

Grounded Cognition

Lawrence W. Barsalou

Department of Psychology, Emory University, Atlanta GA 30322
email: barsalou@emory.edu

May 30, 2007

Annual Review of Psychology, volume, 59, 2008

Key Words

cognitive architecture, imagery, representation, simulation, situated action

Abstract

Grounded cognition rejects traditional views that cognition is computation on amodal symbols in a modular system, independent of the brain's modal systems for perception, action, and introspection. Instead, grounded cognition proposes that modal simulations, bodily states, and situated action underlie cognition. Accumulating behavioral and neural evidence supporting this view is reviewed from research on perception, memory, knowledge, language, thought, social cognition, and development. Theories of grounded cognition are also reviewed, as are origins of the area and common misperceptions of it. Theoretical, empirical, and methodological issues are raised whose future treatment is likely to affect the growth and impact of grounded cognition.

Contents

WHAT IS GROUNDED COGNITION?
THEORIES OF GROUNDED COGNITION
EMPIRICAL EVIDENCE
THEORETICAL AND EMPIRICAL ISSUES
METHODOLOGICAL ISSUES

WHAT IS GROUNDED COGNITION?

Standard theories of cognition assume that knowledge resides in a semantic memory system separate from the brain's modal systems for perception (e.g., vision, audition), action (e.g., movement, proprioception), and introspection (e.g., mental states, affect). According to standard theories, representations in modal systems are transduced into amodal symbols that represent knowledge about experience in semantic memory. Once this knowledge exists, it supports the spectrum of cognitive processes from perception to thought.

Conceptions of grounded cognition take many different forms (Gibbs, 2006; Wilson, 2002). In general, however, they reject the standard view that amodal symbols represent knowledge in semantic memory. From the perspective of grounded cognition, it is unlikely that

the brain contains amodal symbols; if it does, they work together with modal representations to create cognition.

Some accounts of grounded cognition focus on roles of the body in cognition, based on widespread findings that bodily states can cause cognitive states and be effects of them (e.g. Barsalou et al., 2003; Lakoff & Johnson, 1980; L. Smith, 2005b). Most accounts of grounded cognition, however, focus on the roles of simulation in cognition (e.g., Barsalou, 1999; Decety, & Grèzes, 2006; Goldman, 2006). Simulation is the reenactment of perceptual, motor, and introspective states acquired during experience with the world, body, and mind. As an experience occurs (e.g., easing into a chair), the brain captures states across the modalities, and integrates them a multimodal representation stored in memory (e.g., how a chair looks and feels, the action of sitting, introspections of comfort and relaxation). Later, when knowledge is

needed to represent a category (e.g., *chair*), multimodal representations captured during experiences with its instances are reactivated to simulate how the brain represented perception, action, and introspection associated with it.

According to this account, a diverse collection of simulation mechanisms, sharing a common representational system, supports the spectrum of cognitive activities. The presence of simulation mechanisms across diverse cognitive processes suggests that simulation provides a core form of computation in the brain. Mental imagery constitutes the best known case of these simulation mechanisms (e.g., Kosslyn, 1980, 1994). Whereas mental imagery typically results from deliberate attempts to construct conscious representations in working memory, other forms of simulation often appear to become active automatically and unconsciously outside working memory.

Still other accounts of grounded cognition focus on situated action, social interaction, and the environment (e.g., Barsalou, 2003; Barsalou, Breazeal et al., in press; Glenberg, 1997; Rizzolatti & Craighero, 2004; W. Prinz, 1997; Robbins & Aydede, in press; E. Smith & Semin, 2004; Yeh & Barsalou, 2006). From this perspective, the cognitive system evolved to support action in specific situations, including social interaction. These accounts stress interactions between perception, action, the body, the environment, and other agents, typically during goal-achievement.

It is important to note that the phrase, “embodied cognition,” is often used when referring to this collection of literatures. Problematically, however, “embodied cognition” produces the mistaken assumption that all researchers in this community believe that bodily states are necessary for cognition and that these researchers focus exclusively on bodily states in their research. Clearly, however, cognition often proceeds independently of the body, and many researchers address other forms of grounding. “Grounded cognition” reflects the assumption that cognition is typically grounded in multiple ways, including simulations, situated action, and, on occasion, bodily states. Perhaps grounding will one day become such a widely-accepted assumption that “grounded” falls away, leaving “cognition” and thereby solving this problem.

Origins of Grounded Cognition

Perhaps surprisingly, grounded cognition has been the dominant view of cognition for most of recorded history. Nearly all pre-scientific views of the human mind going back to ancient philosophers (e.g., Epicurus, 341-270BC/1987) assumed that modal representations and imagery represent knowledge (Barsalou, 1999; J. Prinz, 2002), analogous to current simulation views. Even nativists, such as Kant (1787/1965) and Reid (1785/1969), frequently discussed modal images in knowledge (among

other constructs).

In the early 20th century, behaviorists attacked late 19th century studies of introspection, banishing imagery from much of psychology for not being sufficiently scientific, along with other cognitive constructs (Watson, 1913). When cognitive constructs reemerged during the Cognitive Revolution of the mid-20th century, imagery was not among them, probably for two reasons. First, the new cognitivists remembered Watson’s attacks on imagery and wanted to avoid the same criticisms. Second, they were enthralled with new forms of representation inspired by major developments in logic, linguistics, statistics, and computer science. As a result, theories of knowledge adopted a wide variety of amodal representations, including feature lists, semantic networks, and frames (Barsalou & Hale, 1993).

When early findings for mental imagery were reported in the 1960s (Paivio, 1971; Shepard & Cooper, 1982), the new cognitivists dismissed and discredited them (e.g., Pylyshyn, 1973). Nevertheless, the behavioral and neural evidence for imagery eventually became so overwhelming that imagery is now accepted as a basic cognitive mechanism (Kosslyn et al., 2006).

Most recently, research in grounded cognition has challenged theories that originated during the Cognitive Revolution on numerous grounds (e.g., Barsalou, 1999; Glenberg, 1997; Harnad, 1990. Lakoff, 1987; Searle, 1980). First, little empirical evidence supports the presence of amodal symbols in cognition. Instead, amodal symbols were adopted largely because they provided elegant and powerful formalisms for representing knowledge, because they captured important intuitions about the symbolic character of cognition, and because they could be implemented in artificial intelligence. Second, traditional theories have been challenged on the grounds that they fail to explain how cognition interfaces with perception and action (the grounding problem). Third, traditional theories increasingly face a lack of understanding about where the brain stores amodal symbols, and about how amodal symbols could be consistent with neural principles of computation.

In place of traditional theories, researchers in grounded cognition have turned away from amodal symbols, focusing instead on simulation, situated action, and bodily states. In many respects, these researchers have rediscovered the classic philosophical assumption that modal representations are central to knowledge, reinventing this assumption in the modern contexts of psychology, cognitive science, and neuroscience. As a result, grounded theories focus increasingly on neural representations in the modalities, and less on conscious imagery.

Common Misperceptions of Grounded Cognition

Because modern grounded approaches are so new, we are far from having a unified view. Furthermore, the diverse approaches that exist are not specified

computationally or formally. For these reasons, vagueness exists and misperceptions follow.

Grounded theories are often viewed as completely empiricist and therefore inconsistent with nativism. As noted earlier, however, classic nativists assumed that imagery played central roles in knowledge. Indeed, there are no a priori reasons why simulation cannot have a strong genetic basis. Genetic contributions almost certainly shape the modal systems and memory systems that capture and implement simulations. Some simulations could have a genetic basis.

Grounded theories are often viewed as recording systems that only capture images (e.g., cameras) and are unable to interpret these images conceptually (e.g., Haugland, 1991; Pylyshyn, 1973). As described later, however, grounded theories are capable of implementing the classic symbolic functions that underlie conceptual interpretation (e.g., Barsalou, 1999, 2005a).

Grounded theories are often viewed as only using sensory-motor representations of the external world to represent knowledge. As a result, it is argued that grounded theories cannot represent abstract concepts not grounded externally. Importantly, however, embodiment researchers since the classic empiricists have argued that internal states such as meta-cognition and affect constitute sources of knowledge no less important than external experience. Recent embodiment theorists propose that knowledge acquired from introspection is central to the representation of abstract concepts (e.g., Barsalou, 1999; Barsalou & Wiemer-Hastings, 2005).

Finally, grounded theories are often viewed as necessarily depending on bodily states or full blown simulations that recreate experience. Researchers in grounded cognition make neither assumption. Bodily states are not necessary for cognitive activity, although they can be closely related to it. Although simulation is a central construct, these researchers agree that simulations rarely, if ever, recreate full experiences. Instead, simulations are typically partial recreations of experience that can contain bias and error (e.g., Barsalou, 1999).

THEORIES OF GROUNDED COGNITION

All grounded theories represent negative reactions to standard theories of cognition based on amodal symbols. Additionally, grounded theories contain insights about mechanisms central to cognition that standard theories have largely ignored, such as simulation, situated action, and bodily states. Although most theories have been descriptive, they have nevertheless generated testable hypotheses addressed in empirical research. Clearly an important goal for future theory is to implement and formalize these theories.

Cognitive Linguistics Theories

Some of the first theories to champion grounded

cognition in modern times arose in cognitive linguistics. These theories were negative reactions to amodal theories of syntax originating in the Cognitive Revolution (e.g., Chomsky, 1957). Positively, these theories championed the roles of bodies, situations, and simulations in language.

Lakoff and Johnson (1980, 1999) proposed that abstract concepts are grounded metaphorically in embodied and situated knowledge (also see Gibbs, 1994). Specifically, these researchers argued that people possess extensive knowledge about their bodies (e.g., eating) and situations (e.g., verticality), and that abstract concepts draw on this knowledge metaphorically. For example, love can be understood as eating (“being consumed by a lover”), and affective experience can be understood as verticality (“happy is up, sad is down”). Extensive linguistic evidence across languages shows that people talk ubiquitously about abstract concepts using concrete metaphors. Such metaphors also arise extensively in literature (e.g., Turner, 1996). A key issue is whether these metaphors simply reflect linguistic convention, or whether they actually represent how people think (e.g., Murphy, 1997). Increasing evidence suggests that these metaphors play central roles in thought (e.g., Boroditsky & Ramscar, 2002; Gibbs, 2006).

Other theories in cognitive linguistics have grounded the syntax and semantics of natural language in components of experience, such as paths, spatial relations, processes, and forces (e.g., Lakoff, 1987; Langacker 1987, 1991; Talmy, 1983, 1988). Cognitive linguists have also grounded reasoning in experience (e.g., Fauconnier, 1985). Other cognitive linguists have developed grammars that use frames and constructions to capture the structure of situations (e.g., Fillmore, 1985; A. Goldberg, 1995). All these theories provide rich sources of hypotheses for scientific research (e.g., Coulson, 2001; Kaschak & Glenberg, 2000; Kemmerer, 2006; Tomasello, 2003).

Theories of Situated Action

These theories reflect another reaction to standard theories of cognition, again rejecting the idea that cognition revolves around computation on amodal symbols. Positively, many of these theories focus on the central roles of perception and action in cognition.

Following Gibson (1979), theories of situated action propose that the environment plays central roles in shaping cognitive mechanisms. Additionally, these theories focus on the close coupling of perception and action during goal achievement (e.g., Clark, 1997; W. Prinz, 1997; Thelen & L. Smith, 1994; Steels & Brooks, 1995), and increasingly on social interaction (e.g., Breazeal, 2002). Many of these theories have originated in robotics. As a result, they are implemented computationally in robots operating in the physical world with other agents. Robotics provides a powerful test bed for developing and evaluating grounded theories of cognition that attempt to explain unified agents, not just component processes (Barsalou, Breazeal et al., in

press).

