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Jennifer Fugate
University of Massachusetts Dartmouth

Sheila Macrine
University of Massachusetts Dartmouth

Christina Cipriano
Yale University

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The role of embodied cognition for transforming learning

Jennifer M. B. Fugate [a], Sheila L. Macrine [b], and Christina Cipriano [a]

[a]Department of Psychology, University of Massachusetts Dartmouth, North Dartmouth, Massachusetts, USA; [b]Department of STEM Education and Teacher Development, University of Massachusetts Dartmouth, North Dartmouth, Massachusetts, USA

ABSTRACT
Cognitive psychology has undergone a paradigm shift in the ways we understand how knowledge is acquired and represented within the brain, yet the implications for how this impacts students' learning of material across disciplines has yet to be fully applied. In this article, we present an integrative review of embodied cognition, and demonstrate how it differs from previously held theories of knowledge that still influence the ways in which many subjects are taught in the classroom. In doing so, we review the literature of embodied learning in the areas of reading instruction, writing, physics, and math. In addition, we discuss how these studies can lead to the development of new learning strategies that utilized the principles of embodied cognition.

KEYWORDS
embodied cognition; embodied learning; classroom body-based learning

Traditional theories of cognition emphasize the body as a "passive" observer to the brain, and necessary only in the execution of motor actions. Moreover, such mental representations within the brain are usual (if not always) abstractions of the original information (i.e., mental representations). Said another way, the body is seen as "*serving the mind*" (cf. Leitan & Chaffey, 2014, p. 3). Theories of embodied cognition, on the other hand, suggest that information is grounded in both perception and action, and that cognition is deeply dependent upon features of the physical body of an agent (e.g., Barsalou, 1999, 2008; see also Clark, 2008; Golonka & Wilson, 2012; Lakoff & Johnson, 1999; Pfeifer & Bongard, 2007; Shapiro, 2011; Willems & Francken, 2012; Winn, 2003; for varying theories of embodiment). Embodied cognition is being researched internationally in different fields. Outlined in the fields of robotics and computer science (e.g., Arbib, 2006; Ziemke, 2002), linguistics (Lakoff, 2012), and philosophy (e.g., Chemero, 2009; Hutto & Myin, 2013; Noë, 2004; Shapiro, 2011; Ziemke, 2002), Krois and colleagues (2007) also mention the fields of art history, literature, history of science, religious studies, biology, and neuroanthropology. Embodied cognition, argue Krois and colleagues (2007), has transformed the scientific study of intelligence and has the potential to reorient cultural studies. This embodied cognition perspective demonstrates that cognition is grounded in bodily interactions with the environment and culture, and that abstract concepts are tied to the body's sensory and motor system (Leung, Qiu, Ong, & Tam, 2011).

The antecedents of embodied cognition in psychology reach back to the work of William James (1884) and John Dewey (1925/1958). It was not until the pioneering perceptual work of James Gibson (1979), however, that psychology understood that the brain has direct access to action th rough distributed networks. According to Gibson's "ecological theory," the environment provides numerous options to action, called "affordances" (Gibson, 1979). The notion of affordance integrates perceptual, cognitive, and motor functions, so that perceiving an object, conducting cognitive operations on it, and executing motor actions with it cannot be considered as independent functions (Pellicano, Borghi, & Binkofski, 2017). Accordingly, action and perception are not seen as two separate entities.

For example, in traditional views of cognition, thinking about writing is fundamentally different from the action of writing itself, where thinking about writing would activate knowledge from semantic memory (e.g., the symbolic storage of words, including feature lists) but not that involved in the actual motor movements associated with writing. As a result, such amodal theories provide the knowledge used in cognitive processes, but do not reflect the original sensorimotor states themselves (see Barsalou, 1999, 2003, 2008). In terms of the brain, amodal descriptions are created when the original content is translated into a new, symbolic format and stored in areas of the association cortex, clearly separate from the sensory and motor cortices within the brain. Theories of embodied cognition, on the other hand, propose that knowledge is reenacted (i.e., simulated) through the perceptual and

CONTACT Jennifer M. B. Fugate jfugate@umassd.edu

sensory systems (e.g., auditory, visual, motor, and somatosensory) such that *thinking* about an action will evoke the same visual stimuli, motor movement, and tactile sensations that occur during the act itself (Barsalou, 2003, 2008). The experience is captured by the sensory and perceptual systems and can be later used to recreate (through simulation) the experience without the actual stimulus (i.e., when just thinking about the knowledge).[1] Such simulations can be partial, biased, and even occur without awareness (Barsalou, 2003). Accordingly, any knowledge associated with a concept is often represented by numerous simulations, specific to individual instances or encounters with the stimulus. As a result, no sole simulation gives a complete account of the entire concept, and multiple simulations underlie any concept (Barsalou, 2003, 2008).

While there are a number of theories of embodied cognition, they all share an emphasis on the body functioning as a "*constituent* of the mind" rather than secondary to it (cf. Leitan & Chaffey, 2014, p. 3; see also Shapiro, 2007). Today, embodied cognition encompasses a loose-knit family of cognitive science research programs that often share a commitment to replacing traditional approaches to cognition and cognitive processing (R. Wilson & Foglia, 2017). In sum, these theories recognize a full range of perceptual, cognitive, and motor capacities that are dependent upon features of the physical body.

