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From the Revolution to Embodiment: 25 Years of Cognitive Psychology

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Abstract
In 1988, the cognitive revolution had become institutionalized: Cognition was the manipulation of abstract symbols by rules. But, much like institutionalized political parties, some of the ideas were becoming stale. Where was action? Where was the self? How could cognition be smoothly integrated with emotions, with social psychology, with development, with clinical analyses? Around that time, thinkers in linguistics, philosophy, artificial intelligence, biology, and psychology were formulating the idea that just as overt behavior depends on the specifics of the body in action, so might cognition depend on the body. Here we characterize (some would say caricature) the strengths and weaknesses of cognitive psychology of that era, and then we describe what has come to be called embodied cognition: how cognition arises through the dynamic interplay of brain controlling bodily action controlling perception, which changes the brain. We focus on the importance of action and how action shapes perception, the self, and language. Having the body in action as a central consideration for theories of cognition promises, we believe, to help unify psychology.

Keywords
action, performance, cognition, language, communication, memory

In 1916, Margaret Floy Washburn, the first woman to receive a doctorate in psychology, championed the need to connect the facts of mental life with those of bodily movement. In contrast, the behaviorists that followed, led by John B. Watson, ousted the study of mental life from scientific psychology—for a time—while retaining the study of motor responses. In the mid-1960s, a backlash to behaviorism, the cognitive revolution, occurred. Mental life was back, not only for people but even for computers, with their gargantuan size, kludgy switches, fans, and paper tapes. By 1988, the cognitive revolution was complete: Behaviorism was vanquished, but in the ensuing enthusiasm for studying the mind, the relation that Washburn had seen as so worthy of study—that human consciousness is grounded in the human body and movements—was nearly forgotten. Thought, and with it consciousness, was seen, by the standard view, as disembodied, with the contribution of action being relegated, along with behaviorism, to the third subbasement. Today, though, the view of disembodied cognition is being challenged by approaches that emphasize the importance of embodiment.

Here we present an idiosyncratic account of what the field of cognition was and how it has evolved since 1988. We then describe our approach to embodied cognition. In preview, the fundamental tenet of embodied cognition research is that thinking is not something that is divorced from the body; instead, thinking is an activity strongly influenced by the body and the brain interacting with the environment. To say it differently, how we think depends on the sorts of bodies we have. Furthermore, the reason why cognition depends on the body is becoming clear: Cognition exists to guide action. We perceive in order to act (and what we perceive depends on how we intend to act); we have emotions to guide action; and understanding even the most abstract cognitive processes (e.g., the self, language) is benefited by considering how they are grounded in action. This concern for action contrasts with standard cognitive psychology that, for the most part, considers action (and the body) as secondary to cognition.

We believe that this approach is pushing the evolution of the field with a surprising (for some of us) but happy

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conclusion: Simple principles of embodiment may provide a unifying perspective for psychology (Glenberg, 2010; Schubert & Semin, 2009).

Cognition in 1988: Thinking Is Symbol Manipulation

The standard approach to the study of cognition in 1988 was formalized a decade earlier by two of the giants in the field, Alan Newell and Herbert Simon, under the guise of the physical symbol system hypothesis (PSSH; Newell & Simon, 1976). Of course, not every cognitive theory was a perfect exemplar of the PSSH, but it provided the background and a set of default assumptions. It was also brilliant. Start with the following conundrum: Computers appear to think. People appear to think. But computers are lifeless silicon and humans are living flesh. What could they have in common that could produce thinking? The answer, according to the PSSH, was that both are symbol processors with three features in common.

Three features of PSSH thinking "machines"

First, the symbols have a physical instantiation (e.g., bistable memory cells that store patterns of zeros and ones in computer memory or, in its strong form, physical objects such as physical tokens). These physical symbols have representational properties, that is, the symbol stands in for real things like colors, emotions, images, and activities. But in contrast to William James's insight that mentally we never descend twice into the same stream, these physical symbols were thought to be context invariant, static, and disembodied. They were characterized by what came to be known as the "trans-situational identity assumption" (Tulving, 1983)—the assumption that a particular symbol was static and immutable, remaining the same regardless of when or how it was used.

Second, the symbols are manipulated by rules, namely the if–then operations of programs in a computer, which were equated to learned rules, associations, and productions in humans. Thought was taken to be the manipulation of symbols using rules, in both computers and people.

Third, and importantly, both the computer symbols and human symbols were seen as arbitrarily (i.e., by convention alone) related to the referent. Thus, just as a sequence of zeros and ones in a computer representing the concept, say, *bird*, does not look or sound or behave as a real bird, neither does the human mental symbol resemble a bird. This arbitrariness ensured that the symbols could be manipulated solely by the properties relevant to the rules; it ensured efficiency because there is nothing in the symbol that is extraneous; it ensured the possibility of limitless symbols even if the human ability to discriminate along some dimension was limited; and finally, it ensured that computer symbols and human symbols were the same in kind.