Rather than adopting computational architectures that manipulate amodal symbols, theories of situated action often adopt dynamic systems as their architecture. From this perspective, fixed representations do not exist in the brain. Instead, multiple systems implement perception, action, and cognition, where each system is capable of residing in one of infinitely many continuous states. Over learning, states of these systems become coupled to reflect patterns of interaction with each other and with the environment effective in achieving goals (attractors). Such theories have been applied to perception and action (e.g., Van Orden et al., 2002), development (e.g., Thelen et al., 2001), and cognition (e.g., Spivey, 2007).

Cognitive Simulation Theories

Perceptual Symbol Systems. The attacks on standard theories from cognitive linguistics, situated action, dynamic systems, and elsewhere might suggest that standard theories have nothing to offer. To the contrary, Barsalou's (1999) theory of Perceptual Symbol Systems (PSS) argued that traditional approaches are correct in postulating the importance of symbolic operations for interpreting experience (Pylyshyn, 1973; Fodor & Pylyshyn, 1988). Although grounded theories are viewed widely as recording systems (Haugeland, 1991), PSS demonstrated that grounded theories can implement symbolic functions naturally (also see Barsalou, 2005a, in press). Through the construct of simulators—corresponding roughly to concepts and types in standard theories—PSS implements the standard symbolic functions of type-token binding, inference, productivity, recursion, and propositions. This approach retains the symbolic functionality of traditional theories but implements it differently, using simulation and dynamic systems. Thus, PSS is a synthetic approach that integrates traditional theories with grounded theories.

PSS further assumes that a single, multimodal representation system in the brain supports diverse forms of simulation across different cognitive processes, including high-level perception, implicit memory, working memory, long-term memory, and conceptual knowledge. According to PSS, differences between these cognitive processes reflect differences in the mechanisms that capture multimodal states and simulate them later. In high-level perception and implicit memory, association areas in a modality capture representations (e.g., in vision) and later trigger simulations that produce perceptual completion, repetition priming, etc. Working memory utilizes the same representation system but controls it differently during simulation, using frontal mechanisms to keep a modal representation active temporarily. Long-term memory again utilizes the same representation system to simulate episodic events but controls it via medial temporal systems and different frontal areas. Finally, conceptual knowledge uses the same representational

system to simulate knowledge, but, controls it via association areas in the temporal, parietal, and frontal lobes. According to PSS, simulation is a unifying computational principle across diverse processes in the brain, taking different forms for each. The convergence zone architecture proposed by Damasio (1989) and extended by Simmons and Barsalou (2003) offers one way to implement a single representation system controlled by multiple simulation mechanisms.

Barsalou (2003) integrated PSS with situated cognition, proposing that simulations typically contextualize the categories that they represent in background situations, which include objects, agents, actions, events, and mental states (also see Yeh & Barsalou, 2006). Barsalou et al. (2003) similarly proposed that situated simulations explain embodiment effects in social psychology through a pattern-completion inference mechanism.

In humans, the simulation system central to PSS is closely integrated with the linguistic system. Paivio (1971, 1986) developed an account of how language and simulation interact—Dual Code Theory—and amassed considerable evidence for it. Glaser (1992) and Barsalou, Santos et al. (in press) offered revisions of this theory that place deep conceptual processing in the simulation system, not in the linguistic system. Barsalou (2005b) further proposed that non-humans have roughly the same simulation system as humans, but lack a linguistic system to control it. Barsalou (in press) proposed that humans' powerful symbolic capabilities emerge from interactions between language and simulation.

Memory theories. Glenberg (1997) argued that traditional accounts of memory focus too much on the passive storage of information and too little on the importance of situated action. Glenberg proposed that memory primarily serves to control situated action, and that the patterns stored in memory reflect the nature of bodily actions and their ability to mesh with situations during goal pursuit. Similar to Gibson (1979), the perception of relevant objects triggers affordances for action stored in memory. Conversely, reasoning about future actions relies on remembering affordances while suppressing perception of the environment (Glenberg et al., 1998).

Rubin (2006) argued that traditional accounts of memory are limited by only attempting to explain simple laboratory paradigms. When richer forms of memory are considered, such as autobiographical memory and oral history, more complex theories are required. Rubin proposed Basic Systems Theory as an account of complex memory phenomena. Similar to PSS and its situated extensions, Basic Systems Theory proposes that a complex memory contains many multi-modal components from vision, audition, action, space, affect, language, etc., and that retrieving a memory involves simulating its multimodal components together. Conway (1990, 2002)

similarly stressed the centrality of multi-modal representations in autobiographical memory.

Social Simulation Theories

Simulation plays increasingly important roles in theories of social cognition (Goldman, 2006). Of particular interest is explaining how we represent the mental states of other people. Simulation theories propose that we represent other people's minds using simulations of our own minds. To feel someone else's pain, we simulate our own pain.

Mirror neuron circuits typically underlie social simulation theories. In primates, a subset of the neural circuit used to manipulate objects becomes active when perceiving another agent perform an action to achieve a goal (Rizzolatti & Craighero, 2004). To recognize and understand another agent's action, primates simulate the perceived action in their own motor system. Notably, mirror neurons within these circuits respond strongest to the goal of the action, not to the action itself. Thus, mirror circuits help perceivers infer an actor's intention, not simply recognize the action performed.

More generally, social neuroscientists propose that mirror circuits provide a general mechanism for understanding diverse mental states in others (e.g., Decety, & Grèzes, 2006; Gallese et al., 2004; Iacoboni, in press). To understand how someone else feels when disgusted, we simulate how we feel when disgusted. From this perspective, simulation provides a general mechanism for establishing empathy. Simulation theorists further propose that simulation supports other important social processes, such as imitation and social coordination. Some simulation theorists propose that mirror circuits contributed to the evolution of human language (Arbib, 2005; Rizzolatti & Arbib, 1998).

EMPIRICAL EVIDENCE

Surprisingly little research has attempted to test the widely accepted assumption that amodal symbols represent knowledge. Indeed, hardly any research before the last ten years attempted to directly assess the format in which knowledge is represented (e.g., amodal symbols, simulation). Furthermore, relatively little research assessed other aspects of the grounded view, such as the roles of situations and bodily states in cognition. During the past ten years, however, many researchers have designed experiments to assess grounded theories explicitly. The results of these experiments suggest increasingly that simulations, situations, and bodily states play central roles in cognition. Because of space limitations, many important findings are not cited.

Perception and Action

Perceptual inference. The simulation process central to accounts of grounded cognition plays ubiquitous roles in perception. During perception, states of perceptual systems become stored in memory (e.g., for

vision and audition). Similar stimuli perceived later trigger these memories, simulating the perceptual states they contain. As these simulations become active, they produce perceptual inferences that go beyond perceived stimuli in useful ways.

Goldstone (1995) taught people simple associations between a shape (e.g., square) and a color (e.g., dark red). Later, when a colored shape was flashed (e.g., a red square), and participants had to reproduce its color, they distorted the color towards the prototypical color associated with the shape seen earlier. Perceiving the object's shape activated a simulation of its prototypical color, which then distorted perception of the current color. Hansen et al. (2006) similarly showed that simulations of an object's natural color (e.g., yellow for banana) distort achromatic perception of the object (e.g., a gray banana) toward the opponent color (e.g., a bluish banana).

During the perception of motion, visual simulations similarly arise that go beyond the physical motion present. In motion continuation, viewers simulate the visual trajectory of an object beyond its actual trajectory, falsely remembering anticipated motion (e.g., Freyd, 1987). Knowledge about whether an object moves quickly or slowly affects the perceived speed of these simulated trajectories (e.g., Reed & Vinson, 1996). During apparent motion, simulations of possible human action similarly shape perception of interpolated motion (e.g., Shiffrar & Freyd, 1990, 1993). Stevens et al. (2000) showed that simulations in the motor system underlie these inferences. Analogous simulations produce somatosensory anticipations of an object tracing a trajectory over the body (Blankenberg et al., 2006).

Lexical knowledge produces simulations that contribute to speech perception. In the phoneme restoration effect, listeners use auditory knowledge about a word to simulate a missing phoneme (e.g., Warren, 1970). Samuel (1997) showed that these simulations utilize early auditory systems.

Perception-action coordination. As people perceive visual objects, simulations of potential actions become active in preparation for situated action. Tucker and Ellis (1998) showed that the perceived handle of a cup activates a grasping simulation that inadvertently affects motor responses on an unrelated task. Tucker and Ellis (2001) showed that viewing an object grasped with a precision or power grip (e.g., a grape vs. a hammer) produces a simulation of the appropriate action. Symes et al. (2007) showed that these simulations are sensitive to whether an object's orientation makes it easily graspable. Glover et al. (2004) showed that the size of an object affects these simulations. Bub et al. (in press) showed that a perceived object (or object name) automatically triggers simulations of both grasping and functional actions. Tucker and Ellis (2004) also showed that these simulations occur when the name of an object is read (e.g., "grape"). Helbig et al. (2006) showed that action simulations speed

visual recognition of objects on which these actions are performed. Using fMRI, Chao and Martin (2000) showed that perceived objects activate the brain's grasping circuit (see Lewis, 2006, for a review).

Researchers increasingly extend these original findings in creative ways. In Bosbach et al. (2005), accurately judging the weight of an object lifted by another agent requires simulating the lifting action in one's own motor and somatosensory systems. In Repp and Knoblich (2004), a pianist's ability to identify auditory recordings of his or her own playing depends on simulating the motor actions underlying it. In Pulvermüller et al. (2006), hearing a word activates the articulatory actions associated with producing it. In Proffitt (2006), simulations of perceived effort affect visual perception (but not action guided movement). Being tired from a run makes a hill look steeper. Carrying a heavy pack makes a path look longer.

Motor simulations are also central to basic motor control. As a simple action is performed, the motor system constructs a feedforward simulation of the action to guide and correct it (e.g., Grush, 2004; Wolpert et al. 1999). These motor simulations also play roles in generating visual inferences about the anticipated actions of perceived agents (Wilson & Knoblich, 2005).

Perception of space. Rather than being isotropic, the perception of space is shaped by the body, the body's relation to the environment, and the body's potential for action (Franklin & Tversky, 1990). Locating objects along the vertical axis of the body is easiest because of the body's perceived asymmetry with respect to the ground. Locating objects along the front-back axis is next easiest because of the potential for action to the front. Locating objects along the left-right axis is most difficult because environmental and bodily cues are lacking. Longo and Laurenci (2007) found that people's perception of near space extends further outward as their arm length increases, suggesting that individual differences in bodies produce individual differences in space perception.

Memory

Implicit memory. Implicit memory appears closely related to perceptual inference. In both, perceptual memories become active and affect perception. As we just saw, simulations during perceptual inference create perceptions that go beyond stimulus information. In implicit memory, simulations increase perceptual fluency and the likelihood that perceptions are categorized correctly (i.e., repetition priming). If, for example, a perceived face activates an implicit memory, the face may be perceived more quickly and accurately.

Several general findings support the conclusion that implicit memory results from the simulation of perceptual memories (Roediger & McDermott, 1993; Schacter et al., 2004). First, perceptual processing is typically important for establishing robust implicit learning, suggesting that

perceptual memories are responsible (e.g., Jacoby, 1983). Second, repetition priming is strongest when the modalities of the memory and the perceived stimulus match, for example, when an auditory memory exists to help process an auditory stimulus (e.g., Kirsner et al., 1989). Third, repetition priming is strongest when perceptual details of the memory and perceived stimulus match, such as orientation, size, font, etc. (e.g., Jacoby & Hayman, 1987; Jolicoeur, 1985). Fourth, imagining a stimulus produces repetition priming similar to actually perceiving it, suggesting that shared perceptual representations underlie both (e.g., Roediger & Blaxton, 1987; Schacter & Graf, 1989). For all these reasons, the simulation of perceptual states appears central to implicit memory.