That said, no single theory of embodied cognition captures all the nuances of this idea, and there remain no shortage of individual theories. In fact, some researchers speculate up to six types of embodiment (see M. Wilson, 2002). Although there are many individual views of embodied cognition, nearly all ascribe to two shared features: (a) Cognition involves the body and its interactions with the world, and (b) such interactions of the body with the world are represented in the brain in a nonabstracted sense (e.g., Barsalou, 1999, 2008; Lakoff & Johnson, 1999; for reviews see also Borghi & Caruana, 2015; Shapiro, 2011; L. B. Smith, 2005). While the ideas of embodied cognition (sometimes also called "grounded cognition") are becoming more accepted in the fields of cognitive psychology and neuroscience, the implications of what this means for how individuals best learn in formal settings such as the classroom (and also for how teachers teach) are less explored.

The purpose of this paper is twofold. First, we review the significant behavioral and neuroscientific findings of embodied cognition from the laboratory. Second, we detail how embodied learning strategies make use of embodied cognitive principles to improve student learning in a variety of classroom content areas. In doing this, we review demonstrations of embodied learning strategies in the domains of reading, writing, physics, and math within the classroom. Ultimately, we show how and why embodied approaches can lead to improved student learning and how they can be incorporated into existing curriculum.

Methods

This paper utilizes an integrative review method that allows for the combination of diverse methodologies (i.e., experimental and nonexperimental research), and has the potential to play a greater role in evidence-based practice (Whittemore & Knalfl, 2005). Data collection involved keyword searches of electronic databases, including PsycINFO, NCBI, PubMED, MEDLINE, EBM Reviews, and Google Scholar in October–November of 2016 and follow-up searches in May–June of 2017. We used search terms that included "embodied cognition," "embodiment," "embodied language," "affordance," "embodied mind," and "embodied learning." Interestingly, a keyword search on Google Scholar using "embodied cognition" alone revealed over twenty thousand books and articles published since the year 2000. Part 1 of this review focuses on empirical behavioral and neuroscientific evidence for embodied cognition, mainly from psychology (outside the classroom). Part 2 focuses on demonstrations of embodied learning in the classroom in the content areas of reading, writing, physics, and math. Table 1 includes the empirical experiments referenced in Part 2. Although the review focuses mainly on empirical studies, we also included theoretical pieces and systematic reviews describing processes and models for assessing educational research related to embodied cognition.

Part 1: Theories of embodied cognition

Embodied cognition has gained much traction over the past 20 years and is supported by numerous empirical research at the behavioral and neurological levels. Here we highlight in brief some of the key demonstrations of embodied cognition in concept understanding and reading, but refer the reader to extensive reviews for more in-depth understanding in each of these areas (e.g., Barsalou, 2008; Glenberg & Kaschak, 2002). The goal is not to provide a comprehensive review of demonstrations of embodiment but rather to provide readers, who may be unfamiliar with embodied

[1]In some theories of embodied cognition, simulation refers only to the motor system, whereas simulation of the other systems amounts to "mental imagery" (e.g., Jeannerod, 2006; Decety & Grèzes, 2006).

Table 1. Empirical studies reviewed in Part II of paper.

Authors	Year	Area	Sample	Procedure	Significant effects/Statistic value
Glenberg, et al., (Study 1 & 3)	2004	Reading	25 first and second graders (Study 1); 25 first and second graders (Study 3)	Participants simulated the meaning of a sentence by either manipulated toys (Study 1) or imagining manipulating them (Study 3) to simulate meaning of the sentence or reread the sentences (control).	Participants who manipulated toys had better free recall, $p = .004$ and cued recall, $p = .001$ (Study 1) and better recall, $p = .005$ free recall only (Study 3) vs. control participants.
Glenberg, Goldberg, et al.	2011	Reading	53 first and second graders	Participants manipulated toys physically (PM condition) or electronically toys (on a computer screen; CM condition) to simulate the meaning of the sentence, or reread sentences (control); multiple session training; Moved by Reading Technique.	Participants in both simulation conditions had higher comprehension scores of familiar sentences vs. control participants, $p = .01$ (CM), $p = .05$ (PM).
Glenberg, Willford al.	2011	Reading	97 third and fourth graders	Participants physically manipulated sentences, then imagined manipulating sentences or reread sentences (control); Moved by Reading Technique.	Participants in the physical/imagined condition solved more problems correctly, had greater proportion of correct solution procedures, and included less irrelevant information vs. controlparticipants, all ps < .05.
Marley et al.	2007	Listening Comprehension	45 third through seventh graders with learning difficulties	Participants listened to narratives in which they manipulated the action, observed the action (visual), or thought about the action (control).	Participants in the manipulate and visual conditions had better cued recall, $p < .05$, and better free recall, $p < .05$, vs. control participants, all ps < .05.
James & Engelhardt	2012	Handwriting	15 children, four-yr and five-yr-old children	Participants trained in typing, tracing, or writing letters; fMRI when shown those letters.	Participants; trained to handwrite letters showed a greater activation of their left posterior and their left anterior fusiform gyrus when viewing letters that they trained on vs. those who traced or typed those letters, $p < .001$.
Kiefer et al.	2015	Handwriting	23 five-yr-old children	Participants engaged in handwritten or typed letter training.	Participants in the handwriting condition showed improved letter recognition ($p < .0003$), and improved letter naming ($p < .001$) vs. the typing condition.
Longcamp et al.	2005	Handwriting	13 adults	Participants shown single letters, single pseudoletters, or a control stimulus while being analyzed by fMRI.	Participants showed more activation in motor areas of the brain when viewing letters and pseudoletters vs. when viewing control stimuli, $p < .001$.
Longcamp et al.	2005	Handwriting	76 children, three-andfive-yr olds	Participants either learned letters by typing or writing.	Participants who learned the letters by writing had more correct responses in letter recognition tests vs. those who learned by typing in the older children, $p < .02$.
Longcamp, et al.	2006	Handwriting	12 adults, mean age 25	Participants learned 10 unknown characters in a period of 3 weeks, either by typing the characters or by physically writing them.	Participants in group who wrote the characters had a better ability to discriminate between correct and incorrectly oriented characters after training vs. those who typed, $p < .001$.
Mueller & Oppenheimer *	2014	Handwriting	67 undergraduate students	Participants given TED Talks to watch and instructed to take notes on them using their normal note-taking strategy (either with a laptop or with a notebook).	Participants who took notes with a laptop performed significantly worse on conceptual questions vs. those who took handwritten notes, $p = .03$.
Peverly et al. *	2013	Handwriting	70 undergraduate students	Participants' notes analyzed after watching a videotaped lecture.	The quality of the participants' handwritten notes was correlated with sustained attention, $p < .01$, and written recall, $p = .01$.
Chao et al. *	2013	Gesture	32 adults	Participants assigned into either an action-based (performance) or a computer-based condition (repeated learning) to memorize phrases.	Participants in the action-based condition had better free recall of learned phrases vs. repeated learning condition, $p = .003$.
Hwang et al. *	2014	Gesture	39 tenth graders	Participants taught vocabulary words either in a body interactive mechanism teaching condition or through a computer program (control).	Participants in the body interactive mechanism condition had better free recall of phrases vs. control group, $p < .05$. Participants in the experimental condition had better retention for the words vs. the control group on follow, $p < .05$.
Macedonia & Klimesch *	2014	Gesture	29 German undergraduate students	Participants learned words either by A-V (read, heard, and spoke) or gesture (with an accompanying gesture).	Participants in the gesture condition improved vocabulary learning over time vs. A-V condition, $p < .001$.
Rauscher et al. *	1996	Gesture	41 undergraduate students	Participants described spatial information (or non-spatial) with gesture allowed or gesture prevented.	Participants who were prevented from gesturing had less fluent speech for spatial information only vs. those allowed to gesture, $p < .001$.
Johnson-Glenberg & Megowan-Romanowicz *	2017	Physics	166 undergraduate Psychology students	Participants either assigned to text or game-like multimedia instruction (high or low embodiment) of physics; Kinect Sensor; 1 hr learning; pre–post.	Participants had greater learning in "high embodied" conditions vs."low/text" conditions, p < .05, and higher engagement for "high embodiment" conditions vs. "low/text" conditions, $p < .001$.

