Few Believe the World is Flat: How Embodiment is Changing the Scientific Understanding of Cognition

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Abstract:

Science has changed many of our dearly held and commonsensical (but incorrect) beliefs. For example, few still believe the world is flat, and few still believe the sun orbits the earth. Few still believe humans are unrelated to the rest of the animal kingdom, and soon few will believe human thinking is computer-like. Instead, as with all animals, our thoughts are based on bodily experiences, and our thoughts and behaviors are controlled by bodily and neural systems of perception, action, and emotion interacting with the physical and social environments. We are embodied; nothing more. Embodied cognition is about cognition formatted in sensorimotor experience, and sensorimotor systems make those thoughts dynamic. Even processes that seem abstract, such as language comprehension and goal understanding are embodied. Thus, embodied cognition is not limited to one type of thought or another: It is cognition.

Throughout history, careful observation and thinking—science—has changed long-held, cherished, and seemingly obvious beliefs. For example, because of science, few still believe the world is flat, although it looks that way to casual observation. Similarly, notions of human exceptionalism have a continuing history of being overthrown by science. In the sixteenth century, the idea that the heavenly bodies revolved around us on earth was challenged by Copernicus; in the seventeenth century Galileo was punished for supporting the idea, but eventually science prevailed over church dogma. In the nineteenth century, Darwin challenged the notion that humans were unrelated to other species. Science continues to support notions of evolution and the descent of humans, but even in the twenty-first century, many (including a startling large number of elected officials in the US) refuse to acknowledge evolution.

Another cherished aspect of human exceptionalism is that our thinking is special. As Mahon (2014) has put it, "it is the independence of thought from perception and action that makes human cognition special…" One goal of the embodied approach to cognition is to show that this idea, although cherished and seemingly obvious, is also wrong.

Introduction to Embodied Cognition

Where did the idea that human thought is independent from perception and action come from? As Barsalou (1999) discusses, great thinkers such as Aristotle, Epicurus, Locke, Berkeley, Hume, Kant, and Russell thought otherwise. However, developments in the mid-twentieth century set the stage for a reversal in thought. First, there were the accomplishments of computer science demonstrating that, at least in a computer, an aspect of thinking, namely computation, can be divorced from perception and action. Second, linguistic analyses purported to show that aspects of language (the supposed “competence” of perfect grammar) could not arise from perception of linguistic input. And finally, there was the backlash against behaviorism and its focus on overt behavior. These intellectual trends culminated in the information processing (or cognitive) approach as exemplified by Newell and Simon’s (1972) Physical Symbol System Hypothesis (PSSH). This hypothesis brilliantly solved an apparent conundrum: How could human thought and a computer’s computations be the same sort of thing? The answer was to propose that thinking of both kinds is the manipulation of abstract symbols, that is, symbols divorced from any perception and action.

Research within the framework provided by the PSSH and related theories (e.g., Atkinson & Shiffrin, 1967; Kintsch, 1988; Landuaer & Dumais, 1997) appeared to make rapid progress. What could be wrong? One of the first cracks in the foundation came from Searle’s (1980) and Harnad’s (1990) discussions of the symbol grounding problem: Closed systems of abstract symbols divorced from perception and action cannot provide an account of meaning. Consider Harnad’s “symbol merry-go-round” argument. Imagine that you land at an airport, perhaps in China, where you don’t speak the local language. You see what appears to be a sign consisting of logograms (or any other non-iconic marks). Although you don’t speak the language, you do have a dictionary written in that language. You look up the first logogram and find its definition, but of course the definition consists of more logograms whose meanings are obscure to you. Undaunted, you look up the definition of the first logogram in the definition, and you find that its definition consists of even more uninterpretable logograms. The point is that no matter how many of the logograms you look up, this closed system of abstract symbols will never produce any meaning for you. But in fact, a process of this sort is exactly the process of meaning-generation proposed by standard cognitive models such as Collins and Quillian (1969), Kintsch (1988), and Landauer and Dumais (1997). For example, Landuaer and Dumais wrote, "Given the strong inductive possibilities inherent in the system of words [logograms if you are in China] itself…the vast majority of referential meaning may well be inferred from experience with words alone" (page 227). [1] Contrary to Landuaer and Dumais (see Glenberg & Robertson, 2000, and Glenberg & Mehta, 2009, for data), we must escape from the symbol merry-go-round by grounding, or associating, those symbols in perception, action, and emotion, and thereby endowing them with meaning.

