through a series of levels in which they encounter a progression of critical ideas and principles in the physics of how objects move in space, such as notions of gravitational acceleration and Kepler's Laws of planetary motion. Feedback about whether the child's ongoing predictions are accurate is delivered within the frame of the metaphor, in real-time simulation prompts that cue the child, for example, to bend their trajectory more sharply around a planet to accurately depict the effects of gravitational forces. Children are able to build their understandings around the movements of their own bodies, with representational supports (graphs and other visualizations) built into the environment in a way that scaffolds this construction of new knowledge. The metaphors at work in *MEteor* do not rest on a page or in a student's mind; they move around actively in a large room, and they are given life through the running and jumping of a child eager to demonstrate mastery of the simulation game (Fig. 1).

We have demonstrated the effectiveness of *MEteor* and the associated enactive metaphor for learning in studies that compare a "strong" enactive condition with a "weak" enactive condition (Lindgren and Moshell 2011; Lindgren et al. 2015). In the weak enactive condition, participants use a desktop computer version of *MEteor* where the asteroid is controlled not by the student's whole bodily movement but by minimal movement of a computer mouse. In the weak enactive condition, a participant's predictions are made via the micro-movements of their hand, and the learning perspective in this case remains distinctly outside of the system that is being studied, as is the case with most formal learning environments which rely on sitting metaphors and other pedagogical approaches that focus on stimulating mental activity. The strong (full-body) and weak (desktop computer) versions of the simulation that were compared were tightly controlled such that all study procedures were essentially identical except that in the strong condition, participants were enacting their understanding with their bodies in a fully immersive room-sized interactive space which allowed them to be "inside" the system they were learning about.

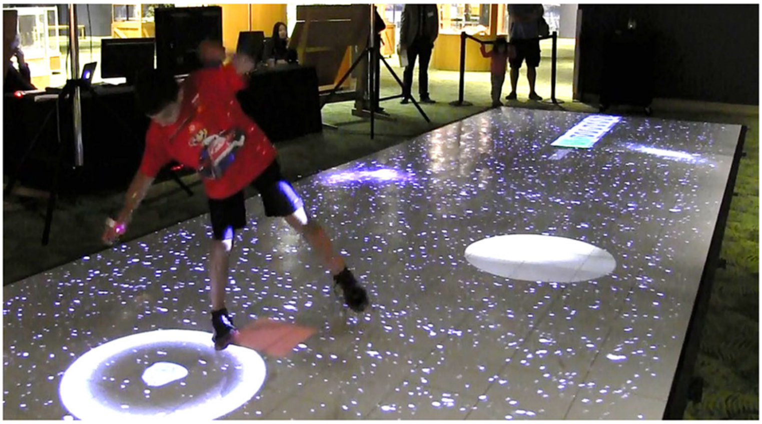

Fig. 1 A participant enacting an asteroid trajectory in *MEteor*

Lindgren and Moshell (2011) found that participants (62 middle school students divided across the two conditions) in the strong enactive group constructed "learning diagrams" after using the simulation that included more dynamic representations (e.g., arrows); they were less reliant on surface features of the simulation (e.g., background stars and planet textures) compared to the participants in the weak enactive condition. The findings suggest that participating in enactive metaphors leads to a more comprehensive and flexible understanding of the domain.

In Lindgren et al. (2015), of 113 middle school participants, 58 used the strong enactive version of the simulation, and 55 used the weak enactive version. Results showed that students in the strong condition scored higher on standardized assessments of physics knowledge. This assessment included not only questions about how objects move in space but also questions that addressed physics understanding more broadly (e.g., the effects of gravity on objects tossed in the air from the Earth's surface). The higher scores on these more general questions suggest that enactive metaphors may have deep and cross-cutting impacts on student reasoning that transfer beyond the specific context of the interactive simulation. There were also important dispositional learning effects, such as higher pre-post changes in reports of science efficacy for the strong enactive metaphor condition, as indicated by the participants' level of agreement with statements such as "I enjoy talking to other people about science." This finding suggests that technology-enabled enactive metaphors may give students greater feelings of control and confidence in their own learning.