A good analogy for understanding the PSSH is language. In many analyses, languages have words that act like symbols and syntax that acts like rules for combining the symbols into new thoughts. It is easy to see that many words are arbitrarily related to their referents. The word *bird* no more looks like, sounds like, or acts like a bird than does the equally arbitrary French *oiseau* or German *Vogel*. This sort of analogy led Fodor (1975) to explicitly propose that thinking is a language-like activity: the language of thought. Just as language has symbols and syntax, thought also has symbols and syntax.

The PSSH provided the background for many cognitive theories of the day, even though the particular assumptions were not often explicitly stated or tested. For example, Anderson's ACT theory (Anderson, 1990), Collins and Quillian's (1969) spreading activation model, and Kintsch's construction-integration theory (Kintsch, 1988) were built on the notion of propositions, or units of meaning consisting of symbols and the relations among them. Those symbols were the arbitrary symbols of the PSSH, and the relations and processes were the rules.

Four problems with PSSH

Symbols. Given the success of PSSH approaches to cognition, what is the problem? Even before the advent of embodied cognition, cognitive theories were evolving away from the PSSH. First, if symbols are part of human cognition, they are not arbitrary but grounded, that is, traceable to referents in the world. Mental operations depend on the brain's neural layers interacting in particular ways that could be thought of as transformations and that have particular functions. These operations take information that originates in the world and subject it to transformations (such as lateral inhibition in the retina, autocorrelation in the memory systems, and Fourier transforms in the auditory system) that are useful to the person or animal. What is important, however, is that even with the transformations, the internal representations at deeper and deeper brain levels are ultimately traceable to the outside world, that is, grounded.

An example of an early model attempting to ground symbols is Metcalfe's CHARM (Metcalfe, 1990; Metcalfe Eich, 1982, 1985) model. Whereas it is true, even in this model, that the numbers used to represent a bird do not in any way look like a bird, the representations were not completely arbitrary—namely, the model used complex operations of convolution and correlation for memory encoding and retrieval, and these operations preserved similarity among symbols across transformations. Also, this model and other related non-PHHS models (e.g., McClelland & Elman, 1986; Murdock, 1982) were beginning to strive for representations that could potentially be instantiated in neurons and that bore a more realistic relation to the structure of semantic memory.

Furthermore, the notion of transsituational identity of symbols, although fine for computers, did not work well for humans. The experimental data demonstrated that it was simply untrue that the symbols used by humans were immutable. The "train" that a person imagined in the context of *freight* was a different "train" than was encoded in the context of *black*, and memory was context specific—dependent on the specificity of encoding (Tulving & Thomson, 1973).

Representations separate from processes. The PSSH makes a strong distinction between representations and the processes that act on them. Whereas this distinction holds for some computer languages, it is not at all clear that the distinction can be made for humans. For example, from a connectionist–constraint satisfaction perspective, representations arise from patterns of activation produced by processing, and they are not separable from the processing. From the dynamic systems perspective, there is no representation without process. From the perception–action perspective, what we perceive is necessarily related to how we act (Gibson, 1979).

The Cartesian distinction. The PSSH makes a Cartesian distinction between thought and action, treating mind as disembodied. That is, according to PSSH, the exact same thoughts occur when a computer is manipulating symbols by using rules and when a person is manipulating the same symbols by using the same rules. The particulars of the body housing the symbol manipulation were thought to be irrelevant. Later, we review work within the tradition of embodied cognition that shows that the Cartesian distinction is false.

The role of the self in cognitive processing. Although PSSH models accounted for much of the data on human memory and cognition, there was no hint of a "self" in these models. Theorists such as Tulving (1993) had insisted that episodic memory involves a special kind of self-knowing or autonoetic consciousness, and evidence was mounting for this view (Wheeler, Stuss, & Tulving, 1997). Autobiographical memory for events that were specific to the individual was extensively studied. But conceptualizing and formally implementing something like a "self" and characterizing its function were then (and largely remain) beyond the scope of models of memory and cognition. One reason may have been that although the operations used in these models were neurologically plausible, they relied only on the perceptual system, not the motor system or any feedback from the latter.

In contrast to the PSSH, memory is radically enhanced when the self is involved. Thus, for example, literally enacting a task, such as breaking a toothpick, produces much better memory for the event than watching another perform the task (e.g., Engelcamp, 1995). Similarly, memory is also enhanced when the encoder relates the items to his- or herself (Cloutier & Macrae, 2008; Craik et al., 1999; Macrae, Moran, Heatherton, Banfield, & Kelley, 2004). What is this self-knowledge, self-involvement, and self-reflective consciousness, what are its effects, and how did it come about? We propose that some notion of embodiment is the needed but missing ingredient.