Explicit memory. Similar to implicit memory, conscious memory of previous episodes relies heavily on modal representations. Extensive reviews of supporting findings can be found in Paivio (1971, 1986), Conway (1990, 2002) and Rubin (2006), who build theories of explicit memory from this evidence. In general, these theories assume that multi-modal simulations of previous episodes are central to episodic recollection. Simulation also appears central to constructing future events based on memories of past events (Schacter & Addis, 2007).

Although particularly strong evidence for multi-modal simulation comes from research on autobiographical memory, even simple laboratory experiments demonstrate simulation. Consider experiments that manipulate whether words are studied visually or auditorally (e.g., Wheeler et al., 2000). When retrieval of these words is tested later in a scanner, visual areas become active following visual study, whereas auditory areas become active following auditory study. Thus, the retrieval of a word simulates the modal operations performed at encoding. Buckner and Wheeler (2001) review many such findings.

Within a single modality, the distributed brain states associated with studying different kinds of stimuli are simulated later at retrieval. Polyn et al. (2005) found that the distributed neural pattern associated with studying faces later reappeared when remembering them, as did the patterns for studying locations or objects. Kent and Lamberts (2006) similarly found that the speed of processing different perceptual dimensions at encoding was linearly related to the speed of processing them at retrieval.

Simulation also provides a natural explanation of various memory effects. Because a stimulus leaves memories in the modal areas that encoded it, greater activation in modal areas occurs when remembering something that actually occurred than when falsely remembering something that did not (Slotnick & Schacter, 2004). Remembering a stimulus specifically produces greater activation in modal areas than remembering it generally (Garoff et al., 2005). Simulating a scene at

encoding that extends the boundary of a studied picture produces reconstructive error later at retrieval (e.g., Intraub et al., 1998). Reinstating actions at retrieval performed earlier during encoding facilitates memory (Ross et al., in press).

Working memory. Neuroscience research with non-humans established the distributed neural circuits that store an absent stimulus in working memory (e.g., Levy & Goldman-Rakic, 2000). To maintain a working memory, neurons in the frontal lobes maintain a simulation of the absent stimulus in the modal system that processed it originally. More specifically, different regions of frontal cortex maintain working memories for different types of modal content. For example, some regions maintain working memories of objects, whereas others maintain working memories of spatial locations. Even more specifically, different populations of frontal neurons are highly selective for the specific features they maintain (Pasternak & Greenlee, 2005). For example, different frontal populations maintain working memories for motion in different directions, for textures of different spatial frequency, etc.

Research on imagery has further established the central role of modal simulation in working memory. Considerable behavioral evidence indicates that visual imagery in working memory simulates visual processing (e.g., Finke, 1989; Kosslyn, 1980; Shepard & Cooper, 1982). Neural evidence strongly corroborates this conclusion (e.g., Kosslyn et al., 2000). Analogously, motor imagery simulates motor processing (e.g., Grèzes & Decety, 2001; Jeannerod, 1995), and auditory imagery simulates auditory processing (e.g., Halpern et al., 2004).

When action is relevant to visual imagery, the motor system becomes engaged, consistent with theories of situated action. For example, when visual rotation of a body part is imagined, bodily constraints shape the rotational trajectory (e.g., Parsons, 1987a,b). Similarly, mental rotation of visual objects is accompanied by motor simulations of making them turn (e.g., Richter et al., 2000).

Knowledge and Conceptual Processing

Although simulation in working memory has been accepted for many years, simulation as the basis of knowledge representation is still considered a radical proposal. Nevertheless, considerable evidence now demonstrates the presence of simulation during conceptual processing.

Behavioral evidence. Researchers have used the property verification task to assess whether conceptual processing utilizes simulation. On each trial, the word for a category is presented (e.g., *HORSE*) followed by a word for a property that is either true or false of the category (e.g., *mane vs. horns*). According to standard theories, participants assess relations between amodal symbols for concepts and properties to verify properties. According to

grounded views, participants simulate the concept and the property and then assess whether the simulated property can be found in the simulated concept.

Consistent with the simulation view, Solomon and Barsalou (2004) found that perceptual variables such as size best predicted verification times and errors. As properties became larger, verifying them became more difficult, consistent with the finding that verifying properties perceptually becomes more difficult as properties become larger (cf. Morrison & Tversky, 1997). Solomon and Barsalou (2001) similarly found that property representations contain detailed perceptual information, difficult to verbalize, suggesting that participants simulated properties to verify them. Borghi et al. (2004) found that the positions of properties in space are simulated during their verification.

If participants simulate properties to verify them, then having to switch from one modality to another while simulating properties should incur a switching cost, analogous to the cost of switching attention from one modality to another in perception (e.g., Spence et al., 2000). Pecher et al. (2003, 2004) found support for this hypothesis, as did Marques (2006) and Vermeulen et al. (in press).

Lesion evidence. Neuropsychologists have reported that lesions in a particular modality increase the likelihood of losing categories that rely it for processing a category (e.g., Cree & McRae, 2003; Damasio & Damasio, 1994; Gainotti, 2006; Gainotti et al., 1995; Humphreys & Forde, 2001; Simmons & Barsalou, 2003; Warrington & McCarthy, 1987; Warrington & Shallice, 1984). For example, damage to visual areas increases the likelihood of losing *animals*, because visual processing is often the dominant modality for interacting with this category. Conversely, damage to motor areas increases the likelihood of losing *tools*, because motor processing is often the dominant modality. Similarly damage to color processing areas can produce deficits in color knowledge (e.g., Miceli et al., 2001), and damage to spatial processing areas can produce deficits in location knowledge (e.g., Levine et al., 1985). Additional research demonstrates that other mechanisms beside modal representations contribute to category-specific deficits (e.g., Caramazza & Shelton, 1998; Cree & McRae, 2003; Tyler et al., 2000; Simmons & Barsalou, 2003).

Neuroimaging evidence. Neuroimaging research further confirms that simulation plays a central role in conceptual processing (Martin, 2001, 2007). When conceptual knowledge about objects is represented, brain areas that represent their properties during perception and action become active. In particular, brain areas that represent the shape and color of objects (fusiform gyrus), the motion they exhibit (middle and superior temporal lobe), and the actions that agents perform on them (premotor and parietal areas) become active to represent these properties conceptually. When people perform the

property verification task described earlier, modal areas for the properties tested become active, including brain areas for shape, color, size, sound, taste, action, and touch (e.g., R. Goldberg et al., 2006; Kan et al., 2003; Kellenbach et al., 2001; Simmons et al., in press).

Further evidence comes from different profiles of multi-modal activation for different categories. When people process animals conceptually, visual areas are especially active; when people process artifacts, motor areas become active (e.g., Kiefer, 2005; Martin, 2001, 2007; Thompson-Schill, 2003). Similarly, when people process foods conceptually, gustatory areas become active (e.g., Simmons et al., 2005). When people process things that smell, olfactory areas become active (e.g., Gonzalez et al., 2006). Additionally, the property areas just noted are often segregated by category (Martin, 2007). Within the motion processing system, for example, distinct areas represent motion conceptually for animals vs. artifacts.

Language Comprehension

Situation models. Although the presence of modal representations in such a high-level cognitive task as comprehension might seem implausible, supporting evidence has existed for decades. Early work on comprehension inferences strongly suggested the presence of spatial representations (e.g., Bransford & Johnson, 1973). Bower and Morrow (1990) found that people represent text meaning with situation models that have spatial properties (also see Glenberg et al., 1987; Rinck & Bower, 2004). Other research has shown that readers take spatial perspectives on scenes described in texts (e.g., Black et al., 1979; Spivey et al., 2000). Intraub and Hoffman (1992) found that readers confused pictures with texts, suggesting that readers simulated text meaning. Gernsbacher et al. (1990) found that individual abilities for comprehending events visually vs. verbally were highly correlated, suggesting that modal representations underlie both. Potter et al. (1986) showed that replacing words with pictures did not disrupt sentence processing, suggesting that the pictures were integrated effortlessly into modal representations of sentence meaning (also see Glaser, 1992).

Perceptual simulation. More recently, researchers have addressed the role of perceptual simulation in representing texts. In much research reviewed by Zwaan and Madden (2005), participants read a sentence and then processed a picture that either matched or mismatched something implied but not stated literally. For example, participants read “The ranger saw the eagle in the sky” and then named a subsequent picture of an eagle either with its wings outstretched or folded. If readers constructed simulations to represent sentences, these simulations should have contained implicit perceptual information such as object shape. Consistent with this prediction, participants were faster to name the eagle with

outstretched wings. Many experiments have demonstrated these matching effects, consistent with the simulation view.

In another line of research, participants maintained irrelevant information in working memory while processing sentences about scenes (Fincher-Kiefer, 2001; Fincher-Kiefer & D'Agostino, 2004). Drawing predictive spatial inferences about the described scenes was worse when working memory contained interfering visual information than when it contained non-interfering verbal information, suggesting that readers represented the texts with simulations.

Motor simulation. Many researchers have demonstrated the presence of motor simulations in comprehension. Across several lines of research, Pulvermüller (2005) found that when participants simply read the word for an action, the motor system becomes active to represent its meaning. More specifically, verbs for head, arm, and leg actions produce head, arm, and leg simulations in the respective areas of the motor system. These simulations become active quickly, within a few hundred milliseconds, as illustrated by MEG. These simulations also play causal roles in lexical processing, given that TMS over the relevant motor areas affects behavioral performance (e.g., Buccino et al., 2005; Pulvermüller et al., 2005). Myung et al. (2006) similarly showed that motor simulations triggered by words produce priming across lexical decision trials.

Many other researchers have assessed whether physical actions affect comprehension. Klatzky et al. (1989) showed the priming a motor action affected the time to judge the sensibility of a simple phrase describing an action. Similarly, comprehension is facilitated when the action to make a response is consistent with text meaning (Glenberg & Kaschack, 2003), and also when the action to control text presentation is consistent (Zwaan & Taylor, 2006). When reading about a sport, such as hockey, experts produce motor simulations absent in novices (Holt & Beilock, 2006).

Other research shows that participants simulate motion through space as they read texts. Richardson et al. (2003) found that readers simulate horizontal and vertical paths implied by both concrete and abstract verbs (e.g., push vs. lift, argue vs. respect). Matlock (2004) found that implied fictive motion (e.g., The road runs through the valley) produces corresponding simulations of motion through space. Richardson and Matlock (2007) found that these simulations produce related eye movements. Meier and Rubenstein (2004) found that reading positively-valenced words orients attention up, whereas reading negatively-valenced words orients attention down. Schubert (2005) similarly found that reading words associated with high vs. low power orients attention up vs. down, respectively. Meier and Rubenstein (2006) found that depression increases downward orientation.

Affective simulation. Researchers have also shown

that people simulate affective states during comprehension. When people read taboo words and reprimands, affective reactions, as measured by skin conductance, are stronger when read in a first language than in a second language acquired at a later age (Harris et al., 2003). Because greater affect is associated with these expressions at younger ages, native language speakers continue to simulate these affective responses when reading them as adults.

A reader's affective state interacts with the affective content of a text. In Havas et al. (in press), participants' faces were configured discretely into states associated with particular emotions prior to judging the sensibility of sentences that contained emotional content. When facial emotion matched sentence emotion, comprehension was better than when they mismatched. Embodied states of the face triggered emotional states, which in turn interacted with sentence comprehension. Barrett (2006) suggests that affective simulation underlies the conceptualization of emotion that occurs in comprehension and other processes.

Gesture. Another important form of embodiment in language is the gesture that spontaneously accompanies speech (McNeill, 2005). Producing gestures helps speakers retrieve words whose meanings are related to the gestures (e.g., Krauss, 1998). Speakers also produce gestures to help listeners comprehend what they say (e.g., Alibali et al., 2001; Kelly, 2001; Valenzeno et al., 2003). In child development, gesture can convey an emerging conceptualization that cannot yet be articulated in speech (e.g., Goldin-Meadow, 2003). Kelly et al. (2002) integrate gesture with grounded theories of language.