Conclusion

Drawing from both cognitive semantics and enactivist approaches to cognition, we have defined the concept of enactive metaphor and have shown the implications that enactive metaphors have for learning. This concept builds on the idea that action and online action-oriented processes shape the way the perceiver-thinker-learner experiences and comes to understand the world. We have argued, looking to empirical evidence, that whole-body engagement framed by enactive metaphors can improve learning outcomes in science, mathematics, and other subjects. Combined with virtual and mixed reality environments, the use of enactive metaphors clearly supports learning.

The empirical studies reviewed above, including examples of pretense and pretend play, starting around 18 months of age, and continuing through early childhood, demonstrate the importance of enactive metaphors for educating young children. This not only is consistent with but also goes beyond long-standing claims that active participation is better than passive observation for learning. It shows that, at least in some circumstances, when learning environments are designed for strong (full-bodied) enactive participation, there is a benefit to learning. In this respect, learning environments that are designed for strong enactive participation (in contrast to passive observation or even weak enactive participation) reinforce what enactive theory claims to be our natural embodied stance toward the world—a stance in which perception is *for-action* and in which agents pragmatically exploit worldly affordances. As learners, we are more "in-the-world" than "in-the-book" or "in-the-head"; we take more from active engagement and interaction than from passive observation.

Acknowledgments Research for this project was supported by the National Science Foundation Informal Science Education grant (DRL-1114621), entitled "Metaphor-Based Learning of Physics Concepts Through Whole-Body Interaction in a Mixed Reality Science Center Program."

References

Abrahamson, D., Trninic, D., Gutiérrez, J. F., Huth, J., & Lee, R. G. (2011). Hooks and shifts: a dialectical study of mediated discovery. *Technology, Knowledge and Learning, 16*(1), 55–85.

Alibali, M. W., & DiRusso, A. A. (1999). The function of gesture in learning to count: more than keeping track. *Cognitive Development, 14*(1), 37–56.

Alibali, M. W., & Nathan, M. J. (2012). Embodiment in mathematics teaching and learning: evidence from learners' and teachers' gestures. *The Journal of the Learning Sciences, 21*(2), 247–286.

Antle, A.N., Droumeva, M., & Corness, G. (2008). Playing with The Sound Maker: do embodied metaphors help children learn? In the *Proceedings of the Conference on Interaction Design for Children IDC '08.* ACM, New York, NY, 178–185.

Cameron, L. (2002). Metaphors in the learning of science: a discourse focus. *British Educational Research Journal, 28*(5), 673–688.

Christidou, V., Kouladis, V., & Christidis, T. (1997). Children's use of metaphors in relation to their mental models: the case of the ozone layer and its depletion. *Research in Science Education, 27*(4), 541–552.

Chu, M., & Kita, S. (2008). Spontaneous gestures during mental rotation tasks: insights into the microdevelopment of the motor strategy. *Journal of Experimental Psychology: General, 137*(4), 706–723.

Cole, J., Gallagher, S., & McNeill, D. (2002). Gesture following deafferentation: a phenomenologically informed experimental study. *Phenomenology and the Cognitive Sciences, 1*(1), 49–67.

Currie, G. (2004). *Arts and minds*. Oxford: Oxford University Press.

Currie, G., & Ravenscroft, I. (2002). *Recreative minds: imagination in philosophy and psychology.* New York: Oxford University Press.

Danziger, S., Levav, J., & Avnaim-Pesso, L. (2011). Extraneous factors in judicial decisions. *Proceedings of the National Academy of Sciences, 108*(17), 6889–6892.

De Jaegher, H., & Di Paolo, E. (2007). Participatory sense-making: an enactive approach to social cognition. *Phenomenology and the Cognitive Sciences, 6*(4), 485–507.

Dewey, J. (1896). The reflex arc concept in psychology. *Psychological Review, 3*(4), 357–370.

Di Paolo, E. A. (2009). The social and enactive mind. *Phenomenology and the Cognitive Sciences, 8*(4), 409–415. doi:10.1007/s11097-009-9143-5.

Di Paolo, E. A., Rohde, M., & De Jaegher, H. (2010). Horizons for the enactive mind: values, social interaction, and play. In J. R. Stewart, O. Gapenne, & E. A. Di Paolo (Eds.), *Enaction: toward a new paradigm for cognitive science* (pp. 33–87). Cambridge, MA: MIT Press.