(*Continued*)

Table 1. (Continued).

Authors	Year	Area	Sample	Procedure	Significant effects/Statistic value
Johnson-Glenberg et al.	2016	Physics	109 undergraduate Psychology students	Participants learned about centripetal force either through high or low embodied condition on one of three learning platforms (SMALLab, Whiteboard, desktop); pre–post & follow-up.	Participants in all conditions improved in declarative knowledge pre–post, *ps* $< .001$. High embodiment conditions vs. low embodiment had higher generative knowledge on follow-up, $p = .03$ (interaction term)
Kontra, et al. (Study 1 & 2)	2015	Physics	44 (Study 1); 36 (Study 2) undergraduate students	Participants assigned in pairs (one active and one observed) to learn about angular momentum; pre–post.	Participants only in active group improved pre–post, $p = .006$ (Study 1); $p = .031$ (Study 2).
Kontra, et al. (Study 3)	2015	Physics	35 college-age students	Participants assigned to either active or observed condition of angular momentum while undergoing fMRI; pre–post.	Participants in active group improved more than observed group pre–post, $p = .049$. Activation in L M1/S1 predicted performance gain for either group, $p = .009$.
Badets and Pesenti	2010	Math	160 undergraduate students	Participants shown large or small numbers with congruent or incongruent hand grip.	Participants took longer to respond to small numbers with an incongruent grip, $p < .001$. Participants also took longer to respond to large numbers with an incongruent grip, $p < .02$.
Berteletti and Booth	2015	Math	40 children 8–13 yrs old	Participants solved small and large math tasks; behavioral and fMRI.	Participants performed more slowly and less accurately on larger tasks vs. smaller, $p < .001$. More complex tasks were correlated with greater activation of motor regions in the brain, $p < .05$.
Broaders, et al., (Study 1)	2007	Math	106 third and fourth graders	Participants divided into 3 groups and asked to solve and explain math problems on a chalkboard, either with or without gesturing while explaining their results.	Participants told to gesture while giving their own explainations solved more math problems correctly post vs. those who did not gesture, $p < .04$. Participants who added gesture had better post-test performance, $p < .03$.
Broaders, et al., (Study 2) *	2007	Math	70 third and fourth graders	Participants divided into groups and asked to solve math problems on chalkboard (as in Study 1), but allowed to supplement gestures to see whether increased problem knowledge.	Participants told to gesture while giving their own explanations solved more math problems correctly on their posttest vs. students who did not gesture during their explanation, $p < .04$.
Di Luca et al.	2006	Math	122 undergraduate students	Participants trained finger-digit mapping based on Arabic numbers 0–9. Either assigned training comparable with global SNARC orientation (small numbers on left and larger numbers on right hand) or opposite orientation.	Participants who were trained in finger-digit mappings that were SNARC-congruent mappings were faster with their responses vs. those trained in SNARC-incongruent mappings, $p < .\ 001$.
Domahs, et al.	2007	Math	137 children (approximately 7 yrs old)	Participants tested individually on simple and complex math tasks for number of split-five errors common for finger counting; longitudinal study.	Participants showed a greater amount of split-five errors compared to other errors for complex math tasks, ps $< .01$.
Martin & Schwartz *	2005	Math	32 children, between 9 and 10-yrs old	Participants filmed solving problems with physical pie wedges or pictorially.	Participants in physical manipulate-condition were more likely to try several strategies and were more accurate vs. drawing-condition, *ps* < 001.
Srinivasan et al. *	2016	Special Populations–ASD	36 ASD children, between 5 and12-yrs old	ASD children assigned to either whole-body rhythm (e.g., imitation, and movement based on rhythm, melody, and phrasing), robotic (e.g., samebut with robots), or standard (tabletop) therapies; pre–post.	Participants in the whole-body rhythm showed higher social bids (total word count) after intervention vs. other conditions, $p < .03$. Robotic group vs. other conditions showed more greater self-directed vocalization vs. other conditions, *ps* $= .001$. No difference between conditions post on the joint attention task (JTAT).

