Cognition, Brain, Behavior. An Interdisciplinary Journal

ISSN: 1224-8398
Volume XV, No. 4 (December), 409-425

EMBODIMENT AND DEVELOPMENT IN COGNITIVE SCIENCE

Aarre LAAKSO[*]

Department of Behavioral Sciences, University of Michigan-Dearborn, USA

ABSTRACT

This paper is a survey of the main issues surrounding the role of embodiment in cognition and development. For most of the history of cognitive science, a "disembodied" model of cognition—according to which cognitive processes are independent of sensorimotor processes—dominated the field. More recently, the field has taken a turn toward embodiment, the view that sensorimotor processes routinely influence (and perhaps even constitute) cognitive processes. This view has diverse historical origins in American pragmatism, phenomenology and ecological psychology. However, in recent years, researchers have adduced many arguments and a great deal of empirical evidence in favor of the embodied cognition hypothesis. Developmental psychologists have played an important role in this transformation of cognitive science, adopting and adapting Piaget's views as a means of explicating the role that embodiment plays in development, as well as collecting developmental data that support the embodied cognition hypothesis. Despite the enthusiasm for embodiment among cognitive scientists generally and developmentalists in particular, however, the embodied cognition hypothesis still faces formidable challenges.

KEYWORDS: *cognition, development, embodiment, sensorimotor systems*

[*] Corresponding author:
E-mail: aarre@umd.umich.edu

Over the last 20 years or so, an enormous amount has been said in the cognitive science literature about the topic of embodiment, some of it specifically about the role that embodiment plays in development. A comprehensive review of the evidence and arguments is not practical in this forum. Instead, the goal of this paper is to give the reader a sense of the main issues regarding the role of embodiment in cognition and development. The first section traces the history of the "disembodied" perspective that dominated cognitive science from the origins of the discipline through the 1980s. The second section traces the history of the "embodied" perspective. In addition, it surveys some arguments for the embodied cognition hypothesis and describes some of the empirical evidence that weighs in its favor. The third section examines some of the evidence and theoretical contributions that have come out of the developmental literature in particular. The fourth section points out important challenges for supporters of the embodied cognition hypothesis.

THE DISEMBODIED PERSPECTIVE IN COGNITIVE SCIENCE

For many years, the orthodox view in cognitive science was that the study of cognition, including the study of conceptual processes and mechanisms, could proceed independently from the study of sensorimotor processes and mechanisms. Researchers assumed that it was sufficient to use discrete, amodal symbols to represent not only the contents of thoughts but also the sensory activities that provide information about the environment and the motor activities that constitute behavior. They considered these sensorimotor processes irrelevant to the core project of cognitive science—explaining cognitive processes, which were thought to take place in an abstract information-processing device. Sensorimotor processes, on this view, were relegated to peripheral input and output devices (M. Wilson, 2002).

The view that cognition can (and should) be studied independently of perception and action had its roots in the computational metaphor of mind, beginning with Turing's concept of a universal computing machine (Turing, 1936). Turing essentially reduced the problem of creating a thinking machine to the problem of calculating mathematical functions (Rohrer, 2007). From its origins in Turing's work, the universal computing machine became the preferred metaphor for the mind through the 1980s (Johnson & Rohrer, 2007).

There was a natural affinity between the computational metaphor of mind and the philosophical position known as functionalism (Putnam, 1960), the view that mental states inherit their contents from their functional roles, that is, their roles in a computational system. Moreover, according to this view, because different kinds of media (such as vacuum tubes or transistors) can compute the same function, cognition can take place in a variety of different media, whether biological or manufactured. Functionalists regard the mind as a "black box" whose inputs and outputs are symbols. The precise mechanisms inside the black box are irrelevant to the function it computes. From this perspective, explaining cognition is a matter of getting the black box to transform the input symbols into the correct output symbols. The physical body disappears (Rohrer, 2007). This point of view was advocated forcefully by Jerry Fodor (Fodor, 1975, 1983) and Zenon Pylyshyn (Pylyshyn, 1984, 1999) and dominated cognitive science until recently.

THE EMBODIED COGNITION HYPOTHESIS

Although the "disembodied" perspective governed cognitive science for many years, there is a very different view that also has an impressive, albeit different, intellectual heritage. This view emphasizes the importance of sensorimotor processes for successful interaction with the environment (M. Wilson, 2002). According to this view, which is often called the "embodied cognition hypothesis," the specific details of how the brain and body embody the mind *do* matter to cognition (Rohrer, 2007).

The embodied cognition hypothesis has origins in American pragmatism, particularly the writings of William James and John Dewey. In the *Principles of Psychology*, James wrote "My thinking is first and last and always for the sake of my doing" (W. James, 1890, p. 333). This observation, which one often hears paraphrased as "thinking is for doing," suggests that thought is intimately entwined with the motor system. Similarly, Dewey writes in *Experience and Nature*:

> To see the organism *in* nature, the nervous system in the organism, the brain in the nervous system, the cortex in the brain is the answer to the problems which haunt philosophy. And when thus seen they will be seen to be *in*, not as marbles are in a box but as events are in history, in a moving, growing never finished process (Dewey, 1925, p. 224).