A second crack in the foundation comes from standing back and considering that humans are animals and a product of evolution. Our morphology, physiology,

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[1] Landuaer and Dumais do acknowledge the symbol grounding problem. "But still, to be more than an abstract system like mathematics words must touch reality at least occasionally" (p. 227). Their proposed solution is to encode, along with the word stream, the streams from other sensory modalities. "Because, purely at the word–word level, rabbit has been indirectly pre-established to be something like dog, animal, object, furry, cute, fast, ears, etc., it is much less mysterious that a few contiguous pairings of the word with scenes including the thing itself can teach the proper correspondences." (p. 227).

This proposed solution to the symbol grounding problem will not work, however, because it presupposes that the symbol grounding problem has been solved. That is, the program in which the Landuaer and Dumain theory is instantiated, LSA, would need to know which pictures contained rabbits and which did not. Similarly, it would need to know which words needed to be associated with which pictures. See Glenberg and Robertson (2000) for further discussion and empirical evidence.

and behavior evolved by selection for survival, that is, they are in the service of action that enhances survival and reproduction.[2] To the extent that cognition evolved, it too must serve effective action, and take into account the body. In escaping a predator, it would do a mole no good to ignore its body and try to fly. Similarly, if humans are to survive they cannot ignore their embodiment. Thus, the **embodied approach to cognition asserts that all cognitive processes are based on sensory, motor, and emotional processes, which are themselves grounded in body morphology and physiology. Within this framework, the goal of cognition is effective action in the service of survival and reproduction.**

Much of the remainder of this essay will demonstrate how these claims about human thought can be aligned with the cherished and seemingly obvious beliefs that thought is abstract and independent of perception and action. To do that, I will briefly discuss the embodiment of perception, object representation, language, and goals. The curious reader can also read about attempts to use embodiment to explain aspects of culture (Soliman, Gibson, & Glenberg, 2013). This review is followed by a sketch for how cognition can be unified by a focus on prediction.

Embodiment in Perception and Action

In 1979, Gibson introduced that term “affordance” to capture the relations between the body, objects, action, and perception. As an example, chairs afford

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[2] How then, can we explain behaviors like over-eating and taking drugs that decrease survival? Two of the many arguments are: 1) Behaviors like over-eating do arise from an evolutionary imperative for high-calorie foods, but that imperative evolved in a different ecology, one in which high-calorie foods were rare. 2) Evolution need not hard-wire every behavior. Instead, for humans, evolution resulted in a plastic brain that learns. But given the probabilistic nature of stimuli and reinforcements, not all learned behavior will be beneficial in all environments.

sitting-on, but only for animals with certain types of bodies, namely human-like bodies. Humans perceive that affordance, but an elephant, for example, would not. A child might perceive that a kitchen chair also affords hiding-under in a game of hide-and-seek, but an adult would not because the adult has the wrong type of body to squeeze under a chair. Thus, the affordance hypothesis is that we perceive what is needed to guide action, and those perceptions are determined by our bodies, including morphology, physiology, and previously learned behaviors. This is not to say that an adult (for example) cannot understand that a chair is hiding place for a child. But this sort of understanding makes use of simulation (see the discussion of embodiment and language) which is itself embodied.