Cognition in 2013: Embodiment

Just as there are many "standard" approaches to cognition, not just the PSSH, there are also many embodied approaches. And these approaches can differ in some fundamental ways. For example, Lakoff and Johnson's (1980) work on metaphor and Barsalou's (1999) work on concepts rely strongly on involvement of representations, whereas Beer's (1996) work on understanding "minimally" cognitive tasks and Gibson's (1979) work on direct perception—which has inspired many embodied cognition theorists—are explicitly representation-less. Nonetheless, there are also some general themes that resonate in the embodiment community.

Cartesian dualism is wrong

As noted above, thinking is not something that is divorced from the body; instead, thinking is influenced by the body and the brain interacting with the environment. This claim can be fleshed out in a number of ways. For example, Proffitt's (2006) work on visual perception demonstrates that perceived distance is affected by the energetic demands of the body needed to traverse the distance. Thus, the same distance looks longer when you are tired, when wearing a heavy backpack, or when of low physical fitness. Casasanto's (2011) studies reveal surprising differences between left-handers and right-handers. Left-handers and right-handers use different parts of the brain when thinking about action verbs; they think about abstract concepts such as "goodness" differently; and, perhaps most amazingly, a few minutes of experimentally induced changes in use of the hands produces differences in how people think about good and bad. Work on brain imaging (e.g., Hauk, Johnsrude, & Pulvermüller, 2004) has shown that when people hear a verb such as "pick," areas of the motor cortex used to control the hands are quickly activated, whereas on hearing a verb such as "kick," areas of motor cortex used to control the legs are activated.

Furthermore, changes in the body produce changes in cognition. Blocking the use of the corrugator (frowning) muscle by cosmetic injection of Botox selectively slows the processing of sentences describing angry and sad events but not happy events (Havas, Glenberg, Gutowski, Lucarelli, & Davidson, 2010). Patients with severe spinal cord injury have a reduction in ability to perceive differences in human gaits, although not in perception of gratings (Arrighi, Cartocci, & Burr, 2011). These results suggest the possibility of what philosophers call "constitution": Activity in the body and sensorimotor cortices of the brain not only contribute to cognition—that activity is cognition.

These data help to explicate the notion that thinking is grounded in the sensorimotor system. Thus, the psychological meaning of distance is grounded in the body's energy consumption; the meanings of words like "kick" and "pick" are grounded in how we interact with the world by using our legs and hands; and the meaning of anger is at least in part its expression using the facial muscles. Ideas are not platonic abstractions that can be as easily implemented in a computer as in a person. Instead, ideas and the very act of thinking are simulations using sensory, motor, and emotional systems.

The importance of action

A second theme of embodiment is an emphasis on action. It seems certain that one evolutionary pressure on cognition is the need to control action: Without action there is no survival. Furthermore, according to the noted biologist Rudolfo Llinas (2001, p. 15), "A nervous system is only necessary for multicellular creatures . . . that can orchestrate and express active movement." And ever since the seminal work of James Gibson (1979) on direct perception and affordances, psychologists are increasingly convinced that action changes perception and animals have perceptual systems because of the need to control action. Thus, the perception–action cycle is at the heart of cognition.

The amazing Held and Hein (1963) kitten carousel experiment illustrates the role of action on perception in development. Pairs of kittens were exposed to a visual environment in which one kitten controlled its own locomotion while the other was in a yoked gondola—receiving the same visual input but without self-controlled locomotion. Whereas all kittens had a normal response to light and visually pursued moving objects, the passive kittens exhibited impaired blink responses and impaired visually guided paw placement. They also failed to discriminate depth, frequently walking over a visual cliff (which in the real world could, of course, be fatal). Campos et al. (2000) documented a similar need to link perception and self-locomotion in human development. Whereas traditional approaches consider perception to operate independently of action, these results demonstrate the necessity of action even for learning how to perceive.

Overview

Below we expand on the action theme in three ways. First, we describe the role of action in perception. Traditional models consider perception to be independent and prior to action; here we describe evidence that action should be considered as an intricate part of perception. Second, we speculate on how an understanding of the underlying mechanisms of action can reveal insights into what appears to be the most abstract of concepts: the self. Consequently, the inclusion of action in processes such as perception and memory results in the inclusion of the self in these processes. Third, we demonstrate the practical side of embodiment by describing an embodied reading comprehension intervention based on action. These three areas of research are not typically associated with action; thus, demonstrating the connection helps to justify our claim that cognition is thoroughly embodied because it is for action.

Action's effect on perception

During the past 25 years, much of the research on perception has resonated with themes found in other areas of cognitive research. Starting with Marr's (1982) seminal book, researchers used the analogy of computers to study perception. Marr distinguished three levels at which a process could be assessed: a computational level (What does a process do?), an algorithmic level (How does the process work?), and an implementation level (How is the process realized?). In this framework, it is irrelevant whether the implementation occurs on neural hardware or computer hardware. The focus was instead on the computations needed to perceive.