"Empirical evidence not referenced in text, but in which readers might be interested."

cognition, with empirical support from specific areas in psychology that have significance for embodied learning in the classroom.

Evidence for embodied concepts

Embodied theories of cognition often suggest that concepts are understood via sensorimotor simulations (Borghi & Pecher, 2011). Feature verification paradigms are often used to test one's understanding of a concept. For example, a participant is asked whether a certain physical property is characteristic or diagnostic of a group (i.e., *Do birds have wings?*). In one classic study of image scaling, participants were slower to verify that a cat has eyes when the cat was imagined next to an elephant, but faster to do so when it was imagined next to a flea (Kosslyn, 1975). This classic finding suggests that a judgment about size of an imagined object relies on the actual size of the object as experienced (at least as imagined) by the visual system. If real-world size was not a part of the concept itself (as predicted by a traditional view), then manipulating the relative size of the cat in one's mind would have no bearing on the speed that participants can use that information. Likewise, when participants read text that mentioned birds in flight, they were faster at recognizing a picture of a bird with its wings outstretched than a picture of the same bird with its wings folded (Zwaan, Stanfield, & Yaxley, 2002). The results demonstrated that new information can be verified by simulating previous knowledge that bears some resemblance.

Other evidence of embodied concepts comes from neuroscientific inquiries. For instance, when people are asked about objects, they often imagine the use or function of that object (i.e., "action features"). To support this supposition, participants who viewed pictures of tools while undergoing neuroimaging showed activation in the parts of the brain that are involved in movement (e.g., motor cortex; Martin, 2007). Therefore, when participants thought about tools, they thought about physically manipulating them *as if* they were actually using them (Grèzes, Tucker, Armony, Ellis, & Passingham, 2003; Tucker & Ellis, 1998). Patients with naturally occurring lesions to the motor cortex were found to be selectively impaired for conceptual processing of action-related verbs, but not nouns (which typically do not activate action features; see Martin, 2007).

Evidence for embodied language

A large number of empirical studies suggest that part of a person's ability to comprehend language involves his or her ability to simulate the action involved in the meaning. In one study, participants were faster to advance sentences presented as a narrative on a computer screen when the action in the sentence matched the action needed to move the text forward (Zwaan & Taylor, 2006). For example, participants who turned a knob counterclockwise to advance the sentence, "When he walked into the room, John turned down the radio," did so faster than those who were asked to turn the knob clockwise (Zwaan & Taylor, 2006). Therefore, movements of the body congruent to the written content facilitated reading. According to the Indexical Hypothesis (Glenberg, 1999), these experiential components are crucial for language comprehension. Therefore, understanding language consists of indexing words to perceptual symbols, deriving affordances (or structural relations) from those symbols, and meshing those affordances to create a simulation of the described situation (Glenberg & Robertson, 1999; see Kaschak & Jones, 2014, for a review).

Neuroimaging studies are also consistent with embodied language comprehension. For example, participants who read or listened to words or phrases of words about specific bodily actions showed activation within the brain consistent with moving that part of the body. To illustrate, participants who simply read an action word (e.g., *kick*) showed strikingly similar activation of the region of the motor cortex dedicated to moving one's foot as those who actually kicked their leg while in the scanner (Hauk, Johnsrude, & Pulvermüller, 2004; for additional examples, see Aziz-Zadeh & Damasio, 2008; Tettamanti et al., 2005).

Even the rules of syntax can be embodied. For example, Glenberg and Gallese (2012) propose that syntax emerges from action control of the body. They believe that the motor system is functionally organized in terms of goal-directed actions (e.g., Rochat et al., 2010), not just motor actions, such that the brain uses contextually appropriate action to solve syntactical meaning. In early language acquisition, a child's syntactical knowledge is limited by the syntactic constructions he or she has experienced, and therefore is not likely to be the same as an adult's. Said another way, the ability to generalize and integrate individual tokens into types is limited by what the child has experienced or witnessed so far in life. As a child experiences more action outcomes, the outcomes are incorporated into the system and eventually become more heavily weighted in further simulations.

Intersting, that a common criticizm is that embodied theory doesn't help a learner deal with abstract information.

Words themselves are shcemas, and restrict the flow of information our brains access

THE POWER AND IMPORTANCEOF WORDS. they not only are schemas, the unifed categories.

We believe that the more the initial information engages the sensory and motor cortices, the richer the simulation, and ultimately the better the recall and use of the material. For example, imagine that a child first learns about an airplane when someone points to one in the sky and labels it. The child encodes the richness of the visual experience, the movement associated with looking upward, the sounds the airplane makes, as well as the sound the person makes to label it. These "experiential traces" are later reactivated when accessing the category "airplane." Fundamentally, these traces bear a resemblance to the perceptual and action processes that generated them (Barsalou, 1999). As a result, the more initial input into the experience, the richer the later simulation.