Thought

Physical reasoning. Much work shows that simulations play central roles in reasoning about physical situations (Hegarty, 2004). When people view a static configuration of gears, for example, they use simulation to infer the direction in which a particular gear will turn. People similarly use simulation to draw inferences about how a configuration of pulleys will work, or when water will spill from a tipped glass.

Numerous sources of evidence support the use of simulation in these tasks. The time to draw an inference is often correlated with the duration of a physical event, such as how long a gear takes to turn (e.g., Schwartz & Black, 1996). Drawing inferences often produces associated gestures (e.g., Hegarty et al., 2005). Carrying out associated actions can improve inference (e.g., Schwartz, 1999). When working memory is filled with visuospatial information, inferences suffer compared to when working memory is filled with verbal information (e.g., Sims & Hegarty, 1997). Individual differences in spatial ability correlate with the ability to draw inferences (e.g., Hegarty & Steinhoff, 1997). Hegarty (2004) concludes that spatial simulation, not visual imagery, plays the central role in reasoning about physical situations. Furthermore, the

simulations that underlie this reasoning appear piecemeal and sketchy, not holistic and detailed.

Abstract reasoning. Abstract forms of reasoning have not received as much attention as physical reasoning. Although Johnson-Laird's (1983) mental model theory could be made compatible with grounded views, the mental models in his theory typically contain amodal symbols, not simulations. Much circumstantial evidence, however, suggests that simulation plays central roles in abstract reasoning. For example, philosophers of science observe frequently that scientific and mathematical discoveries typically arise from simulation (e.g., Barwise & Etchemendy, 1991; Hadamard, 1949; Nersessian, 1999). Widespread content effects in reasoning similarly implicate simulations and situations in abstract reasoning (e.g., Cheng & Holyoak, 1985).

Further evidence that abstract reasoning is grounded comes from research inspired by metaphor theory. When people reason about the abstract concept of time, they use space metaphorically to draw inferences (e.g., Boroditsky, 2000; Boroditsky & Ramscar, 2002). For example, when people hear, "Next Wednesday's meeting has been moved forward two days," their inference about whether the new meeting day is Monday or Friday depends on their current spatial trajectory. Similarly, how people conceptualize time reflects whether their language describes space horizontally or vertically (Boroditsky, 2001).

Social Cognition

Embodiment effects. Social psychologists have reported embodiment effects for decades (Barsalou et al., 2003; Niedenthal et al., 2005). Bodily states can be effects of social cognition. For example, activating the elderly stereotype causes people to walk slowly and to perform lexical decision slowly (e.g., Dijksterhuis & Bargh, 2001). Similarly, seeing an in-group member engages the smiling musculature (e.g., Vanman et al., 1997).

Bodily states are not simply effects of social cognition; they also cause it. When a facial expression or posture is adopted, it elicits associated mental states. For example, engaging the smiling musculature produces positive affect (e.g., Strack et al., 1988), whereas slumping produces negative affect (e.g., Stepper & Strack, 1993). Actions produce similar outcomes. Nodding one's head produces positive affect (e.g., Wells & Petty, 1980), whereas pushing away with the arms produces negative affect (e.g., Cacioppo et al., 1993).

Barsalou et al. (2003) proposed that these embodiment effects reflect a pattern-completion inference mechanism that supports situated action. According to this view, representations of familiar situations that contain embodiments become established in memory (e.g., receiving a gift, feeling positive affect, and smiling). When part of this situation occurs (e.g., receiving a gift), it activates the remainder of the situational pattern, producing associated embodiments (e.g., smiling).

Similarly, if smiling is engaged, it activates representations of situations that contain it, producing associated pattern components (e.g., positive affect, generosity). E. Smith and Semin (2004) review much further evidence that situated action organizes social cognition. Barsalou et al. (2003) examine embodiment in religious cognition.

Social mirroring. Accumulating evidence implicates simulation in many social processes (Decety, & Grèzes, 2006; Gallese et al., 2004; Goldman, 2006; Iacoboni, in press; Rizzolatti & Craighero, 2004). In general, mirror circuits appear to underlie these simulations, establishing empathy between perceivers and perceived actors. Using mirror circuits, perceivers infer the goals of others (e.g., Kohler et al., 2002), and infer their affective states, such as pain and disgust (e.g., Jackson et al., 2005; Wicker et al., 1999). Mirror circuits underlie a variety of other social activities, including imitation (e.g., Iacoboni et al., 1999) and social coordination (e.g., Sebanz et al., 2006).

In general, a mirror circuit does not provide a complete account of a social activity but contributes to a larger system. For example, additional brain areas beyond mirror circuits prevent perceivers from confusing someone else's mental state with their own (Decety, & Grèzes, 2006). In imitation, simulating how the imitation of an action will look and feel is also important (Iacoboni et al., 1999). Joint attention and timing are also central in social coordination (Sebanz et al., 2006).

Individual differences in simulation ability produce individual differences in social cognition. For example, individual differences in the ability to simulate other people's mental states, such as pain, correlate with rated empathy (e.g., Jackson et al., 2005). Individual differences in expertise, such as ballet, correlate with the ability to mirror relevant action (Calvo-Merino et al., 2005).

Development

Newborn infants imitate the facial expressions and bodily movements of adults, simulating the actions that they see physically (Meltzoff, & Moore, 1983). As infants grow older, they understand the perceived actions of others in terms of what they have come to understand about their own actions and intentions (Meltzoff (2007). Once infants experience the occluding effects of a blindfold, for example, they understand that an adult wearing a blindfold cannot see. Thus, mirroring plays a central role in development, as infants use simulations of their own experience to understand the goals and actions of others.

Researchers increasingly demonstrate that development depends critically on bodily states (e.g., L. Smith, 2005b) and situated action (e.g., L. Smith & Gasser, 2005). For example, L. Smith et al. (1999) showed that the development of object permanence is not simply a cognitive achievement (as long believed) but also

a grounded one. Specifically, motor perseveration plays a major role in tasks that measure object permanence. Longo and Bertenthal (2006) similarly showed that motor simulations contribute to perseveration.

Other developmental tasks also exhibit strong dependence on action. For example, the motor actions performed while learning a category influence the visual features abstracted into its representation (L. Smith, 2005a). Similarly, the actions performed on objects during play later cause children to place the objects in spatial clusters that reflect shared categories (Namy et al., 1997). In general, extensive amounts of learning occur between perception, action, and cognition as development progresses (e.g., Greco et al., 1990; Rochat & Striano, 1999).

THEORETICAL AND EMPIRICAL ISSUES

Grounded cognition in its modern form is sufficiently new and controversial that many issues surround it. A sample of these issues follows.

Does the Brain Contain Amodal Symbols?

Researchers who once denied that the modalities had anything to do with cognition now acknowledge that their potential relevance. The empirical evidence that the modalities have something to do with cognition has become compelling. Nevertheless, most researchers in cognitive psychology and cognitive science are not ready to completely abandon traditional theories. One widely held view is that simulations in the modalities play peripheral roles in cognition, while classic operations on amodal symbols still play the central roles.

It will be important for future research to assess this mixed view. Can empirical evidence be found for the amodal symbols still believed by many to lie at the heart of cognition? As mentioned earlier, surprisingly few attempts have been made to establish empirical support for amodal symbols. If amodal symbols are to remain central in cognitive theories, empirical support is necessary. It will be not be enough to rely on the fact that theories built from amodal symbols can mimic cognitive abilities. It will also be important to demonstrate that computation on amodal symbols constitutes the underlying mechanism. Furthermore, modal symbols must be localized in the brain, and neural principles for processing them explained.

Does Simulation Implement Classic Symbolic Operations?

Conversely, can simulation mechanisms be shown to be more than merely peripheral to cognition? Can simulation implement the core cognitive functions that many researchers still believe require amodal symbols? As described earlier, grounded theories, such as PSS and cognitive linguistics grammars, have illustrated how simulation mechanisms can, in principle, implement core

cognitive functions, including type-token binding, inference, productivity, recursion, and propositions. The existence of these operations in the cognitive system is not in question. How the brain actually implements them is. Amodal formalisms for symbolic operations may provide a theoretical shorthand for expressing what the brain computes, but simulation, or something else, may be the mechanism that actually implements these operations.

Clearly, computational implementations are required to demonstrate convincingly that simulation can implement symbolic operations. Empirical evidence will be required to support these accounts. If future research succeeds in these projects, the viability of amodal symbols as plausible cognitive constructs may increasingly come into question.

Are Simulations and Embodiments Causal or Epiphenomenal?

Proponents of amodal views often suggest that amodal symbols play the central causal roles in cognitive computation, with simulations and embodiments simply being epiphenomenal. Establishing whether simulations and embodiments play causal roles is indeed an important issue. Considerable evidence exists already, however, that they do. For example, TMS over motor areas affects linguistic processing (e.g., Buccino et al., 2005; Pulvermüller et al., 2005). If simulations in motor areas are epiphenomenal, then modulating brain activity in these areas should have no effect on the causal sequence of processes underlying language, but they do. Similarly, experimentally-manipulated bodily states, assigned randomly to participants, produce extensive effects throughout social cognition (Barsalou et al., 2003), situated action (e.g., Tucker & Ellis, 1998, 2001, 2004), and linguistic processing (e.g., Glenberg & Kaschak, 2003). If these bodily states are epiphenomenal, they should have no effect on the causal sequence of processes underlying behavioral performance, but again they do.

Conversely, it is essential for proponents of amodal views to demonstrate that amodal symbols play causal roles in cognition (assuming that evidence for their existence in the brain can be found). Consider neuroimaging studies that find activations in modal areas during conceptual processing (e.g., Martin, 2007). If these activations are epiphenomenal, then it is essential to identify alternative amodal brain areas that play the causal role in producing conceptual performance. Interestingly, many of these studies fail to find significant activations outside modal areas, suggesting that amodal processes do not contribute to conceptual processing, and that the active modal areas observed play the causal roles, given that they are the only areas active.

Assessing the causal roles of simulations and embodiments clearly requires much further research. Nevertheless, significant evidence exists already that they are not epiphenomenal.

What Roles Do Statistical Representations Play?

Research inspired by neural networks and Bayesian statistics has clearly shown that the brain is exquisitely sensitive to the statistical structure of experience. Interestingly, these two approaches often (but not always) assume that statistical processing occurs in a modular system separate from the brain's modal systems, much like traditional symbolic theories. In other words, these approaches have remained relatively ungrounded.

By no means is this necessary. To the contrary, statistical processing is central to grounded cognition, as illustrated by dynamic systems approaches. Similarly, theories such as PSS assume that neural networks underlie the convergence zone architecture that implements simulation. Furthermore, Bayesian statistics can be viewed as statistical accounts of the multi-modal information stored in the dynamic systems that generate simulations and guide situated action. Depending on the particular distribution of multi-modal content captured for a category, the Bayesian statistics describing it will vary, as will the simulations and situated actions generated from it. Bayesian theories provide a powerful tool for describing the content and behavior of these systems.

How Is Language Grounded?

Language provides an excellent domain in which to combine symbolic operations, statistical processing, and grounding. Symbolic operations are clearly central to linguistic processing. Thematic roles of verbs are bound to values (e.g., binding the *instrument* role for *EAT* to *spoon*). Open class words for nouns, modifiers, verbs, and adverbs combine productively to form novel phrasal and sentential structures (e.g., combining different *color* modifiers with different *object* head nouns to form noun phrases such as *red hair*, *blond hair*, and *red wine*). Phrasal structures embed recursively (e.g., *The dog the cat chased howled*). Propositions extracted from linguistic utterances represent meaning beyond surface structure (e.g., extracting *cat (chase, dog)* from either "The cat chased the dog" or the "The dog was chased by the cat").

Statistical processing is also central to language use. Much research shows that statistical distributions of word senses contribute to ambiguity resolution during syntactic analysis (e.g., Trueswell, 1996). Similarly, statistical distributions of argument structures and their instantiations contribute to sentence processing (e.g., McRae et al., 2005).