The prevalence of this approach—treating human perception as analogous to the processes of computer symbol manipulators—is revealed by the methods used to study perception. A typical setup is shown in Figure 1. The observer's head is stabilized on a chin rest so as to eliminate head motion, thus allowing the experimenter to have complete control over what the observer views. The observer's task is nearly always a judgment of some sort but not in the context action. Indeed, the setup intentionally removes any potential for action, forcing on the human observer the constraints and limitations of a computer. Furthermore, the conjectured goals of vision also align with those that could be equally shared by a computer program, namely, of formulating a

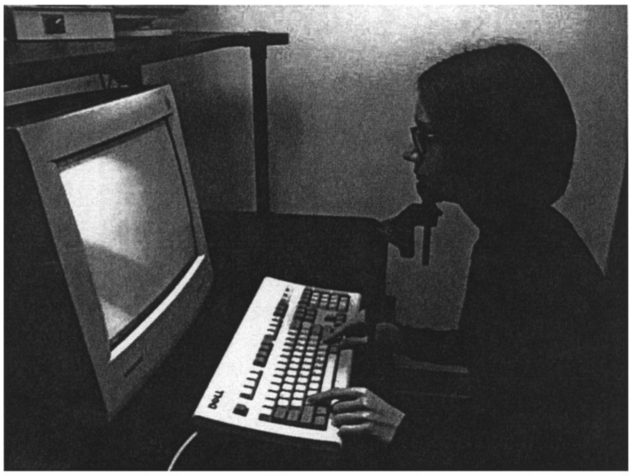

Fig. 1. A typical setup for studying perception. Chin rests are used to minimize head movements.

representation of shape (Marr, 1982), object identification (Yantis, 2000), or spatial layout (Palmer, 1999), based on the impoverished information given in the display uninformed by human action and its consequents.

These PSSH-oriented approaches were challenged by Gibson (1979) in favor of an approach that captures several of the key ideas of embodied cognition, including a role for the self. According to Gibson's theory of direct perception, the information for perception comes from invariants and variants within the optic array as the perceiver moves. These invariants and variants specify both the external environment and the perceiver. For example, the close correlation between self-movement and change in the optic array indicates that the self is moving (e.g., Blakemore, Wolpert, & Frith, 1998); changes in the optic array without self-action indicate a changing world; and the two together specify the dimensionality of space (Philipona, O'Regan, & Nadal, 2003). Consequently, the self is necessarily perceived when perceiving the environment, and perception of the environment could not be achieved without also perceiving the self.

Gibson's theory of affordances emphasized the role of action in perception. Affordances are possibilities for action or for a consequence on the perceiver in a given environment. According to Gibson, affordances are the main object of perception. In making this claim, Gibson stressed action as a key concept in perception, rather than behaviorally independent representations of spatial layout and object identity. But although this concept was accepted for animal vision, mainstream researchers, such as Marr (1982), held to the idea that perception's goal is to recover platonic geometric properties rather than to uncover affordances:

> The usefulness of a representation depends upon how well suited it is to the purpose for which it is used. A pigeon uses vision to help it navigate, fly, and seek out food. . . . Human vision, on the other hand, seems to be very much more general. (p. 32)

Perhaps it is a testament to the importance of action in perception that its role continues to reemerge. Today, there are many different findings of effects of action on perception. For instance, a slight modification to the typical setup for perception experiments—putting one's hands next to the display—modifies visual processes related to attention, such as detection, search, and inhibition (see Brockmole, Davoli, Abrams, & Witt, 2013). Thus, perception is influenced by the mere proximity of one's hands and their potential to act (e.g., Reed, Betz, Garza, & Roberts, 2010). Another example of action's influence is apparent in action observation—the perception of others performing actions (Knoblich, Thornton, Grosjean, & Shiffrar, 2006). For example, apparent motion is the illusion of motion from static images of the endpoints of the motion. What is important is that when the endpoints depict humans, people perceive biologically plausible paths rather than paths along the shortest distance, as would be expected when observing apparent motion with nonbiological objects (Shiffrar & Freyd, 1990). Perception of object features, such as position and direction, is also influenced by the perceiver's actions and intentions to act (Lindemann & Bekkering, 2009; Müsseler & Hommel, 1997).