One common criticism of many embodied theories of language is that they are ill-equipped to deal with abstract information (Zwaan & Madden, 2005; see also Borghi & Caruana, 2015). Several criticisms of EC have been noted, including that the theories offer nothing new, or are unfalsifiable (Mahon, 2015). In that context, some researchers have tried to suggest that embodied and traditional theories are no longer dichotomous and that there is room for both. Specifically, Mahon believes that there is a middle ground that combines the two perspectives, such that sensory and motor information may instantiate online abstract and symbolic processing (Mahon & Caramazza, 2008). However, several approaches to this problem have been introduced. One such solution is that abstract representations are created from concrete representations by way of metaphorical extension (Gallese & Lakoff, 2005; Lakoff, 1987, 2012; Lakoff & Johnson, 1980). Lakoff extensively documented the use of metaphoric language to ground spatial and body-centric metaphors in concrete representations (e.g., "life is a journey," "in over one's head"; see Lakoff & Johnson, 1980). Therefore, the function for such extensive use of metaphors in English, as well as other languages, is not only to communicate such abstract concepts but also to provide a tangible "grounding" to the body and to the physical world. It is likely that some sensory and motor involvements led to better metaphoric extension than others.

Once new action outcomes are acquired, they are unified into a category by application of the same label or word. Such a label or word can serve as an anchor to later simulate the initial action. As a result, as multiple tokens and experiences with the word build up within the brain, the word alone can come to serve as the catalyst of the simulation. This view is similar to that proposed by Borghi and colleagues, in which words serve as "social tools" (Borghi & Binkofski, 2014; Borghi, Scorolli, Caligiore, Baldassarre, & Tummolini, 2013). It is also consistent with developmental psychological research on the acquisition of language. Many studies show that language (e.g., words) can serve as a placeholder to teach category members (Xu, Cote, & Baker, 2005), and that words facilitate learning new categories (Lupyan, Rakison, & McClelland, 2007). Therefore, a word, through its phonetic form, can bind together individualized action outcomes into a meaningful category representation. Said another way, individual tokens are thereby linked into cohesive types (concepts) through words. For a similar view, see the *language-as-context hypothesis*, which suggests that words provide an internal context that helps constrain the flow of information (see Barrett, 2009). Similarly, other theories suggest that words are an effective means of propagating neural activity because they can activate a distributed representation of related content that can be assigned to multiple categories depending on context and goal-relevancy (see Lupyan & Clark, 2015).

Both of these views represent a modern-day Whorfian hypothesis for how language affects thought. To this end, words within a language set the stage for what will become meaningful concepts, which in turn enable the simulations underlying cognitive thought. Said another way, the structural aspects of any language produce a tangible grounding of embodied experiences to produce unified categories in the brain, where the contents of these categories can then, in turn, be accessed by words. The greater the number and precision of words that are linked to the category, the more likely words can be used as analogical mapping tools to further ground abstract categories. In this sense, words are not only human inventions; they are also inventors of new connections. Therefore, in a language that has no word or few words to label an experience, information will be represented and stored differently compared to a language that has many words to describe and make meaningful the same experience.

While we believe that language (including individual words) is *often* embodied, we are not suggesting that language is always so. Likewise, we do not believe that all embodied instances are anchored by words: those that afford direct action may be stored in absence of semantic networks. Thus, even in the absence of linguistic mapping, some action outcomes can still be simulated, but only when the context of that initial action is replicated with near-perfect fidelity. Similar ideas have been put forth by "hybrid" approaches to conceptual processing (Barsalou, Santos, Simmons, & Wilson, 2008; Connell & Lynnot, 2013; Louwerse, 2011; see reviews by

Andrews, Frank, Vigliocco, 2014).[2] According to some of these hybrid views, meaning can occur through embodied simulations, but also through more "shallow" processing, which does not require embodiment, but rather draws upon distributed linguistic shortcuts.

Summary

In part one of this paper, we identified how psychology has undergone a paradigm shift in understanding the workings of the brain. Rather than knowledge being recoded and removed from the initial sensory and motor experience, embodied cognition posits that the brain *simulates* these details when recalling and using the knowledge garnered through that experience. Therefore, the richer and more nuanced the encoding, the richer and more nuanced the simulation of that information will be (i.e., in the use or recall of that information). Individual words within a language are often mapped to embodied instances and set the stage for the category learning. As a result, words come to serve as shortcuts in the later simulation of those instances. Language can also help ground abstract information through linguistic metaphor.

Part II: The embodied cognition classroom

Embodied learning as an extension of embodied cognition is at odds with traditional views of cognition that are described in Part 1. Many educators have noted the effectiveness of body-based learning in the classroom, yet among teachers there is often confusion as to why these strategies are effective and how they relate to embodied cognition. In addition, there is often confusion between embodied learning and technology-based learning. While there are many embodied learning strategies that make use of technology (some which we review below), simply having students use technology or move their bodies does not constitute embodied learning.

Theories of experiential and hands-on learning have been around for more than a century, describing processes that drive learning (Dewey, 1925/1958; Kolb, 2014). For example, the Montessori (1966) learning approach emphasizes independence, freedom within limits, hands-on learning, and respect for a child's natural psychological, physical, and social development. Yet, the specific mechanism through which these processes occur has not been well defined. Embodied cognition is relevant to these pedagogical ideas and offers potentially useful tools for educators. Some educators, however, argue that perceptually rich practices are not optimal and may even be detrimental (e.g., Finkelstein et al., 2005; Pouw, Van Gog, & Paas, 2014). While embodied cognition is one theory for understanding learning, we acknowledge that some information might be better acquired through other approaches. The purpose of this paper, however, is to highlight embodied cognitive strategies in classroom learning.