Dominey, P. F., Prescott, T., Bohg, J., Engel, A.K., Gallagher, S. Heed, T., Hoffmann, M., Knoblich, G., Prinz, W., & Schwartz, A. (2015). Implications of action-oriented paradigm shifts in cognitive science. In *Where's the action? The pragmatic turn in cognitive science*. Cambridge: MIT Press.

Druyan, S. (1997). Effect of the kinesthetic conflict on promoting scientific reasoning. *Journal of Research in Science Teaching, 34*(10), 1083–1099.
Duit, R. (1991). On the role of analogies and metaphors in learning science. *Science Education, 75*(6), 649–672.
Enyedy, N., Danish, J. A., Delacruz, G., & Kumar, M. (2012). Learning physics through play in an augmented reality environment. *International Journal of Computer-Supported Collaborative Learning, 7*(3), 347–378.
Fauconnier, G., & Turner, M. (2002). *The way we think: conceptual blending and the mind's hidden complexities*. New York: Basic Books.
Gallagher, S. (2013a). The socially extended mind. *Cognitive Systems Research, 25–26*, 4–12.
Gallagher, S. (2013b). Enactive hands. In Z. Radman (Ed.), *The hand: an organ of the mind* (pp. 209–225). Cambridge: MIT Press.
Gallagher, S. (2005). *How the body shapes the mind*. Oxford: Oxford University Press.
Gallagher, S., & Bower, M. (2014). Making enactivism even more embodied. *AVANT / Trends in Interdisciplinary Studies (Poland), 5*(2), 232–247.
Gallagher, S., & Varela, F. (2003). Redrawing the map and resetting the time: phenomenology and the cognitive sciences. *Canadian Journal of Philosophy, 29*, 93–132. (Supplementary).
Gentner, D., & Wolff, P. (2000). Metaphor and knowledge change. In E. Districh & A. Marbnau (Eds.), *Cognitive dynamics: conceptual change in humans and machines* (pp. 295–342). Mahwah: Lawerence Erlbaum Associates.
Gibson, J. J. (1977). The theory of affordances. In R. Shaw & J. Bransford (Eds.), *Perceiving, acting, and knowing: toward an ecological psychology* (pp. 67–82). Hillsdale: Lawrence Erlbaum.
Glenberg, A. M. (2008). Embodiment for education. In P. Calvo & T. Gomila (Eds.), *Handbook of cognitive science: an embodied approach* (pp. 355–372). New York: Elsevier.
Glenberg, A. M., Gutierrez, T., Levin, J. R., Japuntich, S., & Kaschak, M. P. (2004). Activity and imagined activity can enhance young children's reading comprehension. *Journal of Educational Psychology, 96*(3), 424–436.
Goldin-Meadow, S., Kim, S., & Singer, M. (1999). What the teacher's hands tell the student's mind about math. *Journal of Educational Psychology, 91*, 720–30.
Goldin-Meadow, S., Nusbaum, H., Kelly, S. D., & Wagner, S. (2001). Explaining math: gesturing lightens the load. *Psychological Science, 12*(6), 516–522.
Han, I., & Black, J. B. (2011). Incorporating haptic feedback in simulation for learning physics. *Computers & Education, 57*(4), 2281–2290.
Huttenlocher, J., & Higgins, E. T. (1978). Issues in the study of symbolic development. In W. Collins (Ed.), *Huttenlocher Minnesota symposia on child psychology* (Vol. 11, pp. 98–140). Hillsdale, NJ: Erlbaum.
Jeannerod, M. (1997). *The cognitive neuroscience of action*. Oxford: Blackwell Publishing.
Johnson, M. (1987). *The body in the mind: the bodily basis of meaning, imagination, and reason*. Chicago: University of Chicago Press.
Johnson-Glenberg, M. C., Birchfield, D. A., Tolentino, L., & Koziupa, T. (2014). Collaborative embodied learning in mixed reality motion-capture environments: two science studies. *Journal of Educational Psychology, 106*(1), 86–104.
Kendon, A. (1990). *Conducting interaction: patterns of behavior in focused encounters*. Cambridge: Cambridge University Press.
Kirsh, D. (2013). Embodied cognition and the magical future of interaction design. ACM Transactions on Computer-Human Interaction (TOCHI), *20*(1), 3.
Lakoff, G. (1987). *Women, fire, and dangerous things: what categories reveal about the mind*. Chicago: University of Chicago Press.
Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. Chicago: University of Chicago Press.
Lakoff, G., & Johnson, M. (1999). *Philosophy in the flesh: the embodied mind and its challenge to western thought*. New York: Basic Books.
Lakoff, G., & Turner, M. (1989). *More than cool reason: a field guide to poetic metaphor*. Chicago: University of Chicago Press.
Leslie, A. (1987). Pretense and representation: the origins of "theory of mind". *Psychological Review, 94*, 412–426.
Lindgren, R., & Moshell, J. M. (2011). Supporting children's learning with body-based metaphors in a mixed reality environment. *Proceedings of the Interaction Design and Children Conference*. ACM: New York, 177–180. doi:10.1145/1999030.1999055.
Lindgren, R., & Johnson-Glenberg, M. (2013). Emboldened by embodiment six precepts for research on embodied learning and mixed reality. *Educational Researcher, 42*(8), 445–452.
Lindgren, R., Tscholl, M., Wang, S. & Johnson, E. (2015). Enhancing learning and engagement through embodied interaction within a mixed reality simulation. Manuscript submitted for publication.
Malafouris, L. (2013). *How things shape the mind*. Cambridge: MIT Press.