Finally, grounding is also central to comprehension, as we saw earlier. As people comprehend a text, they construct simulations to represent its perceptual, motor, and affective content. Simulations appear central to the representation of meaning.

Thus, language use is a domain where the study of symbolic operations, statistical processing, and grounding

can be integrated. Numerous issues challenge the integration of these perspectives. Do amodal symbols or simulation mechanisms implement the symbolic operations that underlie linguistic processing? As sentences are processed incrementally, are simulations constructed incrementally to reflect the semantic contribution of each incoming word? Does the compositional structure of syntax correspond to the compositional structure of simulations? Do language statistics affect the specific simulations constructed during comprehension? Do cognitive linguistics grammars offer useful frameworks for integrating symbolic operations, statistical processing, and grounding?

Does the Brain Contain a Single Representational System?

As described earlier, some simulation theories propose that a single multi-modal representation system underlies diverse cognitive processes, including top-down perception, implicit memory, working memory, explicit memory, and conceptual knowledge. According to this view, simulation is a unifying computational principle throughout the brain, with different control systems operating on a shared representational system to produce different forms of simulation in different processes.

Is this proposal correct? If so, what is the nature of the shared representational system? Within a given modality, is the representational system organized hierarchically, as appears to be the case in the visual and motor systems? If so, do some processes access these hierarchical representations at higher or lower levels than others? For example, explicit memory, conceptual processing, and language might tend to access high-level representations, whereas top-down perception, implicit memory, and working memory might tend to access lower-level representations. Another central issue concerns the different control mechanisms for different processes. Where are they located in the brain, and why do they reside in these particular locations? How do differences between them implement different processes?

How Does the Brain Represent Abstract Concepts?

Abstract concepts pose a classic challenge for grounded cognition. How can theories that focus on modal simulations explain concepts that do not appear modal? This concern often reflects the misperception described earlier that conceptual content in grounded theories can only come from perception of the external world. Because people perceive internal states, however, conceptual content can come from internal sources as well. Preliminary evidence suggests that introspective information is indeed central to the representation of abstract concepts (e.g., Barsalou & Wiemer-Hastings, 2005; Wiemer-Hastings et al., 2000). Such findings suggest that we need to learn much more about how

people perceive and conceptualize internal states. Notably, people simulate internal states similar to how they simulate external states (e.g., Havas et al., in press; Niedenthal et al., 2005). Thus, simulations of internal states could provide much of the conceptual content central to abstract concepts (Barsalou, 1999).

Abstract concepts also appear to depend heavily on situations and situated action (Schwanenflugel, 1990). Processing an abstract concept by itself is difficult but becomes much easier when a background situation contextualizes it. Barsalou and Wiemer-Hastings (2005) report evidence for extensive situational content in abstract concepts.

Because the scientific study of concepts has primarily focused so far on concrete concepts, we actually know remarkably little about abstract concepts, even from the perspective of traditional cognitive theories. Nevertheless, abstract concepts appear to play central roles throughout human cognition, especially in meta-cognition, social interaction, education, industry, and social institutions. Regardless of whether simulations of introspections and situations underlie the representation of abstract concepts, much more effort should be devoted to understanding them.

Do Mirror Neuron Systems Pervade Social Cognition?

Much excitement surrounds the discovery of mirror neuron systems. As described earlier, social simulation theories propose that these systems underlie many important social phenomena. One central issue is assessing whether mirror systems do indeed play all these roles, and perhaps others. If so, then why do humans exhibit such different social abilities than non-human primates who also have mirror systems? What other systems contribute to these differences? Also, to what extent do compromised mirror systems underlie psychopathologies associated with a lack of inter-subjectivity, such as autism and schizophrenia (e.g., Gallese, 2003)?

METHODOLOGICAL ISSUES

Besides addressing theoretical and empirical issues, grounded cognition must address various methodological issues. Future growth and impact of this area is likely to depend on addressing these issues successfully.

Computational and Formal Theories

Grounded cognition suffers from an obvious lack of well-specified theories. Often experiments simply attempt to demonstrate the presence of modal processing in higher cognition. Given the widespread skepticism about grounded cognition ten years ago, demonstration experiments made sense. Now that modal processing in higher cognition is becoming well documented, it is time to develop computational accounts of grounded theories,

along with experiments that test them. Transitioning from demonstration experiments to analytic experiments is a natural trajectory in science, and will undoubtedly occur in grounded cognition. This trajectory is also likely to include increasing attempts to build computational implementations, followed by formal accounts of the principles underlying them. For examples of initial attempts to implement grounded theories see Cangelosi et al. (2000), Cangelosi and Riga (2006), Garagnani et al. (in press), Wennekers et al. (2006), and Goldreich (2007).

Integrating Disciplines and Levels of Explanation

One strength of grounded cognition is its natural fit with the brain. Because grounded cognition rests on the modalities, knowledge of how the brain implements the modalities informs grounded cognition. Furthermore, assessing neural activity in the modalities provides a natural way to test predictions of grounded theories. Clearly, however, much greater integration of cognitive and neural mechanisms must occur than the relatively simple mappings established so far. Nevertheless, the grounded approach appears to have unusual potential for integrating cognition with the brain.

Grounded cognition has significant potential to integrate other research areas as well. For example, a core principle of grounded cognition is that cognition shares mechanisms with perception, action, and introspection. Increasingly specified accounts of how cognition, perception, action, and introspection interact during situated action are likely to follow from future research. Similarly, grounded cognition has also shown potential to integrate cognitive, social, and developmental processes. Research in all three fields has increasingly incorporated simulation, situations, and bodily states as important constructs. Thus, further integration of these areas seems like another natural outcome of research in grounded cognition. As described earlier, robotics offers considerable potential for accomplishing this integration (Barsalou, Breazeal et al., in press).

Grounding Classic Research Paradigms

It is unlikely that grounded cognition will be fully accepted until classic research paradigms can be understood within its framework. In cognitive psychology, for example, how would a classic paradigm such as recognition memory be understood as grounded? Similarly, how might the construct of a production in a production system be understood?

One possibility is that many empirical results and their interpretations would remain the roughly same within the framework of ground cognition. Analogous to how symbolic operations can be retained in grounded views but be realized differently, well-established empirical results and explanations may often retain much of their original form. One focus of change is likely to be at the

representational level. In recognition memory, for example, rather than assuming that a vector of amodal symbols represents a learning episode, its representational elements could instead be mapped into a multi-modal state. At higher theoretical levels, much of the original theory might remain. Similarly, in production systems, rather than viewing the condition and action sides of a production as amodal symbols, the condition could be represented as the state of a perceptual modality, and the action could be represented as a state of the motor system. From the grounded perspective, a production is simply an association between a perception and an action. Above the representational level, the remaining structure of a production system might again remain largely intact.

Clearly, the reinvention of classic paradigms requires careful theoretical and empirical assessment. Until grounding is integrated into classic paradigms, however, it is unlikely that it will be accepted fully. Thus, another major goal for the grounded cognition community is to illustrate how classic paradigms can be made compatible with grounding, and perhaps how grounding can take understandings of these paradigms to new levels.

Acknowledgement

This work was supported by National Science Foundation Grant BCS-0212134 and by DARPA contract BICA FA8650-05-C-7256 to Lawrence Barsalou. Address correspondence to Lawrence W. Barsalou, Department of Psychology, Emory University, Atlanta, GA 30322 (barsalou@emory.edu, <http://www.psychology.emory.edu/cognition/barsalou/index.html>).

Literature Cited

- Alibali, M.W., Heath, D.C., & Myers, H.J. (2001). Effects of visibility between speaker and listener on gesture production: Some gestures are meant to be seen. *Journal of Memory and Language*, 44, 169-188.
- Arbib, M.A., (2005) From monkey-like action recognition to human language: An evolutionary framework for neurolinguistics. *Behavioral and Brain Sciences*. 28, 105-167.
- Barrett, L. F. (2006). Solving the emotion paradox: Categorization and the experience of emotion. *Personality and Social Psychology Review*, 10, 20-46.
- Barsalou, L.W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences*, 22, 577-660.
- Barsalou, L.W. (2003). Situated simulation in the human conceptual system. *Language and Cognitive Processes*, 18, 513-562.

- Barsalou, L.W. (2005a). Abstraction as dynamic interpretation in perceptual symbol systems. In L. Gershkoff-Stowe & D. Rakison (Eds.), *Building object categories* (389-431). Carnegie Symposium Series. Mahwah, NJ: Erlbaum.
- Barsalou, L.W. (2005b). Continuity of the conceptual system across species. *TRENDS in Cognitive Sciences*, 9, 309-311.
- Barsalou, L.W. (in press). Grounding symbolic operations in the brain's modal systems. In G.R. Semin & E.R. Smith (Eds.), *Embodied grounding: Social, cognitive, affective, and neuroscientific approaches*. New York: Cambridge University Press.
- Barsalou, L.W., Barbey, A.K., Simmons, W.K., & Santos, A. (2005). Embodiment in religious knowledge. *Journal of Cognition and Culture*, 5, 14-57.
- Barsalou, L.W., Breazeal, C. & Smith, L.B. (in press) Cognition as coordinated non-cognition. *Cognitive Processing*.
- Barsalou, L.W., & Hale, C.R. (1993). Components of conceptual representation: From feature lists to recursive frames. In I. Van Mechelen, J. Hampton, R. Michalski, & P. Theuns (Eds.), *Categories and concepts: Theoretical views and inductive data analysis* (97-144). San Diego, CA: Academic Press.
- Barsalou, L.W., Niedenthal, P.M., Barbey, A., & Ruppert, J. (2003). Social embodiment. In B. Ross (Ed.), *The Psychology of Learning and Motivation*, Vol. 43 (pp. 43-92). San Diego: Academic Press.
- Barsalou, L.W., Santos, A., Simmon, W.K., & Wilson, C.D. (in press). *Language and simulation in conceptual processing*. In M. De Vega, A.M. Glenberg, & A.C. Graesser, A. (Eds.). *Symbols, embodiment, and meaning*. Oxford: Oxford University Press.
- Barsalou, L.W., & Wiemer-Hastings, K. (2005). Situating abstract concepts. In D. Pecher and R. Zwaan (Eds.), *Grounding cognition: The role of perception and action in memory, language, and thought* (pp. 129-163). New York: Cambridge University Press.
- Barwise, J., & Etchemendy, J. (1991). Visual information and valid reasoning. In W. Zimmerman & S. Cunningham (Eds.), *Visualization in mathematics* (pp. 9-24). Washington: Mathematical Association of America.
- Black, J.B., Turner, T.J., & Bower, G.H. (1979). Point of view in narrative comprehension, memory, and production. *Journal of Verbal Learning and Verbal Behavior*, 18, 187-198.
- Blankenburg, F., Ruff, C.C., Deichmann, R., Rees, G., & Driver, J. (2006). The cutaneous rabbit illusion affects human primary sensory cortex somatotopically. *PLoS Biology*, 4, 459-466.
- Borghi A.M., Glenberg A., Kaschak M. (2004). Putting words in perspective. *Memory & Cognition*, 32, 863-873.
- Boroditsky, L. (2000). Metaphoric Structuring: Understanding time through spatial metaphors. *Cognition*, 75, 1-28.
- Boroditsky, L. (2001). Does language shape thought? English and Mandarin speakers' conceptions of time. *Cognitive Psychology*, 43, 1-22.
- Boroditsky, L. & Ramscar, M. (2002). The roles of body and mind in abstract thought. *Psychological Science*, 13, 185-188.
- Bosbach, S., Cole, J., Prinz, W., & Knoblich, G. (2005). Inferring another's expectation from action: The role of peripheral sensation. *Nature Neuroscience*, 8, 1295-1297.
- Bower, G.H., & Morrow, D.G. (1990). Mental models in narrative comprehension. *Science*, 247, 44-48.
- Bransford, J.D., & Johnson, M.K. (1973). Considerations of some problems of comprehension. In W.G. Chase (Ed.), *Visual information processing*. New York: Academic Press.
- Breazeal, C (2002). *Designing sociable robots*. Cambridge, MA: MIT Press.
- Bub, D.N., Masson, M.E.J., & Cree, G.S. (in press). Evocation of functional and volumetric gestural knowledge by objects and words. *Cognition*.
- Buccino, G., Riggio, L., Melli, G., Binkofski, F., Gallese, V., & Rizzolatti, G. (2005). Listening to action-related sentences modulates the activity of the motor system: A combined TMS and behavioral study. *Cognitive Brain Research*, 24, 355-363.
- Buckner, R.L., & Wheeler, M.E. (2001) The cognitive neuroscience of remembering. *Nature Reviews Neuroscience*, 2: 624-634.
- Cacioppo, J.T., Priester, J.R., & Bernston, G.G. (1993). Rudimentary determination of attitudes: II. Arm flexion and extension have differential effects on attitudes. *Journal of Personality and Social Psychology*, 65, 5-17.
- Calvo-Merino, B., Glaser, D.E., Grèzes, J., Passingham, R.E., & Haggard, P., (2005). Action observation and acquired motor skills: an fMRI study with expert dancers. *Cerebral Cortex* 8, 1243-1249.
- Cangelosi A., Greco A. & Harnad S. (2000). From robotic toil to symbolic theft: Grounding transfer from entry-level to higher-level categories. *Connection Science*, 12, 143-162.
- Cangelosi A., & Riga T. (2006). An embodied model for sensorimotor grounding and grounding transfer: Experiments with epigenetic robots, *Cognitive Science*, 30, 673-689
- Caramazza, A., & Shelton, J.R. (1998). Domain-specific knowledge systems in the brain: The animate-inanimate distinction. *Journal of Cognitive Neuroscience*, 10, 1-34.
- Chao L.L., & Martin A. (2000). Representation of manipulable man-made objects in the dorsal stream. *Neuroimage*, 12, 478-84.