Reading and instruction

The Indexical Hypothesis, introduced in Part 1, suggests that language is learned and understood by evoking the sensorimotor systems to simulate the situation or the intention of the action described by the language (Glenberg & Robertson, 1999; Glenberg & Gallese, 2012; Kaschak & Glenberg, 2000; see Kaschak & Jones, 2014). Therefore, according to an embodied learning view, physically moving or engaging the body and senses in ways that are congruent with the actions of the situation and what the situation affords should enhance beginning reading instruction.

Glenberg and colleagues created the *Moved by Reading* approach that incorporates embodied learning in children's reading comprehension and teaches simulation or "acting-out" reading in two stages (Glenberg, Goldberg, & Zhu, 2011). In the first stage, called physical manipulation, children manipulate toys to simulate the story they are reading. The approach is meant to increase comprehension by indexing the major content words to images or objects, on a word-by-word basis that does not require understanding the full sentence. It also does so by constraining the objects the words index. After a child succeeds in this stage, they can transition relatively easily to the imagined manipulation stage. Now children can imagine or mentally simulate doing these actions themselves while they read. Glenberg and colleagues showed that first and second graders who underwent this approach recalled 33% more information (compared to those who had toys or objects present but were not allowed to manipulate them; Glenberg, Gutierrez, Levin, Japuntich, & Kaschak, 2004). In a Web-based follow-up study, children manipulated the objects or images on a computer screen rather than

[2]More radical views of embodied cognition completely reject the idea of representations of any kind within the brain, such that cognition is considered a dynamical system in which continuously changing variables are interdependent on one another for meaning (see Spivey, 2007; Borghi & Caruana, 2015 for a review). In these views, since there are no mental representations, reenactment of them becomes impossible.

directly hands-on (Glenberg et al., 2009; Glenberg, Willford, Gibson, Goldberg, & Zhu, 2011). They reported a similar-sized effect to the original study. Importantly, the effect transferred to other genres, as well (e.g., mathematical problem stories), demonstrating that this approach can be applied across domains and tasks. More intriguingly, this approach seems to be effective with students with learning differences. One study, utilizing this approach, found that children with learning disabilities had better free and cued recall for propositions, objects, and actions than those in the control condition (where children simply listened to the experimenter and were instructed to think about each sentence; Marley, Levin, & Glenberg, 2007).

Glenberg's (2011) findings also support the decades-old multisensory–multimodal approaches to reading remediation particularly suggested for students with learning disabilities. In 1943, Dr. Grace Fernald developed a multisensory intervention called the Fernald Method of VAKT—Visual, Auditory, Kinesthetic and Tactile. Today's VAKT continues as a successful and prescribed reading intervention for students with learning disabilities and cognitive challenges. This approach uses a combination of verbal and auditory input, while at the same time tactically tracing the letters on the back of the student or on sandpaper to make a "kinesthetic imprint on the brain" (Fernald, 1943). In Fernald's time, it was unclear why this approach worked well and more so than other methods. Today, however, we can attribute the method's success to the principles underlying embodied cognition. Specifically, this includes the idea that perceptual simulations in modality-specific systems underlie conceptual processing.

Writing

Kiefer and colleagues (2015) examined whether handwriting and reading comprehension differed in children who engaged mainly in modes of digital writing (e.g., computers, tablet PCs, or mobile phones) compared to physical writing (Kiefer et al., 2015). They found that physically writing improved the processes of letter recognition, naming, and composition, and increased reading comprehension. They argued that physically writing linked the form to the concept, which promoted the mental representation needed to write and comprehend language at a higher, more symbolic level (see also Kiefer & Trumpp, 2012).

Specifically, we suggest that the benefit comes from the embodied nature of the information acquisition. Handwriting, compared to typing, requires increased motor movements. These increased movements provide a richer encoding of the information, which allows a better representation from which they can later draw. We suggest that future empirical studies test this notion specifically.

Other studies support this idea as well. Physically writing letters and words prompt students to be more thoughtful and engaged, improving their written communication and improving later reading comprehension (James & Engelhardt, 2012). In addition, the National Early Literacy Panel (2008) identified handwriting as a predictor of later reading ability and general learning abilities, even after controlling for IQ and socioeconomic status (see Graham & Santangelo, 2012, for a meta-analysis). Further, both preschool children and adults show better letter recognition when learning to write letters by hand rather than by typing them (Longcamp, Anton, Roth, & Velay, 2003; Longcamp, Zerbato-Poudou, & Velay, 2005). The same stored motor programs in the brain used for handwriting are activated when simply reading letters (Longcamp et al., 2003). These findings provide a close functional relationship between reading and handwriting movements (see James & Engelhardt, 2012). In another study, participants who learned new characters by copying them by hand (compared to typing them on a keyboard) made fewer mistakes about the orientation of letters later on. Specifically, they were less likely to confuse mirror images of the characters for the correct ones (Longcamp, Boucard, Gilhodes, & Velay, 2006). Therefore, the ability to remember correctly was facilitated by the specificity of the movements associated with learning them.

Taken together, these studies demonstrate that handwriting is critical to setting the foundations for learning to read and to understand information at a higher level. These findings come on the heels of a rigorous effort of many school districts to remove writing (namely, cursive) from the curriculum. Many schools view cursive as a long-lost art, replaceable by typing electronically. We argue that nothing is further from the truth. Handwriting (i.e., the physical and tactile act of moving one's pen) provides more stimulation and precision for the brain to capture—and therefore recall—than any keystroke associated with typing. Some state administrators, who originally dropped handwriting, have now reinstated handwriting and cursive instruction into their curriculum (Hochman & MacDermott-Duffy, 2015) Writing, whether print or cursive, provides a range of individualized movements associated with each letter. This specificity has a fuller, more nuanced representation in the brain for this information.