Over the past few decades, researchers have convincingly demonstrated the role of affordances in perception. For example, Proffitt (2006) reviews research showing how perception of slant of hills reflects physiological capabilities: When tired, or when wearing a heavy backpack, a hill looks steeper. When holding a tool that extends the reach, distances look shorter (Witt, Proffitt, & Epstein, 2004). Tucker and Ellis (1998) demonstrated how looking at the picture of an object (e.g., a teacup with a handle) automatically primes the motor system, a phenomenon called motor resonance. Bub and Masson (2012) write that "Motor resonance, far from being an epiphenomenon, is rooted in the conceptual organization of the lexicon," and Yee, Chrysikou, Hoffman, and Thompson-Schill (2013) demonstrate how manual experience shapes object representations and motor resonance.

There are striking reports of how changing the body changes perception. For example, Arrighi, Cartocci, and Burr (2011) studied perception in paraplegics who had lost the use of their legs in accidents. Although the patients showed little disruption of visual acuity, their perception of point-light walkers was severely disrupted. That is, because they could no longer use their motor systems for walking, those systems could not play their usual role in the perception of walking -- motor resonance was disrupted (see mirror neurons, Rizzolatti & Craighero, 2004; Rizzolatti & Sinigaglia, 2010). Van der Hoort, Guterstam, and Ehrsson (2011) were able to demonstrate a related phenomenon. A volunteer was equipped with a head-mounted display that projected either the legs of a giant or the legs of a doll where the volunteer's own legs would be. When the volunteer viewed the artificial legs being stroked, they felt their own legs being stroked, inducing an illusion of body size change. Amazingly, this change in body size induced a change in perception: With large bodies, distances seemed closer, and with small bodies distances seemed farther. That is, we use our own bodies to perceive distances. These effects are consistent with Proffitt and Linkenauger's (2013) claim that perception is scaled by aspects of the body.

Embodiment in Language Comprehension

Language comprehension is not the arrangement of abstract symbols (such as words or lemmas) into syntactic patterns. Instead, comprehension is a simulation process. That is, when understanding, we simulate the content of the language using bodily and neural systems of action, perception, and emotion. Sometimes this simulation is conscious, but often it is not and must be revealed using behavioral or imaging procedures.

Action. Glenberg and Kaschak's (2002) action-sentence compatibility effect (ACE) was among the first behavioral demonstrations of the relation between action and language. Participants read sentences describing transfer toward the reader (e.g., “Art gives you the pen”), away (e.g., “You give Art the pen”), or nonsense (e.g., “You give the pen Art”). The task was to read the sentence and then to indicate if it was sensible by moving to and depressing a yes button or a no button. For half the participants, the yes button required a movement away from the participant’s body, and for the other half, the yes button required a movement toward the body. The ACE was the interaction between sentence direction and action direction: When the two were congruent (e.g., both away), responding was faster than when the two were incongruent. Apparently, participants were using the motor system to simulate the action of the sentence while understanding, and this simulation primed movement in the congruent direction.

But does the ACE reflect comprehension or does it show interference in movement after the sentence is comprehended (Mahon & Caramazza, 2008)? Subsequent research has converged on the former. For example, using transcranial magnetic stimulation, Glenberg et al. (2008) showed increased electrical activity in hand muscles while reading transfer sentences compared to control sentences. Glenberg, Sato, and Cattaneo (2008) further demonstrated that fatiguing (or adapting) the action system (e.g., by moving 600 beans individually from one container to another) slowed comprehension of sentences describing transfer in the same direction.

One of the clearest demonstrations of the use of the motor system in language understanding is provided by Hauk, Johnsrude, and Pulvermüller (2004). Participants listened to action words such as "lick," "pick," and "kick" while their brains were being imaged using fMRI. When listening to a verb describing mouth actions (e.g., "lick"), areas of motor cortex that control the mouth were particularly active; when listening to verbs describing hand actions, areas of motor cortex controlling the hand were active; and similar effects were found for verbs describing leg actions.

Perception. Zwaan and his colleagues have been resourceful in demonstrating perceptual effects during language comprehension. In an early demonstration, Stanfield and Zwaan (2001) had people determine if a picture was of an object named in a preceding sentence. Consider sentences such as "The ranger saw the eagle in the sky" and "The ranger saw the eagle in the nest" followed by a picture of an eagle with outstretched or folded wings. Although both pictures match the word ("eagle") in both sentences, speed of responding was determined by whether the picture matched the simulation. That is, a picture of an eagle with outstretched wings was responded to more quickly following the sentence describing an eagle in the sky compared to in the nest (and vice versa).