In this passage, Dewey not only claims that embodiment is crucial for understanding the mind but also acknowledges the developmental, dynamic nature of cognition.

A further root of the embodied view of mind lies in J. J. Gibson's ecological psychology, which took possible interactions with the immediate environment ("affordances") to be the basis of perception. As Andy Clark and others have noted (Clark, 1999; Kirsh, 1991b; Van Leeuwen, 1998), however, ecological psychology runs into problems when one considers what many take to be the most characteristic form of cognition—cognition in the absence of its objects.

In philosophy, the phenomenologists, particularly Heidegger and Merleau-Ponty, also remarked upon the centrality of embodiment. In *Being and Time* (1927), Heidegger pointed out that human beings, and all of the things humans do, are always in the world. One cannot study being independently of "being-in-the-world," (a Heideggerian term of art) and therefore, one cannot bracket the world when studying human activities.

Merleau-Ponty, the most scientifically informed of the phenomenologists, argued that embodiment in the three-dimensional, physical space of the actual world is a critical fact about human thought. Thus, Merleau-Ponty writes, in the *Phenomenology of Perception*:

> Insofar as, when I reflect on the essence of subjectivity, I find it bound up with that of the body and that of the world, this is because my existence as subjectivity is merely one with my existence as a body and with the existence of the world, and because the subject that I am, when taken concretely, is inseparable from this body and this world (Merleau-Ponty, 1962, p. 475).

These points were taken up again by the Dreyfus brothers in their criticisms of artificial intelligence methodology in the 1990s (Dreyfus & Dreyfus, 1999).

In contemporary philosophy, even many of those who had endorsed functionalism came to the realization that psychology cannot give a complete account of meaning and that, therefore, it is necessary to study mind and language from an embodied, social point of view (Putnam, 1988). Some philosophers also argued that the idea of non-embodied perception is unintelligible (New, 1976) or that there is no reason to believe in the possibility of disembodied existence (Tye, 1983).

A variety of commentators inside and outside of philosophy have offered other a priori arguments for the embodied cognition hypothesis. Some (e.g., Birnbaum, 1991; Kirsh, 1991a; B. C. Smith, 1991) emphasize the connection between embodiment and the "symbol grounding problem." In reflecting upon traditional "disembodied" computational systems, they point out that an agent cannot grasp a concept merely by tokening an arbitrary symbol. To count as grasping a concept, a symbol tokening needs to provide the agent with a variety of abilities, including some that involve sensorimotor processes. For example, no agent could genuinely be counted as having grasped the concept *blue* if it was unable to discriminate blue objects from those that are not blue. Thus, for a symbol to be truly counted as representing a concept, there must be mechanisms that connect it to the outside world. These mechanisms are, of course, the sensorimotor systems.

Other commentators (Evans, 1982; Kirsh, 1991a) have instead focused on the fact that some of our referring expressions (e.g., "over there") are inherently indexical. That is, they have meaning only from the egocentric perspective from which human beings perceive and act in space. That being the case, it is not possible to fully simulate or explain cognition, including language, without appeal to the body and its attitude in space.

Another argument appeals to evolution (M. Wilson, 2002). Human beings evolved from organisms with limited nervous systems wholly dedicated to sensorimotor processes. Their behavior was limited to direct, real time interconnectivity with their surroundings. Thus, cognition in humans (instead of being amodal, symbolic, and separate from sensorimotor processes) may have similarly rich connections with the sensorimotor periphery.

Arguments aside, there is an enormous amount of empirical evidence for the embodied cognition hypothesis. It would not be possible to go through all of it in this forum, but a sampling will be instructive. The following paragraphs discuss seminal early work in cognitive linguistics and (briefly) robotics. The remainder of the section is then devoted to describing a few important illustrative experimental results.

The resurgence of the embodied cognition hypothesis in cognitive science began in the early 1980s, when cognitive linguists started explaining abstract concepts as metaphorical extensions of concrete concepts, particularly those related to the body (Lakoff & Johnson, 1980). This line of work begins with the claim that humans conceive of the world through metaphorical reasoning. That is, humans learn nearly all concepts through metaphor: human beings acquire new concepts almost exclusively by grasping them in terms of previously mastered concepts. To avoid a vicious regress, however, humans must be able to grasp a small number of atomic concepts non-metaphorically. Such atomic concepts, according to Lakoff and Johnson, derive from interactions between the human body and the external world—grasping these concepts depends upon having a body.

Certain spatial concepts, including *up* and *down*, are atomic concepts on this view. Human beings acquire the concepts *up* and *down* because moving requires holding or altering a normally erect posture. Subsequently, bodily concepts like up and down scaffold the acquisition of more complex concepts. *Up* and *down*, in particular, can be used to structure metaphorical conceptions of happiness and sadness, as Lakoff and Johnson (1980) illustrate with examples like: "I'm feeling up" and "I'm feeling down." In other words, metaphorical reasoning, an essential component of concept learning, depends upon contingent properties of the human body. The body is thus directly involved in cognitive processes.