Action-specific account of perception. The main claim of the action-specific account of perception (Proffitt, 2006; Witt, 2011a) is that perception is influenced by a person's ability to act. For example, softball players who are hitting better than others see the ball as bigger (Witt & Proffitt, 2005). In addition to effects of sports performance on apparent target size (e.g., Gray, in press; Lee, Lee, Carello, & Turvey, 2012; Witt & Dorsch, 2009; Witt & Sugovic, 2010), the energetic costs associated with performing an action also influence perception. Hills look steeper and distances look farther to perceivers who are fatigued, out of shape, encumbered by a heavy load, or elderly (Bhalla & Proffitt, 1999; Sugovic & Witt, in press). Furthermore, changes to a perceiver's ability to perform an action, such as via tool use, also influences perception. Targets that would otherwise be beyond reach look closer when the perceiver intends to reach with a tool (Witt, 2011b; Witt & Proffitt, 2008; Witt, Proffitt, & Epstein, 2005; see also Bloesch, Davoli, Roth, Brockmole, & Abrams, 2012; Brockmole et al., 2013; Davoli, Brockmole, & Witt, 2012; Kirsch, Herbort, Butz, & Kunde, 2012; Osiurak, Morgado, & Palluel-Germain, 2012). In addition, changing the apparent size of one's body in virtual reality (Linkenauger, Mohler, & Bülthoff, 2011; Mohler, Creem-Regehr, Thompson, & Bülthoff, 2010; Van der Hoort, Guterstam, & Ehrsson, 2011) or through optic magnification (Linkenauger, Ramenzoni, & Proffitt, 2010; Linkenauger, Witt, & Proffitt, 2011) influences perceived distance to and size of objects. This research demonstrates that the same object, which gives rise to the same optical information, looks different depending on the perceiver's abilities.

That the perceptual system is tightly connected to the motor system seems necessary from an evolutionary perspective. Sensory processes are costly in terms of energetics, and only sensory processes that are useful will confer an adaptive advantage that will likely be promoted through reproduction. Both nonhuman animals and humans have perceptual processes relevant to their specific bodies and capabilities. The time has come to consider the perceptual system as part of an integrated perception–action system.

Necessity of embodiment. The studies mentioned above make a case for a role of embodiment in perception, but they do not speak to whether embodiment is necessary for perception. Indeed, people can perceive objects for which action is not very likely (such as the moon, although of course perception of the moon is not very accurate). There are some reasons to believe that action might be necessary for perception. First, developing the ability to perceive in a way that is useful for acting requires experience with the pairing of perceptual information while acting (Held & Hein, 1963; see also Campos et al., 2000).

In addition, a new proposal for the mechanism of action-specific effects called the perceptual ruler hypothesis suggests that embodiment may be necessary for perception. The perceptual ruler hypothesis (Proffitt & Linkenauger, 2013) solves a problem that is largely ignored: All optical information takes the form of angles, such as angles of retinal projection or angles of disparity, or changes in these angles. To perceive dimensions such as distance and size, these angles must be transformed accordingly. Yet little is known about these transformation processes or "rulers." According to the perceptual ruler hypothesis, these rulers are based on the body. For example, eye height is used to perceive distance and object height (Sedgwick, 1986), the hand is used for scaling the size of graspable objects (Linkenauger, Witt, et al., 2011), and the arm is used for scaling the size of reachable objects (Witt et al., 2005). Similarly, the body's abilities in terms of physiological and behavioral potential scale other aspects of the environment, such as hills, far distances, and the size of targets.

In summary, the perceptual ruler account solves the important problem of scaling visual information (i.e., turning visual angles into meaningful information), and the ruler used to perform the scaling is the body. In fact, no one has proposed a ruler that is not body-based. Thus, this solution emphasizes that the body not only influences perception, it is necessary for perception, too.

Forward models: A mechanism for action simulation, prediction, and the self

Barsalou (1999) made a strong case that tracing the transformations from perception at the level of the retina or the ear, or action at the level of external bodily movement, through to coherent high-level representations is necessary and a central goal of embodied cognition research. In fact, only by grounding representational cognition in the world can symbols take on meaning (Searle, 1980). Although a general well-specified model integrating cognition and action does not yet exist, some inroads have been made. As we shall see, to model actions, both internal representations (simulations) and a computation that provides the basis for a "self"—a missing component in cognitive models—are required.

One of the most striking of these action models comes from endeavors undertaken by Wolpert (e.g., Wolpert, Ghahramani, & Jordan, 1995). The argument is that action, from the simplest finger movement to the most complex social interactions (e.g., Wolpert, Doya, & Kawato, 2003), requires two types of models. A controller model generates the efferents or commands to move the muscles. But how does the system determine that the movement is, or is likely to be, successful? Of course, sensory feedback is important, but for many situations in which action timing is important (e.g., playing the piano, walking down stairs, control of the speech articulators, or holding a conversation), sensory feedback is too slow. The solution is a second type of model variously called a predictor model or forward model. The forward model uses an exact copy of the efferent signal to simulate the action and predict the effects of the action. A comparator can then make several types of computations. First, it can be used to determine whether the action is unfolding correctly: Do the predictions from the forward model match the desired outcomes? Second, it allows knowledge of whether the action was effective: Does the sensory feedback match the prediction from the forward model?