Rueschemeyer, Glenberg, Kaschak, Mueller, & Friederici, (2010) helped to pin down the claim that perceptual systems are used in the simulation process. When reading sentences describing visual motion (e.g., "The car is coming toward you"), they found greater activity in area MT/V5 (associated with the processing of real visual motion) then when reading sentences describing a static visual scene.

Emotion. Language is often used to convey events with emotional connotations. For these sorts of sentences, simulation theory predicts that bodily and neural systems of emotion join with sensorimotor systems in producing the simulation. Havas, Glenberg, Gutowski, Lucarelli, and Davidson (2010) were able to demonstrate this engagement using a type of natural (or unnatural, if you will) experiment. The participants were women receiving cosmetic Botox treatments in the corrugator (frowning) muscle of the forehead. The Botox paralyzes the muscle, which then reduces lines in the forehead, but it also makes it impossible for the muscle to be used in frowning. That is, the muscle can no longer contribute to simulations of anger and sadness. As predicted, injection of Botox in the corrugator muscles slowed comprehension of sentences describing angry and sad situations, but not happy situations.

Abstract language. Importantly, there have now been a number of demonstrations of embodied understanding of sentences describing abstract situations. Among those are Glenberg and Kaschak (2002) and Glenberg et al., (2008). A particularly impressive set of findings was reported by Urrutia, Gennari, and de Vega (2012). Participants read counterfactual sentences (e.g., "If Mary had cleaned the room, she would have moved the sofa") that differed in the amount of effort required in the situation described (e.g., "moved the sofa/photograph"). Thus the sentences described situations that had never occurred, and hence are abstract, and they differed in regard to implied forces, another abstract concept. Nonetheless, fMRI data indicated that participants used parts of the motor system to construct a simulation and that the simulation reflected the presumed effort.

Principles of embodied cognition have also been applied to the learning of abstract ideas in educational settings. In brief, the embodied notion is that the abstract symbols of education—words, syntax, mathematical notation—must be grounded in the body for students to make sense of those symbols (Glenberg, 2008). A powerful demonstration of this principle is provided by Kontra, Lyons, Fischer, and Beilock (in press). Their research examined processes of learning about the seemingly abstract concepts of torque and angular momentum. Participants first read a description of angular momentum. After an initial test, the participants either a) directly experienced torque and angular momentum by holding and manipulating spinning bicycle wheels or b) observed while their partner held and manipulated the wheels. These experiences were followed by a posttest. Participants with direct experience improved from the initial test to the posttest, whereas the observers did not. Furthermore, in one experiment, participants took the posttest while brain activity was monitored by fMRI. There was a correlation of .58 between activity in motor regions of the brain and performance on the posttest. That is, understanding the "abstract" concept of angular momentum was facilitated by an embodied simulation using the motor system.

The embodiment of goals and causation

The notion of goals and intentions seem particularly abstract. Nonetheless, it appears that we can often infer other people's goals and intentions from just watching them act. Do we use a set of abstract principles to make these inferences? In fact, the answer is simpler and more elegant: We can often infer goals and intentions using a motor resonance process (Gallese, Keysers, & Rizzolatti, 2004;

Rizzolatti & Craighero, 2004; Rizzolatti & Sinigaglia, 2010). Visually perceiving an action activates neurons (mirror neurons) in our own motor system, which are also activated when we take that or a similar action. This mirror neuron activation appears to encode the goal of the action that we have when performing the action in context. Note that this resonance process requires that we have the motor competence to complete the action, thus developmental psychologists who study the acquisition of motor competence have been able to make impressive contributions to understanding of goals. (See the following discussion of Osiurak and Badets (2014) for a sensorimotor account of goals in the absence of motor competence.)