Also in the 1980s, roboticists began demonstrating that sophisticated behavior could be achieved by combining simple environmental interactions instead of handcrafting complex internal representations. Brooks (1986), in particular, advocated the idea of a "subsumption architecture," which involves building robots by successively adding limited control mechanisms over raw sensory and motor systems in order to progressively obtain more sophisticated behavior. Such an approach highlights the role of the sensorimotor systems in driving complex behavior while minimizing—or possibly eliminating—the role of central representations (e.g., concepts) in doing so, as Brooks (1991) emphasizes.

More recently, a wide variety of experimental findings in psychology have provided empirical support for the embodied cognition hypothesis. Richardson, Spivey, Barsalou, and McRae (2003), for example, demonstrated that comprehending verbs with horizontal or vertical image schemas interacted with perceptual and memory tasks. Thus, for example, participants who heard a sentence and saw two pictures, of the agent and the patient of the sentence, were later faster to recognize the picture pairs if they were presented in the same orientation as the image schema of the verb in the associated sentence. Richardson et al. argue that such effects suggest that linguistic representations have a sensorimotor character.

Zwaan, Madden, Yaxley, and Aveyard (2004) found that participants were faster to judge that two sequentially presented visual objects were the same when the implied motion between the stimuli matched the movement described in an accompanying sentence. For example, if the sentence was "The pitcher hurled the softball to you" and the second visual stimulus, depicting a softball, was slightly larger than the first, which was also a softball (implying motion toward the participant), then responses were facilitated. The result, they argue, suggests that language comprehension routinely involves the activation of visual motion (i.e., sensorimotor) representations. Moreover, they suggest, it provides converging evidence for the hypothesis that language comprehension generally involves perceptual simulation of the described situation, contrary to theories postulating that language is represented propositionally, that is, amodally (e.g., Pylyshyn, 1984).

These sorts of findings are not limited to aspects of visual perception (orientation, implied motion), nor are they limited to linguistic stimuli. For example, Simmons, Martin, and Barsalou (2005) found, using event-related fMRI, that pictures of appetizing foods not only activate visual shape areas but also activate areas of cortex specialized for taste and food reward. That is, they showed that a visual stimulus activates gustatory areas. To give another example, N. L. Wilson and Gibbs (2007) showed that moving the body in a particular way (e.g., shaking), or even just imagining doing so, primes comprehension of metaphorical phrases related to that action (e.g., "shake off a feeling"). In this case, a motor act facilitates processing of a linguistic stimulus. Simmons et al. (2007) found, again using event-related fMRI, that the same cortical area (the left fusiform gyrus) is active both when perceiving color and when processing color property words such as "blue" and "green." That is, there appears to be a common neural substrate for perceiving colors and conceptualizing (retrieving knowledge about) colors.

In light of these arguments and evidence over the last 30 years, the embodied cognition hypothesis has increasingly become the mainstream position in cognitive science.

EMBODIMENT IN DEVELOPMENT

Developmental researchers have made crucial contributions of evidence and arguments supporting the embodied cognition hypothesis. In addition to the origins discussed in the previous section, the embodied cognition hypothesis can be traced to Jean Piaget's developmental psychology, specifically to his emphasis on the way that cognitive skills emerge out of a foundation of sensorimotor abilities (M. Wilson, 2002). Piaget thought the earliest stage of development consisted primarily if not exclusively of sensorimotor capabilities and saw the issue of how adult cognition arises from those limitations as the core question for developmental psychology.

Thelen (2000), however, argues that development of mature cognition does not require overcoming or abandoning these early sensorimotor skills but rather refining them and making them more flexible. In line with that view, Thelen, Schöner, Scheier, and Smith (2001) describe a dynamic systems model of the "A-not-B" error. This is the phenomenon, documented by Piaget (1963), that 7- to 12-month-old infants who have been successful in finding a toy at one location, A, continue to reach for that location even after they see the toy hidden in another location, B. Thelen et al. (2001) dispute standard accounts, according to which the A-not-B error results from a deficit in infants' knowledge about objects. Instead, they claim, it is best explained in terms of operations like perceiving, planning, deciding, reaching and remembering. Some of those operations (i.e., planning, deciding and remembering) sound characteristically cognitive, but the model supports the embodied cognition hypothesis by implementing them in the same dynamic field as that used to capture the reaching movement. The authors maintain that this dynamic engagement between the mental and the sensorimotor is characteristic of cognition at all ages (Thelen et al., 2001).

The notion of embodiment in use in the developmental literature differs slightly from that in the adult literature. Linda B. Smith, for example, defines the "embodiment hypothesis" as "the idea that intelligence emerges in the interaction of an organism with an environment and as a result of sensory-motor activity" (L. B. Smith, 2005b; L. B. Smith & Gasser, 2005). Note the emphasis on how intelligence "emerges." This is because a developmental perspective focuses inquiry on the issue of explaining change. The disembodied approach, besides assuming that cognition can be explained independently of sensorimotor processes, also makes the assumption that David Kirsh (1991a) called "learning can be added later." This is the assumption that adult human cognition (the only kind that matters) can be explained independently of development and learning. In the developmental literature, advocates of the embodied approach challenge both assumptions. L. B. Smith and Gasser (2005), for example, argue that starting out embodied and embedded in the world is necessary for the development of human cognition. L. B. Smith and Sheya (2010) argue that the very *reason* that mainstream cognitive science failed to explain developmental change for so many years was the fact that it was based on a disembodied approach.