Critically, the forward model can also be used imaginatively, in mental practice, to evaluate outcomes without performing them (e.g., Grush, 2004). That is, imagination is generating motor commands but inhibiting the efferent signal before the muscles are moved. Nonetheless, generating the efferent commands also generates the signal used by the forward model, and the predictions generated by the forward model are tantamount to imagery.

Combining the notions of imagination, prediction, and action prompted several independent applications of forward models to language. Pickering and Garrod (2013) developed the idea that forward models are used to predict how and what conversational partners are going to say, and thus forward models provide a mechanism for coordinating discourse through alignment in speaking rate, word choice, and syntax. The action-based language theory of Glenberg and Gallese (2012) suggests that forward models play an essential role in predicting (simulating), and thus understanding, the content of language. In fact, Lesage, Morgan, Olson, Meyer, and Miall (2012) demonstrated that disrupting forward models in the motor system (using repetitive transcranial magnetic stimulation of the cerebellum) disrupted prediction in language processing.

Forward models and the self. Although the comparator model rests firmly in the domain of the motor system, an extension of this model to the role of the self in cognition has been explicitly proposed. Many investigators (e.g., Blakemore et al., 1998) realized that a close match of actual and predicted outcomes justifies the inference that the person himself or herself was in control. A mismatch implies the work of external forces and a lack of personal control. This simple mechanism, then, provides a basis for people's knowledge of their own agency. Discrepancies between one's own intention and the outcome could be used in making judgments of self- or other attribution. Indeed, Blakemore, Wolpert, and Frith (2002; and see Blakemore & Frith, 2003; Decety & Lamm, 2007) soon proposed brain-based frameworks using the comparator model to make testable predictions concerning people's feelings of agency—their feelings of the involvement of self.

Action, the self, and memory. The "self" in memory tasks has always been mysterious. William James referred to it in his seminal writings. Tulving, too, makes use of this construct, in distinguishing between semantic memory and episodic memory and in discussing different purported kinds of consciousness. The "highest" of these, he claimed, is self-knowing—autonoetic—consciousness. Nevertheless, the construct of self has always been slightly disreputable for cognitive psychologists, perhaps because it is difficult to define and elusive to model.

Even so, the many cases where the involvement of the "self" has a large impact on memory involve either physical or mental action. The connection to the motor system may not be accidental. Enactment effects, wherein memory is enhanced for those things one does oneself, as compared with those that someone else does (e.g., Engelcamp, 1995), is pervasive for all but some people with autism. The benefits of active versus passive learning are probably due to involvement of the self. Nairne and Pandeirada's (2008) findings that survival-relevant scenarios are easily remembered may also be due to "self" involvement or some implicit threat to the self (and see Humphrey, 2006). The generation effect, whereby memory is greatly improved when the answers are self-generated rather than given externally, also implicates an active self, which alters memory processing. It seems, then, that despite its elusiveness, the self has importance for human memory, and the motor system—which appears to be the basis of this construct—may be implicated at deep levels.

Action and language

At first blush, the notion that action systems play a role in language seems close to absurd: Language appears to be a mental activity, not a bodily one (e.g., Hauser, Chomsky, & Fitch, 2002). But in fact, the data are clear that action systems play an important role in language production, perception, and comprehension (e.g., Glenberg & Gallese, 2012). In this section, we review the data supporting this claim and then demonstrate its importance for both theory and practice by describing an embodied reading comprehension intervention called Moved by Reading (MbR).

Language comprehension as a simulation process. Work in cognitive neuroscience demonstrates many links between language and action. As noted before, Hauk et al. (2004) used functional MRI to demonstrate that just hearing words such as "pick" activated motor areas of the brain controlling the hand. Furthermore, language–action links are bidirectional (e.g., Aravena et al., 2010): Preparing to move the hand affects understanding language about hand movements, and language understanding affects motor preparation. Even the specifics of motor experience matter. For instance, hockey experience modifies motor areas of the brain (including those used in prediction), and those areas are then used in the understanding of language about hockey (Beilock, Lyons, Mattarella-Micke, Nusbaum, & Small, 2008).

Behavioral data tell a similar story. For example, turning a knob clockwise or counterclockwise to reveal the next portion of a story affects the reading of sentences implying clockwise (e.g., "He turned the key to start the car") or counterclockwise actions as shown by Zwaan, Taylor, and De Boer (2010).

These results support the claim that language comprehension is a simulation process (Aziz-Zadeh, Wilson, Rizzolatti, & Iacoboni, 2006; Barsalou, 1999; Glenberg & Gallese, 2012). In brief, words and phrases are transformed into a simulation of the situation described. Furthermore, the simulation takes place in neural systems normally used for action, sensation, and emotion. Thus, language about human action is simulated using motor cortices; comprehending descriptions of visual scenes activates areas of the brain used in visual perception (e.g., Rueschemeyer, Glenberg, Kaschak, Mueller, & Friederici, 2010); and understanding language about emotional situations calls on neural systems engaged by emotion (e.g., Havas et al., 2010). In all of these cases, forward models based in the motor system are used to guide the simulations, but the forward models make use of sensory and emotional systems.