- Cheng, P.W., & Holyoak, K.J. (1985). Pragmatic reasoning schemas. *Cognitive Psychology*, *17*, 391-416.
- Chomsky, N. (1957). *Syntactic structures*. The Hague: Mouton.
- Clark, A. (1997). *Being there: Putting brain, body, and world together again*. Cambridge, MA: MIT Press.
- Conway, M.A. (1990) *Autobiographical memory: An introduction*. Buckingham: University Press.
- Conway, M.A. (2002). Sensory-perceptual episodic memory and its context: Autobiographical memory. In A. Baddeley, J.P. Aggleton, & M.A. Conway (Eds.), *Episodic memory: New directions in research* (pp. 53-70). Oxford: Oxford University Press.
- Coulson, S. (2001). *Semantic leaps: Frame shifting and conceptual blending in meaning construction*. New York: Cambridge University Press.
- Cree, G. S., & McRae, K. (2003). Analyzing the factors underlying the structure and computation of the meaning of chipmunk, cherry, chisel, cheese, and cello (and many other such concrete nouns). *Journal of Experimental Psychology: General*, *132*, 163-201.
- Damasio, A.R. (1989). Time-locked multiregional retroactivation: A systems-level proposal for the neural substrates of recall and recognition. *Cognition*, *33*, 25-62.
- Damasio, A.R., Damasio, H. (1994). Cortical systems for retrieval of concrete knowledge: The convergence zone framework. In C. Koch & J.L. Davis (Eds.), *Large-scale neuronal theories of the brain* (61-74). Cambridge, MA: MIT Press.
- Decety, J., & Grèzes, J. (2006). The power of simulation: Imagining one's own and other's behavior. *Brain Research*, *1079*, 4-14.
- Dijksterhuis, A., & Bargh, J.A. (2001). The perception-behavior expressway: Automatic effects of social perception on social behavior. In M.P. Zanna (Ed.), *Advances in Experimental Social Psychology* (Vol. 23, pp. 1-40). San Diego, CA: Academic Press.
- Epicurus (341-270BC). Sensation, imagination, and memory. In A.A. Long & D.N. Sedley (1987), *The Hellenistic philosophers*, Vol. 1. New York. Cambridge University Press.
- Fauconnier, G. (1985). *Mental spaces*. Cambridge, MA: MIT Press.
- Fillmore, C.J. (1985). Frames and the semantics of understanding. *Quaderni di Semantica*, *6*, 222-255.
- Fincher-Kiefer, R. (2001). Perceptual components of situation models. *Memory & Cognition*, *29* 336-343.
- Fincher-Kiefer, R., & D'Agostino, P.R. (2004). The role of visuospatial resources in generating predictive and bridging inferences. *Discourse Processes*, *37*, 205-224.
- Finke, R.A. (1989). *Principles of mental imagery*. Cambridge, MA: MIT Press.
- Fodor, J.A., & Pylyshyn, Z.W. (1988). Connectionism and cognitive architecture: A critical analysis. *Cognition*, *28*, 3-71.
- Franklin, N., & Tversky, B. (1990). Searching imagined environments. *Journal of Experimental Psychology: General*, *119*, 63-76.
- Freyd, J.J. (1987). Dynamic mental representations. *Psychological Review*, *94*, 427-438.
- Gainotti, G. (2006). Anatomical functional and cognitive determinants of semantic memory disorders. *Neuroscience and Biobehavioral Reviews*, *30*, 577-594
- Gainotti, G., Silveri, M.C., Daniele, A., & Giustolisi, L. (1995). Neuroanatomical correlates of category-specific semantic disorders: A critical survey. *Memory*, *3*, 247-264.
- Gallese, V. (2003). The roots of empathy: The shared manifold hypothesis and the neural basis of intersubjectivity. *Psychopathology*, *36*, 171-180.
- Gallese, V., Keysers, C., & Rizzolatti, G. (2004). A unifying view of the basis of social cognition. *TRENDS in Cognitive Sciences*, *8*, 396-403.
- Garagnani, M., Wennekers, T., & Pulvermüller, F. (in press). A neural model of the language cortex. *Neurocomputing*.
- Garoff, R.J., Slotnick, S.D., & Schacter, D.L. (2005). The neural origins of specific and general memory: The role of the fusiform cortex. *Neuropsychologia*, *43*, 847-859.
- Gernsbacher, M.A., Varner, K.R., & Faust, M.E. (1990). Investigating differences in general comprehension skill. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *16*, 430-445.
- Gibbs, R.W., Jr. (1994). *The poetics of mind: Figurative thought, language, and understanding*. New York: Cambridge University Press.
- Gibbs, R.W., Jr. (2006). *Embodiment and cognitive science*. New York: Cambridge University Press.
- Gibson, J.J. (1979). *The ecological approach to visual perception*. New York: Houghton Mifflin.
- Glaser, W.R. (1992). Picture naming. *Cognition*, *42*, 61-105.
- Glenberg, A.M. (1997). What memory is for. *Behavioral and Brain Sciences*, *20*, 1-55.
- Glenberg, A.M., & Kaschak, M.P. (2003). The body's contribution to language. In B. Ross (Ed.), *The Psychology of Learning and Motivation*, Vol. 43 (pp. 93-126). New York: Academic Press.
- Glenberg, A.M., Meyer, M., & Lindem, K. (1987). Mental models contribute to foregrounding during text comprehension. *Journal of Memory and Language*, *26*, 69-83.
- Glenberg, A.M., Schroeder, J.L., & Robertson, D.A. (1998). Averting the gaze disengages the environment and facilitates remembering. *Memory & Cognition*, *26*, 651-658.
- Glover, S., Rosenbaum, D.A., Graham, J., & Dixon, P.

- (2004). Grasping the meaning of words. *Experimental Brain Research*, 154, 103-108.
- Goldberg, A. (1995). *Constructions. A construction grammar approach to argument structure*. Chicago: University of Chicago Press.
- Goldberg, R.F., Perfetti, C.F., & Schneider, W. (2006). Perceptual knowledge retrieval activates sensory brain regions. *Journal of Neuroscience*, 26, 4917-4921.
- Goldin-Meadow, S. *Hearing gesture: How our hands help us think*. Cambridge, MA: Harvard University Press, 2003.
- Goldman, A. (2006). *Simulating minds: The philosophy, psychology, and neuroscience of mindreading*. Oxford: Oxford University Press.
- Goldreich, D. (2007). A Bayesian perceptual model replicates the cutaneous rabbit and other tactile spatiotemporal illusions. *PLoS ONE*, 2, e333.
- Goldstone, R.L. (1995). Effects of categorization on color perception. *Psychological Science*, 5, 298-304.
- Gonzalez, J., et al. (2006). Reading cinnamon activates olfactory brain regions. *Neuroimage*, 32, 906-912.
- Greco, C., Hayne, H., & Rovee-Collier, C. (1990). Roles of function, reminding, and variability in categorization by 3-month-old infants. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 16, 617-633.
- Grèzes, J., & Decety, J. (2001). Functional anatomy of execution, mental simulation, observation, and verb generation of actions: A meta-analysis. *Human Brain Mapping*, 12, 1-19.
- Grush, R. (2004). The emulation theory of representation: motor control, imagery, and perception. *Behavioral and Brain Sciences* 27, 377-442.
- Hadamard, J. (1949). *The psychology of invention in the mathematical field*. New York: Dover Books.
- Halpern, A.R., Zatorre, R.J., Bouffard, M. & Johnson, J.A. (2004) Behavioral and neural correlates of perceived and imagined timbre. *Neuropsychologia*, 42, 1281-1292.
- Hansen, T., Olkkonen, M., Walter, S., & Gegenfurtner, K.R. (2006). Memory modulates color appearance. *Nature Neuroscience*, 9, 1367-1368.
- Harnad, S. (1990). The symbol grounding problem. *Physica D*, 42, 335-346.
- Harris, C.L., Aycicegi, A., & Berko Gleason, J. (2003). Taboo words and reprimands elicit greater autonomic reactivity in a first than in a second language. *Applied Linguistics*, 24, 561-579.
- Haugeland, J. (1991). Representational genera. In W. Ramsey, S.P. Stich, & D.E. Rumelhart (Eds.), *Philosophy and connectionist theory* (pp. 61-89). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Havas, D.A., Glenberg, A.M., & Rinck, M. (in press). Emotion simulation during language comprehension. *Psychonomic Bulletin & Review*.
- Hegarty, M. (2004). Mechanical reasoning as mental simulation. *TRENDS in Cognitive Sciences*, 8, 280-285.
- Hegarty, M., Mayer, S., Kriz, S. & Keehner, M. (2005). The role of gestures in mental animation. *Spatial Cognition and Computation*, 5, 333-356.
- Hegarty, M. & Steinhoff, K. (1997). Use of diagrams as external memory in a mechanical reasoning task. *Learning and Individual Differences*, 9, 19-42.
- Helbig, H.B., Graf, M., & Kiefer, M. (2006). The role of action representations in visual object recognition. *Experimental Brain Research*, 174, 221-228.
- Holt, L.E., & Beilock, S.L. (2006). Expertise and its embodiment: Examining the impact of sensorimotor skill expertise on the representation of action-related text. *Psychonomic Bulletin & Review*, 13, 694-701
- Humphreys, G. W., & Forde, E. M. E. (2001). Hierarchies, similarity, and interactivity in object recognition: "Category-specific" neuropsychological deficits. *Behavioral & Brain Sciences*, 24, 453-509.
- Iacoboni, M., (in press). Understanding others: Imitation, language, empathy. In S. Hurley & N. Chater, (Eds.), *Perspectives on imitation: From cognitive neuroscience to social science*. Cambridge, MA: MIT Press.
- Iacoboni M., Woods, R.P., Brass, M., Bekkering, H., Mazziotta, J.C., & Rizzolatti, G. (1999). Cortical mechanisms of human imitation. *Science*, 286, 2526-2528.
- Intraub, H., Gottesman, C.V., & Bills, A.J. (1998). Effects of perceiving and imagining scenes on memory for pictures. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 24, 186-201.
- Intraub, H., & Hoffman, J.E. (1992). Reading and visual memory: Remembering scenes that were never seen. *American Journal of Psychology*, 105, 101-114.
- Jackson, P.L., Meltzoff, A.N., & Decety, J. (2005). How do we perceive the pain of others: A window into the neural processes involved in empathy. *NeuroImage*, 24, 771-779.
- Jacoby, L. (1983). Remembering the data: Analyzing interactive processes in reading. *Journal of Verbal Learning and Verbal Behavior*, 22, 485-508.
- Jacoby, L.L., & Hayman, C.A.G. (1987). Specific visual transfer in word identification. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 13, 456-463.
- Jeannerod, M. (1995). Mental imagery in the motor context. *Neuropsychologia*, 33, 1419-1432.
- Johnson-Laird, P.N. (1983). *Mental models*. Cambridge, MA: Harvard University Press.
- Jolicoeur, P. (1985). The time to name disoriented natural objects. *Memory & Cognition*, 13, 289-303.
- Kan, I.P., Barsalou, L.W., Solomon, K.O., Minor, J.K., & Thompson-Schill, S.L. (2003). Role of mental imagery in a property verification task: fMRI