As an example, consider the "sticky mittens" procedure used by Sommerville, Woodward, and Needham (2005) to study goals in three-month old infants. These infants do not usually have the motor competence to hold and manipulate objects. However if the infant wears mittens with a Velcro surface and swipes at an object with a complementary surface, then the object can be brought under control and examined by the infant. In the experiments, half the children did exactly that and acted on a ball and a teddy bear. The infants then repeatedly saw a mittened hand reach for one of the objects (e.g., the ball), until the infants habituated and stopped looking. Next, the infant saw one of two events. A *new goal* event showed the mittened hand make the same movement, but now the movement was toward a new goal (e.g., the teddy bear). A *new path* event showed the mittened hand make a different movement, but end at the same goal (e.g., the ball, again). The question is which of these new events will attract the infant's attention, that is, which is treated as different from the habituated event of watching the mittened hand reach for the ball? Those infants without the sticky mitten experience paid equal (and modest) attention to the *new goal* and *new path* events. For the infants given experience with the sticky mittens, however, their attention was strongly attracted by the *new goal* event. That is, the infants who had developed some motor competence with the objects were able to discriminate between the goal of reaching for a ball and the goal of reaching for a teddy bear. For these infants, goals reflected (and perhaps were constituted by) motor competence.

Other sticky mitten research has demonstrated contributions of motor competence to cognitive skills long considered abstract. For example, Rakison and Krogh (2010) demonstrated the role of motor competence in understanding causal situations. Möhring and Frick (2013) demonstrated a contribution of motor competence to skill in mental rotation.

Masson (2015) discusses data in Osiurak and Badets (2014) that seem to demonstrate that goals are abstract, rather than embodied. In their experiment, participants were primed to open or close pliers, but the pliers could be normal (which close by closing the hand) or inverse (which close by opening the hand). The "opening" or "closing" prime was beneficial when it matched the goal (e.g., close the pliers) rather than the required hand action. These data are consistent with the claim that not all goals are represented by movements. But, do the data imply that goals are abstract, that is, non-embodied? In fact, as discussed by Osiurak and Badets, these data are compatible with the embodied ideomotor principle, namely, that goals are encoded in terms of expected sensory effects. In this case, the goal of "opening" is represented as the visual sensory state corresponding to open pliers, regardless of the specific movements required to get the pliers open. Osiurak and Badets go on to quote Mechsner, Kerzel, Knoblich, and Prinz (2001) "…voluntary movements are, in general, organized by way of a simple representation of the perceptual goals…" (p. 72). Thus, not all goals are encoded as movements, but the data are consistent with the claim that goals are embodied, that is, sensori (perceptual)-motor.

Is there a coherent account?

Demonstrations of the importance of embodiment are becoming increasingly frequent. At the same time, there has been a growing criticism that the demonstrations do not provide a unified account of cognition comparable to that provided by the PSSH. But one such account, based on the notion of prediction, is taking shape.

How is prediction embodied? First, action control (and the motor system) is intimately concerned with prediction. That is, every action is accompanied by predicted changes in our proprioception and perception of the world so that the system can determine if the action was successfully completed. For example, in reaching for a glass of water, the system predicts how far the arm will have to reach, how wide the fingers need to open, and the feel of the cool, smooth glass.

When predictions match the sensory consequences, those consequences are cancelled (or their importance reduced) to reduce information overload. One demonstration of this cancelling is the inability to tickle oneself (Blakemore, Goodbody, & Wolpert, 1998). Vision provides another demonstration. Close one eye and sweep the other back and forth across the visual field. Although stimulation on the retina changes radically when the eye moves, the world appears stable. That stability comes about because predictions based on the planned eye movements are used to cancel the sense of movement that would otherwise accompany changes in the visual field. That is, the perceptual system correctly attributes the changes to self-movement rather than to movement of the world. What happens when cancelling based on prediction fails? To literally see the result, move your one open eye by nudging it with a finger. Now the world seems to jump around with each nudge. Because there is no eye movement signal from which predictions can be made, the changes on the retina (due to the nudge) cannot be cancelled, and hence the perceptual system attributes the changes to instability in the world.