The most important empirical evidence for embodiment to come out of the developmental literature has been a series of findings showing that developmental changes in body posture and motor activity have surprising and wide-ranging effects on putatively cognitive tasks. Clearfield (2004), for example, showed that infants who learned to find a hidden goal location in a large space while crawling could no longer do so after the transition to walking, suggesting that infants' spatial learning is linked to their mode of locomotion. In another example, Broaders, Cook, Mitchell, and Goldin-Meadow (2007) demonstrated that telling children to gesture while explaining their (incorrect) answers to novel arithmetic problems improves their ability to solve the problems correctly later, suggesting that the children's mathematical learning is linked to their motor activity.

Karin Harman James has documented similar effects using fMRI. K. H. James (2009) showed that preschool children who practiced printing letters subsequently had greater activity in visual association cortex during letter perception than those who had merely practiced visual letter recognition. In other words, the motor experience associated with printing letters augmented processing in the visual system.

The developmental neuroimaging results are not limited to effects of the motor system on perceptual systems such as vision. K. H. James and Maouene (2009) found that listening to verbs—but not adjectives—activated motor systems in the frontal cortex of preschool children. Moreover, verbs associated with different body parts by adults (Maouene, Hidaka, & Smith, 2008) activated different parts of motor cortex in children. An additional study using novel verbs (K. H. James & Swain, 2010) showed that the motor system in preschoolers is only activated during auditory perception of a verb if the verb has been learned by self-generated (active) exploration of an object with which the verb was paired. Passively viewing manipulation of an object paired with a verb resulted in substantially lower activation of motor regions.

Indeed, theorists of child language have emphasized for some time that language emerges from action (Bates, Camaioni, & Volterra, 1975; Bruner, 1975; Iverson & Thelen, 1999; Kelly et al., 2002). Recently, Iverson (2010) has argued that the acquisition of motor skills gives infants the chance to hone skills that will later be needed for language acquisition. For instance, rhythmic arm movements (such as hand banging) provide opportunities for the infant to practice the sort of temporally precise, recurrent patterns of movement that are necessary for babbling. In addition, Iverson argues, the achievement of certain motor development milestones alters infants' relations with the world in ways that contribute to language acquisition. For instance, the onset of crawling, by increasing the infant's proximity to dangerous objects and contexts while simultaneously decreasing the infant's proximity to the caretaker, increases the frequency and intensity of distal communication from the caretaker. These developments motivate the infant to find the object of the caregiver's communication, and this motivation contributes to improvements in the infant's ability to follow gaze and pointing gestures. That is, crawling indirectly leads to improvements in the ability to maintain joint attention, which is critical for language acquisition among other things.

In a commentary on Iverson's paper, Adolph, Tamis-LeMonda, and Karasik (2010) argue that Iverson may not go far enough. Whereas Iverson claims only that aspects of motor development are "normally participatory" in language acquisition but neither necessary nor sufficient, Adolph et al. (2010) suggest that motor development should be central not only to developmental psychology but to psychology in general. Similarly, L. B. Smith and Sheya (2010) offer a synthesis of the developmental research that places action at the center. In their view, bodily actions routinely bring an individual's various sensorimotor systems into dynamic couplings with each other, changing the sensorimotor systems themselves. These changes, over time, transcend single modalities and particular tasks, leading ultimately to the sort of complex, flexible behavior that characterizes adult cognition.

CHALLENGES FOR THE EMBODIED COGNITION HYPOTHESIS

The previous sections have shown that there is a wide variety of evidence that sensorimotor processing accompanies conceptual processing of various sorts, both in adults and in children. Most researchers have taken these results as evidence for the embodied cognition hypothesis, that is, as evidence that sensorimotor processes influence or constitute cognitive processes. However, as Mahon and Caramazza (2008) note, that inference is invalid on two grounds. One is that most of the empirical evidence to date can be explained just as well by a "disembodied" theory supplemented by hypotheses about spreading activation between the conceptual system and sensorimotor systems. Another is that there is some neuropsychological evidence that specifically weighs *against* the embodied cognition hypothesis. The next few paragraphs discuss some of the neuropsychological evidence for and against the embodied cognition hypothesis; the final paragraphs of this section address the point that the evidence usually marshaled for the embodied cognition hypothesis is also consistent with a kind of disembodied theory.