- evidence for perceptual representations of conceptual knowledge. *Cognitive Neuropsychology*, 20, 525-540.
- Kant, E. (1787/1965). *The critique of pure reason* (N.K. Smith, Trans). New York: St. Martin's Press.
- Kaschak, M.P.; Glenberg, A.M. (2000). Constructing meaning: The role of affordances and grammatical constructions in sentence comprehension. *Journal of Memory and Language*, 43, 508-529.
- Kellenbach, M.L., Brett, M., & Patterson, K. (2001). Large, colorful, or noisy? Attribute- and modal activations during retrieval of perceptual attribute knowledge. *Cognitive, Affective, and Behavioral Neuroscience*, 1, 207-221.
- Kelly, S.D. (2001). Broadening the units of analysis in communication: Speech and nonverbal behaviours in pragmatic comprehension. *Journal of Child Language*, 28, 325-349.
- Kelly, S.D., Iverson, J., Terranova, J., Niego, J., Hopkins, M., & Goldsmith, L. (2002). Putting language back in the body: Speech and gesture on three timeframes. *Developmental Neuropsychology*, 22, 323-349.
- Kemmerer, D. (2006). The semantics of space: Integrating linguistic typology and cognitive neuroscience. *Neuropsychologia*, 44, 1607-1621.
- Kent, C., & Lamberts, K. (2006). Modeling the time course of feature perception and feature information retrieval. *Journal of Memory and Language* 55, 553-571.
- Kiefer, M. (2005). Repetition priming modulates category-related effects on event-related potentials: Further evidence for multiple cortical semantic systems. *Journal of Cognitive Neuroscience*, 17, 199-211.
- Kirsner, K., Dunn, J.C., Standen, P. (1989). Domain-specific resources in word recognition. In S. Lewandowsky, J.C.Dunn, & K. Kirsner (Eds.), *Implicit memory: Theoretical views* (pp. 99-122). Hillsdale, NJ: Erlbaum
- Klatzky, R.L., Pelligrino, J.W., McCloskey, B.P., & Doherty, S. (1989). The role of motor representations in semantic sensibility judgments. *Journal of Memory and Language*, 28, 56-77.
- Kohler, E., Keysers, Cl, Umiltà, M.A., Fogassi, L., Gallese, V., & Rizzolatti, G. (2002). Hearing sounds, understanding actions: action representation in mirror neurons. *Science*, 297, 846-848.
- Kosslyn, S.M. (1980). *Image and mind*. Cambridge, MA: Harvard University Press.
- Kosslyn, S.M. (1994). *Image and brain*. Cambridge, MA: MIT Press.
- Kosslyn, S.M., Ganis, G., & Thompson, W.L. (2000). Neural foundations of imagery. *Nature Reviews Neuroscience*, 2, 635-642.
- Kosslyn, S.M., Thompson, W.L., & Ganis, G. (2006). *The case for mental imagery*. Oxford: Oxford University Press.
- Krauss, R.M. (1998). Why do we gesture when we speak? *Current Directions in Psychological Science*, 7, 54-59.
- Lakoff, G. (1987). *Women, fire, and dangerous things: What categories reveal about the mind*. Chicago: University of Chicago Press.
- Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. Chicago: University of Chicago Press.
- Lakoff, G., & Johnson, M. (1999). *Philosophy in the flesh: The embodied mind and its challenge to western thought*. New York: Basic Books.
- Langacker, R.W. (1987). *Foundations of cognitive grammar: Vol. 1. Theoretical prerequisites*. Stanford, CA: Stanford University Press.
- Langacker, R.W. (1991). *Foundations of cognitive grammar, volume II: Descriptive application*. Stanford, CA: Stanford University Press.
- Lewis, J.W. (2006). Cortical networks related to human use of tools. *The Neuroscientist*, 12, 211-231.
- Levine, D.N., Warach, J., & Farah, M.J. (1985). Two visual systems in mental imagery: Dissociation of "What" and "Where" in imagery disorders due to bilateral posterior cerebral lesions. *Neurology*, 35, 1010-1018.
- Levy, R., & Goldman-Rakic P.S. (2000). Segregation of working memory functions within the dorsolateral prefrontal cortex. *Experimental Brain Research*, 133, 23-32.
- Longo, M.R., & Bertenthal, B.I. (2006). Common coding of observation and execution of action in 9-month-old infants. *Infancy*, 10, 43-59.
- Longo, M.R., & Laurenci, S.F. (2007). Space perception and body morphology: Extent of near space scales with arm length. *Experimental Brain Research*, 177, 285-290.
- Martin, A. (2001). Functional neuroimaging of semantic memory. In R. Cabeza & A. Kingstone (Eds.), *Handbook of functional neuroimaging of cognition* (pp. 153-186). Cambridge, MA: MIT Press.
- Martin, A. (2007). The representation of object concepts in the brain. *Annual Review of Psychology*, 58, 25-45.
- Marques, J.F. (2006). Specialization and semantic organization: Evidence for multiple-semantics linked to sensory modalities. *Memory & Cognition*, 34, 60-67.
- Matlock, T. (2004). Fictive motion as cognitive simulation. *Memory & Cognition*, 32, 1389-1400.
- McNeill, D. (2005). *Gesture and thought*. Chicago: University of Chicago Press.
- McRae, K., Hare, M., Elman, J.L., & Ferretti, T.R. (2005). A basis for generating expectancies for verbs from nouns. *Memory & Cognition*, 33, 1174-1184.
- Meier, B.P., & Robinson, M.D. (2004). Why the sunny side is up: Associations between affect and vertical position. *Psychological Science*, 15, 243-247.
- Meier, B.P., & Robinson, M.D. (2006). Does "feeling

- down" mean seeing down? Depressive symptoms and vertical selective attention. *Journal of Research in Personality*, 40, 451-461.
- Meltzoff, A.N. (2007). 'Like me': A foundation for social cognition. *Developmental Science* 10, 126-134.
- Meltzoff, A.N., & Moore, M.K. (1983). Newborn infants imitate adult facial gestures. *Child Development*, 54, 702-709.
- Miceli, G., Fouch, E., Capasso, R., Shelton, J.R., Tomaiuolo, F., & Caramazza, A. (2001). The dissociation of color from form and function knowledge. *Nature Neuroscience*, 4, 662-667.
- Morrison, J.B., & Tversky, B. (1997). Body schemas. In M.G. Shafto & P. Langley (Eds.), *Proceedings of the Cognitive Science Society* (pp. 525-529). Mahwah, NJ: Erlbaum.
- Murphy, G. L. (1997). Reasons to doubt the present evidence for metaphoric representation. *Cognition*, 62, 99-108.
- Myung, J., Blumstein, S.E., Sedivy, J.C. (2006). Playing on the typewriter, typing on the piano: Manipulation knowledge of objects. *Cognition*, 98, 223-243.
- Namy, L.L., Smith, L.B., & Gershkoff-Stowe, L. (1997). Young children discovery of spatial classification. *Cognitive Development*, 12, 163-184.
- Nersessian, N. J. (1999). Model-based reasoning in conceptual change. In Magnani, L., Nersessian, N. J., & Thagard, P. (Eds.) *Model-Based Reasoning in Scientific Discovery*. Kluwer Academic/Plenum Publishers, New York.
- Niedenthal, P.M., Barsalou, L.W., Winkelman, P., Krauth-Gruber, S., & Ric, F. (2005). Embodiment in attitudes, social perception, and emotion. *Personality and Social Psychology Review*, 9, 184-211.
- Paivio, A. (1971). *Imagery and verbal processes*. New York: Holt, Rinehart & Winston.
- Paivio, A. (1986). *Mental representations: A dual coding approach*. New York: Oxford University Press.
- Parsons, L.M. (1987a). Imagined spatial transformations of one's body. *Journal of Experimental Psychology: General*, 116, 172-191.
- Parsons, L.M. (1987b). Imagined spatial transformations of one's hands and feet. *Cognitive Psychology*, 19, 178-241.
- Pasternak, T., & Greenlee, M.W. (2005). Working memory in primate sensory systems. *Nature Reviews Neuroscience*, 6, 97-107.
- Pecher, D., Zeelenberg, R., & Barsalou, L.W. (2003). Verifying properties from different modalities for concepts produces switching costs. *Psychological Science*, 14, 119-124.
- Pecher, D., Zeelenberg, R., & Barsalou, L.W. (2004). Sensorimotor simulations underlie conceptual representations: Modality-specific effects of prior activation. *Psychonomic Bulletin & Review*, 11, 164-167.
- Polyn, S.M., Natu, V.S., Cohen, J.D., & Norman, K.A. (2005). Category-specific cortical activity precedes retrieval memory search. *Science*, 310, 1963-1966.
- Potter, M.C., Kroll, J.F., Yachzel, B., Carpenter, E., & Sherman, J. (1986). Pictures in sentences: Understanding without words. *Journal of Experimental Psychology: General*, 115, 281-294.
- Prinz, J. (2002). *Furnishing the mind: Concepts and their perceptual basis*. Cambridge, MA: MIT.
- Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology*, 9, 129-154.
- Proffitt, D.R. (2006). Embodied perception and the economy of action. *Perspectives on Psychological Science*, 1, 110-122.
- Pulvermüller, F. (2005). Brain mechanisms linking language and action. *Nature Reviews Neuroscience*, 6, 576-582.
- Pulvermüller, F., Hauk, O., Nikulin, V.V., & Ilmoniemi, R.J. (2005). Functional links between motor and language systems. *European Journal of Neuroscience*, 21, 793-797.
- Pulvermüller, F., Huss, H., Kherif, F., Martin, F.M.P., Hauk, O., & Shtyrov, Y. (2006). Motor cortex maps articulatory features of speech sounds. *PNAS*, 103, 7865-7870.
- Pylyshyn, Z.W. (1973). What the mind's eye tells the mind's brain: A critique of mental imagery. *Psychological Bulletin*, 80, 1-24.
- Reed, C.L., & Vinson, N.G. (1996). Conceptual effects on representational momentum. *Journal of Experimental Psychology: Human Perception and Performance*, 22, 839-850.
- Reid, T. (1785/1969). *Essays on the intellectual powers of man*. Cambridge, MA: MIT Press.
- Repp, B.H., & Knoblich, G. (2004). Perceiving action identity: How pianists recognize their own performances. *Psychological Science*, 15, 604-609.
- Richardson, D.C., & Matlock, T. (2007). The integration of figurative language and static depictions: An eye movement study of fictive motion. *Cognition*, 102, 129-138.
- Richardson, D.C., Spivey, M.J., Barsalou, L.W., & McRae, K. (2003). Spatial representations activated during real-time comprehension of verbs. *Cognitive Science*, 27, 767-780.
- Richter, W. et al. (2000). Motor area activity during mental rotation studied by time-resolved single-trial fMRI. *Journal of Cognitive Neuroscience*, 12, 310-320.
- Rinck, M., & Bower, G.H. (2004). Goal-based accessibility of entities within situation models. In B.H. Ross (Ed.), *The psychology of learning and motivation: Advances in research and theory*, Vol. 44. (pp. 1-33). New York: Elsevier Science.
- Rizzolatti, G., & Arbib, M.A. (1998). Language within our