Note that predictions of this sort are usually not consciously experienced, probably take little effort, and are fast and automatic, at least in highly practiced domains of action such as grasping and eye movements. Furthermore, prediction ties action to perception and vice versa. As with the eye-movement example, the predictions are about how the world will look (after action). Eder, Rothermund, De Houwer, and Hommel (in press) have proposed that a similar mechanism may fuse emotion into the action/perception representations, and Wolpert, Doya, and Kawato (2003) describe how the prediction model can be applied to social interactions.

The notion of prediction has been used to develop accounts of action control (Wolpert & Kawato, 1998), imagery (Grush, 2004), language perception and production (Pickering & Garrod, 2013), and language comprehension (Glenberg &

Gallese, 2012). Clark, (2013) proposes a unified account of prediction and suggests that "Such accounts offer a unifying model of perception and action, illuminate the functional role of attention, and may neatly capture the special contribution of cortical processing to adaptive success." Thus, although the very notion of prediction seems non-embodied (unrelated to sensory, motor, and emotional systems), in fact prediction is at the core of those systems and ties them together to promote coherent perception and effective action.

Do non-embodied systems play any role in cognition?

This is still an open question. Nonetheless, it is hard to see a role for non-embodied systems. By non-embodied, I mean systems (representations or processes) that are unrelated to perception, action, and emotion, for example the classic symbol systems envisioned by PHHS. From the perspective of evolution, it is hard to see how those sorts of systems could arise. They are even harder to understand from a functional perspective. What role is there for a system that does not contribute to perception and action? Furthermore, if one proposes that a non-embodied system does contribute to perception and action, there is a difficult engineering problem: how does the non-embodied system connect to the embodied system to control action? Descartes suggested communication through the pineal gland. Modern-day Cartesians who propose abstract symbol systems haven't offered a much better explanation. This problem is made even more puzzling by the data reviewed above indicating that embodied systems do just fine accounting for perception, action, concrete cognition, and abstract cognition (see also Barsalou's, 1999, arguments for the formal adequacy of perceptual symbol systems for abstract thought).

Some domains of cognition do seem to be particularly abstract and, one might wonder if they are non-embodied. With some thought, however, even these domains can aligned with embodiment. For example, mathematics seems to be particularly abstract. But, empirical work has now demonstrated how the body is involved in simple mathematics (Adriano, Diez, & Fernandez, 2014; Andres, Seron, & Olivier, 2007; Sato, Cattaneo, Rizzolatti, & Gallese, 2007), intermediate mathematics such as algebra (Landy, Brookes, & Smout, 2014), and even advanced mathematics involving imaginary numbers (Nemirovsky, Rasmussen, Sweeney, & Wawro, 2012). Another domain that seems particularly abstract is statistical learning, that is, the ability of infants and adults to learn the statistical structure of a domain through simple exposure. But even here, there is some work supporting an embodied basis for this form of learning (Marsh & Glenberg, 2010).

Nonetheless, it is probably impossible to empirically demonstrate that abstract representations and processes play no role in cognition. In part this is because science does not have the tools to prove non-existence. Another difficulty in ruling out abstract representations is related to the philosophical concept of constitution (e.g., Shapiro, 2011). That is, as scientists we can demonstrate causal connections (e.g., between sensorimotor system activation and understanding). But, we do not have the tools to show that sensorimotor system activation constitutes cognition, that is, that the sensorimotor activation *is* cognition. Consequently, we are left with an argument based on simplicity: Given that embodied constructs can explain cognition and action, there is no need to invoke abstract symbols.

In the early days of embodiment research, cognitive scientists were skeptical: At one conference, a prominent cognitive scientist publicly suggested that notions of embodiment were the equivalent of “fairy dust” and challenged researchers to demonstrate the validity of the ideas. Using the methods of science, the field rose to that challenge. Now the onus is on traditional cognitive scientists, those who wish to maintain a Cartesian distinction between human thought and action, a cherished and seemingly obvious belief, but ultimately, a type of flat-world hypothesis.

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