Math and physics

Embodied learning has been shown to be effective in advancing students' STEM achievement, particularly mathematics (e.g., Clements, 2000; Martin & Schwartz, 2005). Historically, finger-counting was disapproved of within formal education and shamed by the public (Moeller, Martignon, Wessolowski, Engel, & Nuerk, 2011). Current evidence, however, suggests that both hand and finger representations positively influence children's and adults' numerical processing (Badets & Pesenti, 2010; Di Luca & Pesenti, 2008; Domahs, Krinzinger, & Willmes, 2008). For example, when 8–12-year-old students are given complex subtraction problems to solve *without* using their fingers, there is still increased activation in the somatosensory area of the brain that is normally activated by tactile sensations (e.g., using the fingers to count) (Berteletti & Booth, 2015). Interestingly, the more complex the math problem (i.e., subtraction), the more activation of the somatosensory area of the brain. In a math meta-analysis of children ages 7–11 years, instruction involving concrete manipulatives provided children with the most benefit. Older children benefited less than younger children, however, a finding that can be partly explained by their increased ability to reason abstractly (Carbonneau, Marley, & Selig, 2013).

Other demonstrations show that the better knowledge of one's fingers is in the first grade, the better the number comparison and estimation in the second grade (Boaler & Chen, 2016). Such knowledge even predicts students' calculus scores in college (Berteletti & Booth, 2015; see also Penner-Wilger & Anderson, 2013). Finally, when students are told to use gestures when solving math problems (including finger counting), they produce new and novel insights into problem solving, as well as benefiting more from formal instruction compared to those students who do not gesture (Broaders, Cook, Mitchell, & Goldin-Meadow, 2007). This suggests that finger-based numerical representations are beneficial for later numerical development, and that children might build upon concrete structured representations to learn mental representations (Moeller et al., 2011). Furthermore, embodied mathematical cognition is thought to broaden the range of activities and emerging technologies that count as mathematical, and helps students to envision alternative forms of engagement with mathematical ideas (e.g., De Freitas & Sinclair, 2014). Here cultural influences on the representation of numbers come into play: Finger-based counting and other body-based counting is performed differently in different cultures (e.g., Liutsko, Veraksa, & Yakupova, 2017; Selin, 2001), resulting in different embodied representations of numbers within the brain.

The Seeing Change Project brings these ideas to life in the classroom (Abrahamson, 2012). Here, students learn about compound probability problems through embodied games. The project uses both traditional media (marbles, cards, crayons) and computer-based modules (NetLogo simulations), which allow students to work off their basic intuitions to establish mathematical models. As part of the project, students often learn how their preanalytic judgments are incorrect. The idea is that students will modify their erroneous theory in the face of empirical evidence that contradicts their inferences (Abrahamson, 2012). With this hands-on approach of bridging informal and formal visualizations of probability experiments, students in Grades 4–6 show better abilities to predict probabilities (Abrahamson, 2012).

In another applied-math learning project called the Kinemathics project, students (Grades 4–6) move their arms in proportional distances to measurements of similar magnitude displayed on a screen (Abrahamson, Trninic, Gutiérrez, Huth, & Lee, 2011). Correct answers make a screen turn green, and incorrect make the screen turn red. Using this embodied learning strategy, students mainly engaged in trial and error to learn the rules underlying the relationship. Qualitative data suggest that students who learned through this strategy were more productive in their problem solving (Abrahamson et al., 2011).

Outside of math, there are emerging applications for effective embodied learning strategies in the STEM fields. One successful example with college-aged students comes from physics (Kontra, Lyons, Fischer, & Beilock, 2015). Students were tested on their knowledge about angular momentum after actually feeling forces (by spinning a wheel) or watching someone else perform the same action. Brief exposure to actually feeling the force (the embodied manipulation) improved quiz scores by approximately 10% (Kontra et al., 2015, Experiment 1). Moreover, when these students underwent neuroimaging, the activation in the sensorimotor cortices predicted the improvement and understanding of the properties associated with angular momentum.

In one specialized application, Abrahamson and Lindgren (2014) developed *MEteor*, an interactive MR simulation that uses a laser and floor-projected imagery to help middle-schoolers develop ideas about how objects move through space. In this application, a student *becomes* an asteroid by attaching himself to a digital asteroid that is launched into a simulated outer space where other objects affect the asteroid's movement. The student must move his or her body to move the digital asteroid around objects that are coming toward him or her. This requires learning about formal concepts such as gravitational acceleration and mass. In one evaluation of the technology, students improved their performance by 76% on the second trial compared with 51% for those who used the simulation without bodily cues (as reported in Abrahamson & Lindgren, 2014).

In another study, college students engaged in one of three different simulated conditions to learn about centripetal force (Johnson-Glenberg, Megowan-Romanowicz, Birchfield, & Savio-Ramos, 2016). Each had a low and high embodied condition, in which the "high embodied" condition had students physically move their bodies to examine the construct. The "low embodied" condition replaced the individual activities with button pushes depicting the same information. Students' learning of the lesson was significantly better across all "high embodiment" conditions compared to the "low embodiment" condition. Moreover, only students in the "high embodiment" condition maintained their knowledge after one week (Johnson-Glenberg et al., 2016). These demonstrations show the value of physical experience in science learning, and lead the way for classroom practices where movement with the physical world is an integral part of learning.

We recommend that students in the STEM fields engage in various learning modalities that utilize multiple sensory and motor domains. These could include project-based learning and haptic technology (e.g., touch-screen tablet displays with feedback in visual and auditory domains). Other potentially beneficial haptic technologies might include new motion-tracking technologies, augmented reality, and gesture recognition. These instructional strategies can be adapted and generalized to support young children's and older students' science and mathematics learning in the classroom.