- grasp, *Trends in Neuroscience*, 21, 188-194.
- Rizzolatti G., & Craighero L. (2004). The mirror-neuron system. *Annual Review of Neuroscience*, 27, 169-92.
- Robbins, P., & M. Aydede (Eds.) (in press). *Cambridge handbook of situated cognition*. New York: Cambridge University Press.
- Rochat, P., & Striano, T. (1999). Emerging self-exploration by 2-month-old infants. *Developmental Science*, 2, 206-218.
- Roediger, H.L., & Blaxton, T.A. (1987). Effects of varying modality, surface features, and retention interval on priming in word fragment completion. *Memory & Cognition*, 15, 379-388.
- Roediger, H.L., & McDermott, K.B. (1993). Implicit memory in normal human subjects. In F. Boller & J. Grafman (Eds.), *Handbook of Neuropsychology*, Vol. 8, (pp. 63-131). Amsterdam: Elsevier.
- Ross, B.H., Wang, R.F., Kramer, A.F., Simons, D.J., & Crowell, J.A. (in press). Action information from classification learning. *Psychonomic Bulletin & Review*.
- Rubin, D.C. (2006). The basic-systems model of episodic memory. *Perspectives on Psychological Science*, 1, 277-311.
- Samuel, A.G. (1997). Lexical activation produces potent phonemic percepts. *Cognitive Psychology*, 32, 97-127.
- Schachter, D.L., & Addis, D.R. (2007). The cognitive neuroscience of constructive memory: Remembering the past and imagining the future. *Philosophical Transactions of the Royal Society (B)*, 362, 773-786.
- Schacter, D.L., Dobbins, I.G., & Schnyer, D.M. (2004). Specificity of priming: A cognitive neuroscience perspective. *Nature Reviews Neuroscience*, 5, 853-862.
- Schacter, D.L. & Graf, P. (1989). Modality specificity of implicit memory for new associations. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 15, 3-12.
- Schubert, T. (2005). Your Highness: Vertical positions as perceptual symbols of power. *Journal of Personality and Social Psychology*, 89, 1-21.
- Schwanenflugel, P.J. (1991). Why are abstract concepts hard to understand? In P.J. Schwanenflugel (Ed.), *The psychology of word meaning* (pp. 223-250). Mahwah, NJ: Erlbaum.
- Schwartz, D.L. (1999) Physical imagery: kinematic vs. dynamic models. *Cognitive Psychology*, 38, 433-464.
- Schwartz, D.L. and Black, J.B. (1996) Analog imagery in mental model reasoning: depictive models. *Cognitive Psychology*, 30, 154-219
- Searle, J.R. (1980). Minds, brains, and programs. *Behavioral and Brain Sciences*, 3, 417-424.
- Sebanz, N., Bekkering, H., & Knoblich, G. (2006). Joint action: Bodies and minds moving together. *TRENDS in Cognitive Sciences*, 10, 70-76.
- Shepard, R.N., & Cooper, L.A. (1982). *Mental images and their transformations*. New York: Cambridge University Press.
- Shiffrar, M., & Freyd, J.J. (1990). Apparent motion of the human body. *Psychological Science*, 4, 257-264.
- Shiffrar, M., & Freyd, J.J. (1993). Timing and apparent motion path choice with human body photographs. *Psychological Science*, 6, 379-384.
- Simmons, W.K., & Barsalou, L.W. (2003). The similarity-in-topography principle: Reconciling theories of conceptual deficits. *Cognitive Neuropsychology*, 20, 451-486.
- Simmons, W.K., Martin, A., & Barsalou, L.W. (2005). Pictures of appetizing foods activate gustatory cortices for taste and reward. *Cerebral Cortex*, 15, 1602-1608.
- Simmons, W.K., Ramjee, V., Beauchamp, M.S., McRae, K., Martin, A., & W. Barsalou, L.W. (2007). Common neural substrates for perceiving and knowing about color and action. *Neuropsychologia*, 45, 2802-2810.
- Sims, V.K. & Hegarty, M. (1997). Mental animation in the visual-spatial sketchpad: Evidence from dual-task studies. *Memory & Cognition*, 25, 321-332.
- Slotnick, S.D., & Schachter, D.L. (2004). A sensory signature that distinguishes true from false memories. *Nature Neuroscience*, 7, 664-672.
- Smith, E.R., & Semin, G.R. (2004). Socially situated cognition: Cognition in its social context. *Advances in Experimental Social Psychology*, 36, 53-117.
- 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.
- Smith, L.B. & Gasser, M. (2005). The development of embodied cognition: Six lessons from babies. *Artificial Life*, 11, 13-30.
- Smith, L.B., Thelen, E., Titzer, R., & McLin, D. (1999) Knowing in the context of acting: The task dynamics of the A-not-B Error. *Psychological Review*, 106, 235-260.
- Solomon, K.O., & Barsalou, L.W. (2001). Representing properties locally. *Cognitive Psychology*, 43, 129-169.
- Solomon, K.O., & Barsalou, L.W. (2004). Perceptual simulation in property verification. *Memory & Cognition*, 32, 244-259.
- Spence, C., Nicholls, M. E. R., & Driver, J. (2000). The cost of expecting events in the wrong sensory modality. *Perception & Psychophysics*, 63, 330-336.
- Spivey, M. (2007). *The continuity of mind*. New York: Oxford University Press.
- Spivey, M., Tyler, M., Richardson, D., & Young, E. (2000). Eye movements during comprehension of

- spoken scene descriptions. *Proceedings of the 22nd Annual Conference of the Cognitive Science Society*, (pp.487-492). Mahwah, NJ: Erlbaum.
- Steels, L., & Brooks, R. (1995). *The artificial life route to artificial intelligence: Building embodied situated agents*. Mahwah, NJ: Lawrence Erlbaum Associates.
- Stepper, S., & Strack, F. (1993). Proprioceptive determinants of emotional and nonemotional feelings. *Journal of Personality and Social Psychology*, *64*, 211- 220.
- Stevens, J.A., Fonlupt, P., Shiffrar, M., & Decety, J. (2000). New aspects of motion perception: Selective neural encoding of apparent human movements. *NeuroReport*, *11*, 109-115.
- Strack, F., Martin, L.L., & Stepper, S. (1988). Inhibiting and facilitating conditions of the human smile: A nonobtrusive test of the facial feedback hypothesis. *Journal of Personality and Social Psychology*, *54*, 768-777.
- Symes, E., Ellis, R., & Tucker, M. (2007) Visual object affordances: Object orientation. *Acta Psychologica*, *124*, 238-255.
- Talmy, L. (1983). How language structures space. In H. Pick & L. Acredelo (Eds.), *Spatial orientation: Theory, research, and application* (225-282). New York: Plenum Press.
- Talmy, L. (1988). Force dynamics in language and cognition. *Cognitive Science*, *12*, 49-100.
- Thelen, E., Schoner, G., Scheier, C. & Smith, L.B. (2001) The Dynamics of embodiment: A field theory of infant perseverative reaching. *Behavioral and Brain Sciences*, *24*, 1-86.
- Thelen, E., & Smith, L.B. (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT Press.
- Thompson-Schill, S.L. (2003), Neuroimaging studies of semantic memory: inferring "how" from "where". *Neuropsychologia*, *41*: 280-292.
- Tomasello, M. (2003). *Constructing a language: A usage-based theory of language acquisition*. Harvard University Press.
- Trueswell, J.C. (1996). The role of lexical frequency in syntactic ambiguity resolution. *Journal of Memory and Language*, *35*, 566- 585.
- Tucker, M. & Ellis, R. (1998). On the relations between seen objects and components of potential actions. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 830-846.
- Tucker M., & Ellis R. (2001). The potentiation of grasp types during visual object categorization. *Visual Cognition*, *8*, 769-800.
- Tucker M., Ellis R. (2004). Action priming by briefly presented objects. *Acta Psychologica*, *116*, 185-203.
- Turner, M. (1996). *The literary mind*. New York: Oxford University Press.
- Tyler, L. K., Moss, H. E., Durrant-Peatfield, M. R., & Levy, J. P. (2000). Conceptual structure and the structure of concepts: A distributed account of category-specific deficits. *Brain & Language*, *75*, 195-231.
- Valenzeno, L., Alibali, M.W., & Klatzky, R.L. (2003). Teachers' gestures facilitate students' learning: A lesson in symmetry. *Contemporary Educational Psychology*, *28*, 187-204.
- Van Orden, G.C. Holden, J.G. Turvey, M.T. (2005) Human cognition and 1/f scaling. *Journal of Experimental Psychology: General*, *134*, 117-123.
- Vanman, E. J., Paul, B. Y., Ito, T. A., & Miller, N. (1997). The modern face of prejudice and structural features that moderate the effect of cooperation on affect. *Journal of Personality and Social Psychology*, *73*, 941-959.
- Vermeulen, N., Niedenthal, P.M., & Luminet, O. (in press). Switching between sensory and affective systems incurs processing costs. *Cognitive Science*.
- Warren, R.M. (1970). Perceptual restoration of missing speech sounds. *Science*, *167*, 392-393.
- Warrington, E.K., & McCarthy, R.A. (1987). Categories of knowledge: Further fractionations and an attempted integration. *Brain*, *110*, 1273-1296.
- Warrington, E.K., & Shallice, T. (1984). Category specific semantic impairments. *Brain*, *107*, 829-854.
- Watson, J.B. (1913). Psychology as the behaviorist sees it. *Psychological Review*, *20*, 158-177.
- Wells, G. L., & Petty, R. E. (1980). The effects of overt head movements on persuasion: Compatibility and incompatibility of responses. *Basic and Applied Social Psychology*, *1*, 219-230.
- Wenckers, T. Garagnani, M. & Pulvermüller, F. (2006). Language models based on Hebbian cell assemblies. *Journal of Physiology, Paris*, *100*, 16-30.
- Wheeler, M.E., Petersen, S.E., & Buckner, R.L. (2000). Memory's echo: Vivid remembering reactivates sensory-specific cortex. *PNAS*, *97*, 11125-11129.
- Wicker, B. et al. (2003) Both of us disgusted in my insula: The common neural basis of seeing and feeling disgust. *Neuron* *40*, 655-664
- Wiemer-Hastings, K., Krug, J., & Xu, X. (2001). Imagery, context availability, contextual constraint, and abstractness. *Proceedings of the 23rd Annual Conference of the Cognitive Science Society*, 1134-1139. Mahwah, NJ: Erlbaum.
- Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, *9*, 625-636.
- Wilson, M., & Knoblich, G. (2005). The case for motor involvement in perceiving conspecifics. *Psychological Bulletin*, *131*, 460-473.
- Wolpert, D.M., Ghahramani, Z., & Jordan, M.I. (1999). An internal model for sensorimotor integration. *Science*, *269*, 1880-1882.
- Yeh, W., & Barsalou, L.W. (2006). The situated nature of concepts. *American Journal of Psychology*, *119*, 349-

384.

Zwaan, R.A., & Madden, C.J. (2005). Embodied sentence comprehension. In D. Pecher and R. Zwaan (Eds.), *Grounding cognition: The role of perception and action in memory, language, and thought* (pp. 224-245). New York: Cambridge University Press.

Zwaan, R.A., & Taylor, L.J. (2006). Seeing, acting, understanding: motor resonance in language comprehension. *Journal of Experimental Psychology: General*, 135, 1-11.