Action and language: An implication for education. Given that language comprehension is a process of simulation, it follows that one component in teaching children how to read for comprehension should be teaching them to simulate. That is the goal of the MbR intervention.

The MbR computer program consists of two parts. In the first part, physical manipulation (PM), children read multiple texts from a scenario (e.g., stories that take place on a farm). After reading an action-oriented sentence (indicated to the child by a green traffic light), the child manipulates images on the computer screen to simulate the content of the sentence (See Fig. 2). For example, if the child reads, "The farmer drives the tractor to the barn," the child moves the image of the farmer to the tractor and then moves the conjoined image of the tractor and farmer to the image of the barn. In the second stage, called imagine manipulation (IM), the child is taught to imagine manipulating the scene in the same way that he or she physically manipulated the scene. IM, in contrast to simple imagery instructions, is likely to engender a significant motor component in addition to visual imagery.

The PM and IM procedures enhance simulation and comprehension by encouraging (a) vocabulary development by grounding word meaning in the neural representation of the pictures and objects, (b) appreciation of the function of syntax by grounding the syntax (i.e., the who does what to whom) in the child's own actions, and (c) the integration of words in a sentence and the integration of sentences across the text as the visually depicted scene is updated by the child. The advantages of MbR have been demonstrated for texts that have been trained with the technique (Glenberg, Gutierrez, Levin, Japuntich, & Kaschak, 2004), generalize to texts read after training, can be implemented in small reading groups (Glenberg, Brown, & Levin, 2007), extend to solving math problems (Glenberg, Willford, Gibson, Goldberg, & Zhu, 2012), and benefit nonnative speakers (Marley, Levin, & Glenberg, 2007, 2010).

If a child understands oral language, and thus is simulating language by using appropriate neural systems, why does the child need to be taught how to simulate when reading? In learning an oral language, the linking of symbols (spoken words and phrases) to sensorimotor activity is frequent and immediate. For example, a mother will say, "Here is your bottle" and give the baby the bottle; or, a father will say, "Wave bye-bye" and gesture waving. From these interactions, the process of moving from the auditory linguistic symbol to the neural representations of objects and actions is highly practiced and becomes fast and automatic. The key to MbR is to make reading more like oral language: Teach the child how to ground written words in sensorimotor activity.

Conclusion

Approaching solutions to four problems

Earlier, we noted four problems with the PSSH. Does the embodied approach help to solve those problems? Consider first arbitrary, ungrounded symbols. Although there are debates among embodied cognition theorists as to necessity of representations, they all agree that cognition is grounded in the body's actions in the world and is not just the manipulation of arbitrary symbols. Instead, what we perceive is related to how we can act in the world; our sense of self is determined by the relations among our actions, their expected effects, and the observed effects; our understanding of language depends on simulations using neural and bodily systems of action, perception, and emotion.

Second, are there static symbols that form the core of our knowledge? Perhaps there are some, but the data strongly imply that our activity influences and coordinates that knowledge. Our skill in acting affects how we perceive the world, and changing that skill changes what we perceive (Lee et al., 2012; Witt, Linkenauger, Bakdash, & Proffitt, 2008; Witt & Proffitt, 2005).

Third, is the mind disembodied? Can there be a brain or mind in a vat? Not if that vat is unconnected to a sensing and acting body. But is it right to consider the bodily activity as part of cognition rather than just the mechanism of input and output? Shapiro (2011) makes an interesting analogy. A car engine's exhaust seems to be just an external waste product of the generation of energy. But consider when the exhaust powers a turbocharger that forces more air into the cylinders, thereby boosting energy output. The exhaust now becomes an integral component of energy production. Similarly, the predictions of sensory feedback generated by forward models, bodily activity, and the feedback from activity become integral to cognition.