Martin, T., & Schwartz, D. L. (2005). Physically distributed learning: adapting and reinterpreting physical environments in the development of fraction concepts. *Cognitive Science, 29*(4), 587–625.
McNeill, D. (1992). *Hand and mind: what gestures reveal about thought*. Chicago: University of Chicago Press.
Merleau-Ponty, M. (1962). *Phenomenology of perception* (trans C. Smith). London: Routledge and Kegan Paul.
Milgram, P., & Kishino, A. F. (1994). Taxonomy of mixed reality visual displays. *IEICE Transactions on Information and Systems, E77-D*(12), 1321–1329.
Mitchell, R. W. (Ed.). (2002). *Pretending and imagination in animals and children*. Cambridge: Cambridge University Press.
Nathan, M. J. (2012). Rethinking formalisms in formal education. *Educational Psychologist, 47*(2), 125–148.
Noë, A. (2004). *Action in perception*. Cambridge: MIT Press.
Ortman, S. (2000). Conceptual metaphor in the archaeological record. *American Antiquity, 65*(4), 613–45.
Plummer, J. D. (2009). Early elementary students' development of astronomy concepts in the planetarium. *Journal of Research in Science Teaching, 46*(2), 192–209.
Rucinska, Z. (2014). Basic pretending as sensorimotor engagement. *Contemporary Sensorimotor Theory, 15*, 175–187.
Sainsbury, R. M. (2009). *Fiction and fictionalism*. London: Routledge.
Shoval, E. (2011). Using mindful movement in cooperative learning while learning about angles. *Instructional Science, 39*(4), 453–466.
Solomon, J., Bevan, R., Frost, A., Reynolds, H., Summers, M., & Zimmerman, C. (1991). Can pupils learn through their own movements? A study of the use of a motion sensor interface. *Physics Education, 26*(6), 345–670.
Stull, A. T., Hegarty, M., Dixon, B., & Stieff, M. (2012). Representational translation with concrete models in organic chemistry. *Cognition and Instruction, 30*(4), 404–434.
Sutton, J. (2006). Introduction: memory, embodied cognition, and the extended mind. *Philosophical Psychology, 19*(3), 281–289.
Sutton, J., & Williamson, K. (2014). Embodied remembering. In L. Shapiro (Ed.), *Routledge handbook of embodied cognition* (pp. 315–325). London: Routledge.
Thompson, E. (2007). *Mind in life: biology, phenomenology, and the sciences of mind*. Cambridge: Harvard University Press.
Thompson, E., & Varela, F. J. (2001). Radical embodiment: neural dynamics and consciousness. *Trends in Cognitive Sciences, 5*(10), 418–425.
Varela, F. J., Thompson, E., & Rosch, E. (1991). *The embodied mind: cognitive science and human experience*. Cambridge: MIT Press.
Vygotsky, L. S. (1978). *Mind in society: the development of higher psychological processes*. Cambridge: Harvard University Press.
Winner, E., McCarthy, M., Kleinman, S., & Gardner, H. (1979). First metaphors. *New Directions for Child and Adolescent Development, 1979*(3), 29–41.