Mahon and Caramazza (2008) consider the disorder apraxia as an example of neuropsychological evidence against the embodied cognition hypothesis. Apraxia consists of an inability to use objects; that is, it is an impairment of motor processes. The embodied cognition hypothesis requires that motor processes causally influence cognitive processes. Strong versions require that motor processes (together with sensory processes) are constitutive of cognitive processes. If the embodied cognition hypothesis is true, then, one might expect that apraxia would also impair object recognition or action recognition. However, apraxia affects neither object recognition nor action recognition. Patients with apraxia can name objects that they are unable to use, and they can recognize pantomimes of actions that would be appropriate for objects they are unable to use. Therefore, apraxia demonstrates that certain motor processes are not necessary for corresponding cognitive processes. Indeed, even paraplegia does not interfere with object recognition, so clearly many motor processes are not necessary for object recognition! By contrast, if sensorimotor processes were actually constitutive of cognitive processes (like object or action recognition), one would expect that the inability to use objects would cause failures in the abilities to recognize the objects and the actions appropriate to them. The phenomenon of apraxia (not to mention paraplegia) therefore rules out extreme forms of the embodied cognition hypothesis.

However, both apraxia and paraplegia are consistent with weaker forms of the embodied cognition hypothesis. Sensorimotor processes (such as using an object) may influence central processes (such as recognizing the object) without being necessary for them. The burden is then on the proponent of the embodied cognition hypothesis to explain in exactly what sense sensorimotor processes influence cognitive processes short of being necessary for them. In addition, the weaker versions of the embodied cognition hypothesis that are consistent with apraxia and paraplegia are less radical and therefore, perhaps, less interesting. Explaining apraxia and paraplegia seems to require postulating that central processes like recognition can sometimes operate independently of relevant sensorimotor processes. That is, explaining apraxia and paraplegia seems to require leaving room for cognitive processing independent of sensorimotor processing. Doing so raises questions about the centrality of sensorimotor processing in cognition. In other words, if sensorimotor processing is not necessary for cognitive processing, then sensorimotor processing may not be so interesting after all.

There is evidence that relevant sensorimotor processing is *sometimes* necessary for cognitive processing, including object recognition. For example, preventing gesture results in speech disfluencies, particularly for spatial content (Rauscher, Krauss, & Chen, 1996). In some sense, then, gesture (i.e., a sensorimotor activity) is sometimes necessary for fluent speech (i.e., producing language, a characteristically cognitive activity).

Further evidence that sensorimotor processing is sometimes necessary for certain kinds of cognitive processing comes from the fact that people at different levels of expertise (e.g., novice as opposed to expert musicians or chess players) perceive stimuli differently. For instance, professional basketball players are better than college students at recognizing basketball dribbles from point-light displays, and are better at identifying their own dribbles than those of others from such displays (Hohmann, Troje, Olmos, & Munzert, 2011). That is, the particular sensorimotor experiences accumulated in the course of attaining expertise at something like basketball seem to be necessary for the task of recognizing an expert activity such as dribbling and identifying who is performing that activity from informationally impoverished stimuli. Note, however, that the necessity in this case is on a different time scale than that involved in apraxia. Apraxia demonstrates that relevant sensorimotor processes *in real time* are not always necessary for cognitive processes like recognition. Basketball expertise, by contrast, demonstrates that relevant sensorimotor processes active during the *development* of expertise are sometimes necessary for *later* cognitive processes like recognition and identification. Moreover, the phenomenon of expertise is consistent with weaker versions of the embodied cognition hypothesis. That is, the fact that *earlier* sensorimotor processes are sometimes necessary for *later* cognitive processes does not impugn the claim that cognitive processes sometimes occur in the absence of relevant sensorimotor processes acting *in real time*.

Along similar lines, it is worth considering object agnosia, which may be conceptualized as the converse deficit to apraxia. Object agnosia consists of an inability to visually recognize familiar objects, but object agnosics can mimic actions appropriate to objects they cannot recognize (Magnié, Ferreira, Giusiano, & Poncet, 1999). For instance, there is the famous example of a man who cannot recognize a picture of a combination lock but pantomimes opening a combination lock while looking at the picture. Indeed, there are many reports (e.g., Brain, 1941) of severe object agnosics who can still move through the world and act appropriately on objects. Arguably, such cases reinforce the notion that the motor system stores certain kinds of object-specific information as motor programs that can be accessed independently of explicit visual recognition. Object agnosia is therefore also evidence against strong versions of the embodied cognition hypothesis. That is, to the extent that motor processes constitute cognitive processes, one might expect that the availability of an object-specific motor program would be sufficient for recognizing the object. However, object agnosia shows that the availability of an object-specific motor program is not sufficient for recognizing an object.

At the same time, object agnosia does not tell against weaker versions of the embodied cognition hypothesis. Object-specific motor programs may causally affect cognitive processes such as recognition without thereby being sufficient for them. Once again, however, the weaker versions of the embodied cognition hypothesis that are consistent with the phenomenon are less radical and, perhaps, less interesting than the strong version of the hypothesis. Explaining object agnosia, in particular, seems to require postulating that sensorimotor processes can sometimes operate independently of relevant cognitive processes. That is, as with apraxia and paraplegia, explaining object agnosia seems to require leaving room for cognitive processing independent of sensorimotor processing. Doing so raises questions about the centrality of sensorimotor processing in cognition. Once again, if sensorimotor processing is not sufficient for cognitive processing, then sensorimotor processing may not be so interesting after all.