Importance of cross-cultural considerations in embodied cognition and learning

An embodied cognition approach can help educators to rethink their pedagogy and consider ways of learning that are inclusive of both individual and cultural perspectives (Cohen & Leung, 2009; Cohen, Leung, & Ijzerman, 2009; Leung et al., 2011). To the extent that a person's interaction with the world is individualized (acquired through their own motor and perceptual systems), and that those instances are made meaningful by previous interactions, they will be influenced by culture (see Leung et al., 2011). Therefore, particular instances will be situated differently in various cultures, as well as the degree to which particular instances are utilized (see also Gibson, 1979; Schubert & Semin, 2009; Varela, Thompson, & Rosch, 1991). Simply put, the cognitive structure of an individual, as defined by his or her own experiences and those supported by cultural norms and language, informs how information is first experienced, as well as later simulated. This implies two things: First, similar actions will be integrated and mapped differently within the brains of different individuals since their perceptual and motor systems will have a different set of experiences that inform the current. Second, the representation of this information will be different for different cultures, which have different priorities, rules, words, and linguistic metaphors to explain the world around them. To illustrate: Consider that Westerners tend to adopt a first-person perspective in which social interactions are often referenced from an egocentric point of view, whereas Easterners tend to adopt a third-person point of view (cf. Leung et al., 2011). European Americans tend to describe actions as *going toward others*, whereas Asian Americans are more likely to describe action as *coming toward them* (Leung & Cohen, 2007). The body will not only represent the action differently in each case, but also such metaphors will further affect the representation and understanding of this information.

Wilson (2010) calls the effects of culture on cognitive thought *cognitive retooling*, in which an individual's cultural knowledge and experiences not only shape (in development) but also reshape his or her cognitive system over their lifetime. Kövecses (2002) describes this idea eloquently when he writes: "Social constructions are given bodily basis and bodily motivation is given social-cultural substance" (p. 14).

Summary and significance for designing embodied curriculum

In this paper, we reviewed how embodied cognition differs from traditional theories of cognitive functioning, while summarizing some of the key empirical laboratory-based demonstrations in concept learning and reading. We also showed how these principles can be applied in the classroom to facilitate learning in the fields of reading, writing, math, and physics. Specifically, we proposed that the more nuanced the encoding (including the more the senses and the body are involved, as well as the more instances of encoding), the better the recall and use of that information.

Although we have reviewed numerous applications of embodied learning in the classroom, there is still much room for systematic empirical studies that compare embodied versus traditional theories back-to-back. In addition, we need more research to help researchers and others to further implement embodied cognition into students' curriculum (including mandatory curriculum), to assess the gains in knowledge as a result, to develop teacher pedagogy, and finally to leverage this knowledge for curriculum and policy makers in the future. One key thing to consider is that assessments should be developed in tandem with the curriculum, such that assessments that emphasize the format in which the material was learned may show better outcomes, especially for early learners who are more driven by concrete manipulatives.

Increased understanding of embodied cognition among educators will likely show improved learning in the classroom. For example, providing teachers with instruction in neuroscience and cognitive functioning has the potential to directly transform teacher preparation and professional development, and ultimately to affect how students think about their own learning (e.g., Dubinsky, Roehrig, & Varma, 2013). Then, when teachers shared that knowledge with their students, the students' own metacognitive awareness for their performance is increased (e.g., Dubinsky et al., 2013).

To conclude, it is important for contemporary cognitive science to continue to investigate the implications of embodied cognition, including testing the success of newly developed body-based learning strategies in the classroom. It should also be understood and highlighted that different individuals—from different cultures with a different set of cultural norms and habits and speaking different languages—might have vastly different representations within the brain because any new experience is grounded within previous experiences. As a result, more cross-cultural research is needed to address individual differences within and across cultures in how particular cognitive tasks are embodied while being cognizant of local cultural variations. In sum, embodied cognition shows *promise* for learning effectiveness and this understanding can further the deployment of embodied teaching and learning in the classroom and in teacher education.

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About the authors

Jennifer Fugate, PhD, is an Assistant Professor at the University of Massachusetts Dartmouth. Her research focuses on how language shapes emotion percepts, and the role that language plays in grounding abstract categories. She is the author of several book chapters and articles, and her work on facial depictions of emotion has received recognition in several popular press books and in the Court of Law. She is a certified FACS-coder.

Sheila Macrine, PhD, is a Professor at the University of Massachusetts Dartmouth. Her research interests focus on two areas: 1) school psychology including alternative assessment and embodied cognition; and 2) connecting the cultural, political, and institutional contexts of critical pedagogy as they relate to the public sphere, democratic education and social imagination. She is a critical feminist and has published numerous articles, grants and books including: *Critical Pedagogy in Uncertain Times: Hope and Possibilities.*

Christina Cipriano, PhD, is an Assistant Professor at the University of Massachusetts Dartmouth. Her research focuses on serving vulnerable youth through systematic examination of the interactions within their homes, schools, and communities to promote pathways to optimal developmental outcomes. She is a Service Learning Fellow, Community Engaged Research Scholar, and Principle Investigator of the Recognizing Excellence in Learning and Teaching (RELATE) Project. She directs several research initiatives and regularly disseminates her science in both academic journals and professional development workshops for pre-service and inservice educators and school personnel.

ORCID

Jennifer M. B. Fugate http://orcid.org/0000-0003-0831-4234
Sheila L. Macrine http://orcid.org/0000-0002-8600-0938
Christina Cipriano http://orcid.org/0000-0002-7414-1821

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