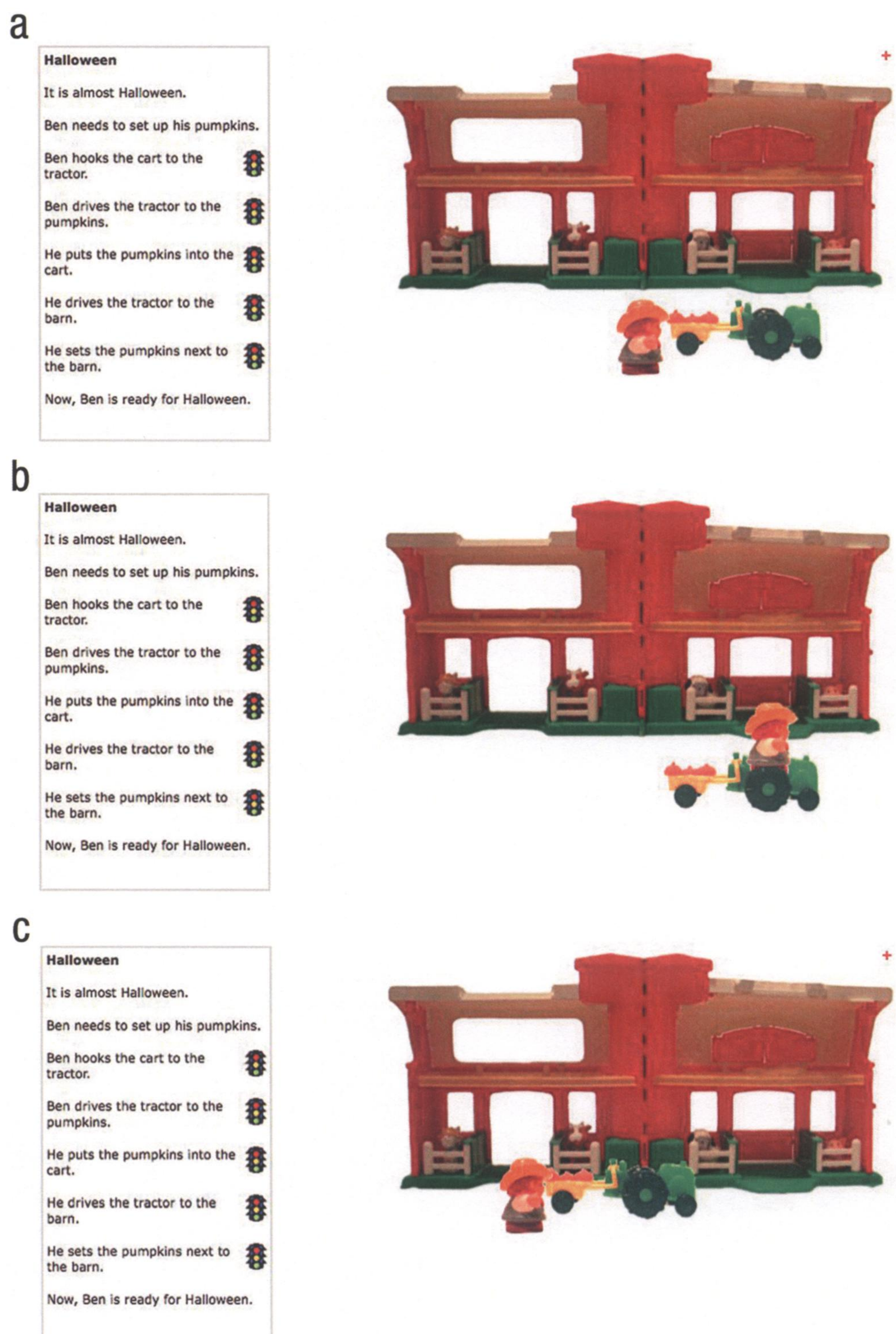

Fig. 2. The screenshots illustrate physical manipulation (a) before reading the sentence "He drives the tractor to the barn" (b) midway through manipulating for the sentence, and (c) after successful manipulation. The green traffic light is the signal for the child to manipulate the toys to correspond to the sentence.

Finally, as a result of the interaction between action and feedback, the very perception of the self is grounded in activity—it is embodied.

The notion that embodiment can help to unify psychology is hinted at in this essay where we have tried to illustrate links between perception, action, memory, language, the self, and applications of psychology. Given that the body is present when we are sensing, thinking, acting, emoting, socializing, and obeying cultural imperatives, it is a good bet that considering the effects of the body in these endeavors will lead to a more unified, coherent, comprehensive, and useful psychology.

Cognition in 2038

Even the best forward models are hard-pressed to predict more than a second or two into the future, let alone 25 years. Whether or not embodiment survives as a viable theoretical framework for decades to come, it has set a salutary course that we hope will continue—namely, it provides new perspectives, new theories, and new methods that may help to unify psychology. If this unification is to emerge by 2038, much work needs to be done. In particular, embodiment researchers must move from demonstrations of embodiment to theoretical approaches that have broad reach. These theoretical approaches must make strong predictions about the directions of the effects, and must be able to describe the underlying mechanisms, including how information from forward models is incorporated into other processes, such as memory and perception. In addition, the concept of the self needs development. Here, we described the self as if it were a singular concept, but it is likely there are multiple aspects of the self that play different roles in cognition (e.g., Damasio, 2010).

Theoretical approaches also need to continue to make the distinction between the idea that the body can influence cognition and the idea that the body is necessary to understand cognition. Given the omnipresence of the body in human activity, we think that developing such an approach is not only possible but essential for development and unification of our field.

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