The neuropsychological literature is full of interesting interactions and dissociations like these between sensorimotor processes and cognitive processes. However, it is important to keep in mind that the relations between sensorimotor processes and cognitive processes are multifaceted and graded. Even visual agnosics can recognize some objects, and apraxics have not been exhaustively tested on learning to recognize novel objects without typical motor interaction. Many of the more interesting effects that neuropsychologists have discovered have only emerged clearly from exhaustively testing the abilities and inabilities of patients, but this sort of testing is by no means routine. Hence, it is likely that neuropsychology will continue to provide surprises in the coming years. Given the current state of knowledge, however, it does not make sense to place a lot of theoretical weight on particular neuropsychological observations.

The second challenge to the embodied cognition hypothesis that is raised by Mahon and Caramazza (2008) is the claim that the empirical data that have been taken to support embodied cognition can equally well be explained by a version of a disembodied cognition hypothesis that postulates spreading activation between sensorimotor areas and conceptual areas. This is a version of an argument that advocates of embodiment often hear—that embodied cognition amounts essentially to associative learning between sensorimotor experiences and cognitive processes. That is, associative learning could easily explain all of the examples cited in the previous two sections of this paper. The Simmons et al. (2005) experiment showing that gustatory regions are activated by viewing picture of appetizing foods, for example, could be explained in terms of associative learning. The explanation would posit that viewing images of tasty foods activates regions of gustatory cortex because people have previously learned to associate the objects depicted in the images with good tastes. In general, people learn associations among descriptions or representations of things, the things to which these descriptions or representations refer in the physical world, and the effects typically caused by such things. These learned associations may explain the existing data thought to favor the embodied cognition hypothesis.

One way to respond to such concerns is to grant that embodiment describes associative learning, but argue that is not really the point. Rather, the point is that words, images and concepts in general, in order to have meanings, must be associated with real things in the world with which a person has had prior experience. Those prior experiences ground the concepts in the world via sensorimotor systems. This kind of response, though, begs the argument put forth by Mahon and Caramazza (2008). The foe of embodiment may grant that the meanings of ordinary, everyday concepts are grounded in *previous* sensorimotor experiences in much the same way that a basketball professional's concept of a dribble is grounded in previous sensorimotor experiences. Doing so, however, is not the same as granting that sensorimotor processes are causally active in the processing of such concepts *in real time*, let alone that sensorimotor processes happening in real time *constitute* the processing of such concepts. The defense provided by the grounding argument is therefore only a defense of a weak version of the embodied cognition hypothesis. On the weak version, sensorimotor processes participate in grounding concepts by being active simultaneously with (and so associated with) both the referents and the nascent concepts during concept acquisition. However, on the weak version of the hypothesis, sensorimotor processes are not causally involved with, let alone constitutive of, mature conceptual processes happing in real time. The sensorimotor associations remain, of course, but they manifest themselves in both neuroimaging studies and behavioral studies as inert byproducts of the learning process rather than as causes or constituents of conceptual processing.

For the embodiment theorist to address this challenge, it is necessary to demonstrate not merely that sensorimotor processing is associated with cognitive processing, nor even that cognitive processing affects sensorimotor processing, but that sensorimotor processing *causally* affects (or constitutes) cognitive processing in real time. Taking up this challenge, Pezzulo et al. (2011) cite several behavioral studies demonstrating that particular motor actions affect responses on cognitive tasks. For example, L. B. Smith (2005a) showed that repeatedly performing actions on an object changes 2.5-year-olds' cognitive representation of the object. Specifically, children who moved a symmetrical object horizontally tended to extend its name to similar but wider objects, whereas those who moved the symmetrical object vertically tended to extend its name to similar but taller objects. As Pezzulo et al. (2011) acknowledge, however, there is at present a relative paucity of evidence that sensorimotor processing causally affects cognitive processing, compared to the many results demonstrating a mere association or a causal link in the other direction. Thus, an important remaining challenge for the embodied approach is to empirically document phenomena that are consistent with the embodied cognition hypothesis but *not* with the hypothesis that "disembodied" cognition spreads activation to sensorimotor systems as a mere side-effect of previously learned associations.

While Pezzulo et al. (2011) clearly support the embodied approach, they also describe in detail a number of additional challenges that it must meet if it is to live up to its ambitions. These include producing more empirical results demonstrating that sensorimotor processing causally influences characteristically high-level cognitive processes, such as language, decision making, reasoning and problem solving. Of particular note is their challenge for the robotics community to implement embodied computational models explicitly demonstrating how sensorimotor processes may comprise cognitive processes. As they note, such models will improve theories of embodied cognition by elucidating and examining their essential features, including the degree to which sensorimotor processes causally affect cognitive processing. In so doing, the models will thereby also open new frontiers for research on embodied cognition.

CONCLUSION

For most of the history of cognitive science, the “disembodied” view that cognition and development can be studied independently of sensorimotor processes has dominated the field. Recently, however, cognitive science has assimilated several other intellectual traditions (such as American pragmatism, phenomenology, Piagetian cognitive development, and ecological psychology) that emphasize the important roles that the body plays in cognition. The result has been a flourishing theoretical and empirical research effort on the embodied cognition hypothesis, one that has produced many novel and interesting findings. The ultimate fate of the embodied cognition hypothesis, however, depends on the extent to which it can meet several outstanding challenges. Among these are the need to document more thoroughly via empirical studies the causal role that sensorimotor processes may play in cognitive processes, particularly higher cognitive processes, and the need to produce and study mechanistic implementations of the theory in robots. Developmental scientists will continue to play critical roles in answering both of these challenges, as well as the other challenges that will undoubtedly arise as the embodied cognition hypothesis is tested, revised and elaborated.

REFERENCES

Adolph, K. E., Tamis-LeMonda, C. S., & Karasik, L. B. (2010). Cinderella indeed — a commentary on Iverson's 'Developing language in a developing body: The relationship between motor development and motor development'. *Journal of Child Language, 37*, 269-273.

Bates, E., Camaioni, L., & Volterra, V. (1975). The acquisition of performatives prior to speech. *Merrill-Palmer Quarterly, 21*(3), 205-226.

Birnbaum, L. (1991). Rigor mortis: A response to Nilsson's 'Logic and artificial intelligence'. *Artificial Intelligence, 47*, 57-78.

Brain, W. R. (1941). Visual object-agnosia with special reference to the Gestalt theory. *Brain: A Journal of Neurology, 64*, 43-62. doi: 10.1093/brain/64.1.43

Broaders, S. C., Cook, S. W., Mitchell, Z., & Goldin-Meadow, S. (2007). Making children gesture brings out implicit knowledge and leads to learning. *Journal of Experimental Psychology: General, 136*(4), 539-550.

Brooks, R. A. (1986). A robust layered control system for a mobile robot. *IEEE Journal of Robotics and Automatation, 2*(1), 14-23.

Brooks, R. A. (1991). Intelligence without representation. *Artificial Intelligence, 47*, 139-159.

Bruner, J. S. (1975). The ontogenesis of speech acts. *Journal of Child Language, 2*, 1-19.

Clark, A. (1999). An embodied cognitive science? *Trends in Cognitive Sciences, 3*(9), 345-351.
Clearfield, M. W. (2004). The role of crawling and walking experience in infant spatial memory. *Journal of Experimental Child Psychology, 89*, 214-241.
Dewey, J. (1925). Experience and nature. In J. A. Boydston (Ed.), *John Dewey: The Later Works, 1925-1953* (Vol. 1): Southern Illinois University.
Dreyfus, H. L., & Dreyfus, S. E. (1999). The challenge of Merleau-Ponty's phenomenology of embodiment for cognitive science. In G. Weiss & H. F. Haber (Eds.), *Perspectives on Embodiment: The Intersections of Nature and Culture* (pp. 103-120). New York, NY: Routledge.
Evans, G. (1982). *The Varieties of Reference*. Oxford: Oxford University Press.
Fodor, J. A. (1975). *The Language of Thought*. Cambridge, MA: Harvard University Press.
Fodor, J. A. (1983). *The Modularity of Mind*. Cambridge, MA: MIT Press.
Hohmann, T., Troje, N. F., Olmos, A., & Munzert, J. (2011). The influence of motor expertise and motor experience on action and actor recognition. *Journal of Cognitive Psychology, 23*(4), 403-415. doi: 10.1080/20445911.2011.525504
Iverson, J. M. (2010). Developing language in a developing body: The relationship between motor development and language development. *Journal of Child Language, 37*, 229-261.
Iverson, J. M., & Thelen, E. (1999). Hand, mouth and brain: The dynamic emergence of speech and gesture. *Journal of Consciousness Studies, 6*(11-12), 19-40.
James, K. H. (2009). Sensori-motor experience leads to changes in visual processing in the developing brain. *Developmental Science, 13*, 279-288.
James, K. H., & Maouene, J. (2009). Auditory verb perception recruits motor systems in the developing brain: An fMRI investigation. *Developmental Science*, F26-F34.
James, K. H., & Swain, S. N. (2010). Only self-generated actions create sensori-motor systems in the developing brain. *Developmental Science*, 1-6.
James, W. (1890). *The Principles of Psychology* (Vol. 2). New York: Henry Holt.
Johnson, M., & Rohrer, T. (2007). We are live creatures: Embodiment, American pragmatism, and the cognitive organism. In J. Zlatev, T. Ziemke, R. Frank & R. Dirven (Eds.), *Body, Language and Mind, Volume 1: Embodiment* (pp. 17-54). Berlin: Mouton de Gruyter.
Kelly, S. D., Iverson, J. M., Terranova, J., Niego, J., Hopkins, M., & Goldsmith, L. (2002). Putting language back in the body: Speech and gesture on three timeframes. *Developmental Neuropsychology, 22*(1), 323-349.
Kirsh, D. (1991a). Foundations of AI: The big issues. *Artificial Intelligence, 47*, 3-30.

Kirsh, D. (1991b). Today the earwig, tomorrow man? *Artificial Intelligence, 47*, 161-184.
Lakoff, G., & Johnson, M. (1980). *Metaphors We Live By*. Chicago, IL: University of Chicago Press.
Magnié, M.-N., Ferreira, C. T., Giusiano, B., & Poncet, M. (1999). Category specificity in object agnosia: Preservation of sensorimotor experiences related to objects. *Neuropsychologia, 37*(1), 67-74. doi: 10.1016/s0028-3932(98)00045-1
Mahon, B. Z., & Caramazza, A. (2008). A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. *Journal of Physiology-Paris, 102*, 59-70. doi: 10.1016/j.jphysparis.2008.03.004
Maouene, J., Hidaka, S., & Smith, L. B. (2008). Body parts and early-learned verbs. *Cognitive Science, 32*, 1200-1216.
Merleau-Ponty, M. (1962). *The phenomemology of perception* (C. Smith, Trans.). London: Routledge & Kegan Paul.
New, C. (1976). Look, No Eyes. *Analysis, 36*, 137-141.
Pezzulo, G., Barsalou, L. W., Cangelosi, A., Fischer, M. H., McRae, K., & Spivey, M. J. (2011). The mechanics of embodiment: a dialog on embodiment and computational modeling. *Frontiers in Psychology, 2*(5), 1-21. doi: 10.3389/fpsyg.2011.00005
Piaget, J. (1963). *The origins of intelligence in children*. New York: Norton.
Putnam, H. (1960). Minds and machines. In S. Hook (Ed.), *Dimensions of Mind*. New York: New York University Press.
Putnam, H. (1988). *Representation and Reality*. Cambridge, MA: MIT Press.
Pylyshyn, Z. W. (1984). *Computation and Cognition*. Cambridge, MA: MIT Press.
Pylyshyn, Z. W. (1999). Is vision continuous with cognition? The case for cognitive impenetrability of visual perception. *Behavioral and Brain Sciences, 22*(3).
Rauscher, F. H., Krauss, R. M., & Chen, Y. (1996). Gesture, speech, and lexical access: The role of lexical movements in speech production. *Psychological Science, 7*(4), 226-231. doi: 10.1111/j.1467-9280.1996.tb00364.x
Richardson, D. C., Spivey, M. J., Barsalou, L. W., & McRae, K. (2003). Spatial representations activated during real-time comprehension of verbs. *Cognitive Science, 27*(5), 767-780.
Rohrer, T. C. (2007). The body in space: Dimensions of embodiment. In T. Ziemke, J. Zlatev & R. M. Frank (Eds.), *Body, Language and Mind, Volume 1: Embodiment* (pp. 339-378). New York: Mouton de Gruyter.
Simmons, W. K., Martin, A., & Barsalou, L. W. (2005). Pictures of appetizing foods activate gustatory cortices for taste and reward. *Cerebral Cortex, 15*(10), 1602-1608.
Simmons, W. K., Ramjee, V., Beauchamp, M. S., McRae, K., Martin, A., & Barsalou, L. W. (2007). Common neural substrates for perceiving and knowing about color and action. *Neuropsychologia, 45*(12), 2802-2810.

Smith, B. C. (1991). The owl and the electric encyclopedia. *Artificial Intelligence, 47*, 251-288.

Smith, L. B. (2005a). Action alters shape categories. *Cognitive Science, 29*, 665-679.

Smith, L. B. (2005b). Cognition as a dynamic system: Principles from embodiment. *Developmental Review, 25*, 278-298. doi: 10.1016/j.dr.2005.11.001

Smith, L. B., & Gasser, M. (2005). The development of embodied cognition: Six lessons from babies. *Artificial Life, 11*(1-2), 13-29.

Smith, L. B., & Sheya, A. (2010). Is cognition enough to explain cognitive development? *Topics in Cognitive Science*, 1-11.

Thelen, E. (2000). Grounded in the world: Developmental origins of the embodied mind. *Infancy, 1*(1), 3-28.

Thelen, E., Schöner, G., Scheier, C., & Smith, L. B. (2001). The dynamics of embodiment: A field theory of infant perseverative reaching. *Behavioral and Brain Sciences, 24*, 1-34. doi: 10.1017/s0140525x01003910

Turing, A. M. (1936). On computable numbers, with an application to the entsheidungsproblem. *Proceedings of the London Mathamatical Society, Second Series 42*, 230-265.

Tye, M. (1983). On the possibility of disembodied existence. *Australasian Journal of Philosophy, 61*, 275-282.

Van Leeuwen, C. (1998). Perception. In W. Bechtel & G. Graham (Eds.), *A Companion to Cognitive Science* (pp. 265-281): Blackwell.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review, 9*, 625-636.

Wilson, N. L., & Gibbs, R. W., Jr. (2007). Real and imagined body movement primes metaphor comprehension. *Cognitive Science, 31*, 721-731.

Zwaan, R. A., Madden, C. J., Yaxley, R. H., & Aveyard, M. E. (2004). Moving words: Dynamic representations in language comprehension. *Cognitive Science, 28*, 611-619. doi: 10.1016/j.cogsci.2004.03.004