PERSPECTIVES ON PSYCHOLOGICAL SCIENCE

Relating Psychology and Neuroscience

Taking Up the Challenges

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ABSTRACT—*Advances in brain research have invigorated an ongoing debate about the relations between psychology and neuroscience. Cognitive science has historically neglected the study of neuroscience, although the influential subfield of cognitive neuroscience has since attempted to combine information processing approaches with an awareness of brain functioning. Although cognitive neuroscience does not necessarily support a reductionist approach, certain philosophers of mind have suggested that psychological constructs will eventually be replaced with descriptions of neurobiological processes. One implicitly popular response to this proposal is that neuroscience represents a level of implementation that is separate from a level of cognition. Although recent work in the philosophy of mind has gone some way to explicating the concept of psychological and neuroscience approaches as different levels, it is suggested here that a tidy framework of levels is somewhat tenuous. A particular challenge comes from the metatheoretical position of embodiment, which places the mind within the body and brain of an active organism which is deeply embedded in the world. In providing an integration of brain, body, mind, and culture, embodiment exemplifies an important line of defense against claims of the possible reduction of psychology by neuroscience.*

The ongoing rise in the status and visibility of neuroscience has invigorated a historical debate concerning the relations between neuroscience and psychology and the utility of neuroscience data in addressing questions of a psychological nature. Although flagship psychology journals have not seen a large increase in neuroscience-based content (Robins, Gosling, & Craik, 1999), more specialized journals publishing material at the interface of psychology and neuroscience have experienced significant growth in recent years (Spear, 2007). At the same time, membership in the Society for Neuroscience has increased rapidly (Tracy, Robins, & Gosling, 2004), and many psychology departments and programs are reorienting themselves to the rise in visibility of neuroscience (Spear, 2007). This reorientation involves adjusting to changing priorities in the allocation of research funding, the increasing encouragement of interdisciplinary collaborations by university administrations, and changes in the interests and worldviews of students of psychology.

The emergence and visibility of cognitive neuroscience (Gazzaniga, 1995), as well as of smaller subdisciplines such as social neuroscience (Cacioppo et al., 2002), affective neuroscience (R.J. Davidson & Sutton, 1995), and social cognitive neuroscience (Ochsner & Lieberman, 2001), reinforce the notion that neuroscience research related to psychological constructs is becoming increasingly prevalent. These and other factors have energized a continuing debate about the current and future relations between psychology and neuroscience. There are a multitude of views in this debate, each of which can be broadly characterized as lying somewhere on a continuum between the preservation of psychology as a wholly autonomous discipline with little relation to neuroscience and the opposing belief that psychological constructs will ultimately be reduced to neuroscientific terms.

One prediction from the former end of the continuum is that neuroscience-based approaches will split from psychology in the coming decades, with this divorce leaving psychology as an autonomous social science of behavior and inferred experience (e.g., Kagan, 2006). At the other end of the continuum, it has been proposed that much of psychology will ultimately be reduced to neuroscience, resulting in the elimination of most psychological terms (e.g., Bickle, 2003). It seems important for the future of psychology as an integrative discipline that those of us who would support a more intermediate view are able to clearly articulate the structure of such a position. One moderate

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position places psychological and neuroscientific approaches as separate but complementary levels of analysis (e.g., Miller & Keller, 2000), with continuing tension between these levels being a productive force. From this perspective, addressing questions on each level gives more explanatory power than does working on one level alone. However, my premise here is that such a position has not become well delineated within the psychological literature, in part because the principal models of mind (and also of brain) that have come to dominate psychology over the last decades have prevented the development of an integrative, transformational conceptualization of the relations between psychology and neuroscience.

In this article, I outline various challenges and opportunities in conceptualizing a fruitful relation between psychological and neuroscientific approaches. After a brief review of the mind–brain problem, I begin with a discussion of neuroscience (taken generally) in relation to the study of mental representations, with an emphasis on the historical divide between neuroscience and cognitive psychology. The cognitive neuroscience approach is then described as an attempt to reduce this separation by combining an information-processing perspective with an awareness of brain functioning. I then discuss reductionist suggestions that the language of psychology will ultimately be replaced by neuroscientific terms. I briefly describe responses to these suggestions, including the popular view that neuroscience represents a separate level of implementation. My central premise is that this approach has been severely undermined by emerging perspectives within embodied cognition (Clark, 1998) and that reconsidering brain and mind in the context of postcognitivist, embodied approaches has the potential to provide a more integrative perspective on the relations between psychology and neuroscience. Indeed, the grounding of the mind in an embodied, embedded agent is, I will argue, a key defense against the potential reduction of psychology to neuroscience. The aim of this article is to outline some of the main issues involved in such a reconsideration, beginning with the metaphysical problem presented by the mind–brain division.

THE MIND–BRAIN PROBLEM

Psychological scientists occupy a strange space "mounted above the philosophical gap between mind and body" (Tschacher & Haken, 2007, p. 1). Indeed, the metaphysical question of how the mind is physically instantiated is one of the most central questions in the philosophy of mind, in which a wide variety of theoretical positions have proliferated. Historically, these positions have tended to focus on abstract formulations of the relations between mental states and physical states. One such position is *supervenience* (D. Davidson, 1980; Kim, 1993). From this perspective, the brain implements the mind, and the mind supervenes on the brain: Changes at the mental level must be accompanied by changes in the brain, but neurophysiological changes need not be accompanied by mental changes. This asymmetric dependence of the mental on the neurobiological avoids falling into the philosophically problematic trap of type materialism, in which a one-on-one correspondence between a specific brain state and a specific mental state is required (Smart, 1959).

In that it recognizes that the mind is a product of the brain while also precluding the elimination of psychological constructs through reduction, supervenience appears to be an implicitly attractive perspective (e.g., Frith, 2007; Miller & Keller, 2000). It is also consistent with the position in cognitive neuroscience that leveraging information about localization of cognitive functions in the brain does not require an exact neural signature to be consistently associated with a specific mental state or cognitive process at a fine-grained level of neural activation (e.g., Saxe, Brett, & Kanwisher, 2006). However, despite its implicit attractiveness, supervenience cannot be regarded as having solved the problem of how the mind is instantiated by the brain. Among others, de Jong (2002) has noted that supervenience is basically a statement that a higher level phenomenon (i.e., mental life) depends, albeit in an asymmetric fashion, on a lower level phenomenon (i.e., neuronal activity), and as such it does not actually explain very much (see also Kim, 1993). Put another way, "mind-body supervenience states the mind-body problem—it is not a solution . . ." (Kim, 1998, p. 14). Rather than becoming entangled in such circular notions, it is better to examine conditions that may lead to an integrative framework for the psychology–neuroscience relation. My suggested direction begins from the fact that a coherent conceptualization was retarded by the decades-long dominance of a particular model of the mind within cognitive science, and that recent developments promise to open the ground for a vastly reconfigured, integrative view of brain and mind.

THE HISTORICAL SEPARATION OF COGNITIVE PSYCHOLOGY AND NEUROSCIENCE

One of the foundations of cognitive science is the construct of mental representation, in which representations are typically seen as information-bearing structures or states in intelligent systems that have semantic properties such as content, reference, or meaning. However, arguments about the status and specific properties of representations have been a consistent source of division within cognitive science as well as within psychology. The nature (and even the very existence) of representations and the ways in which they are formed and manipulated are deeply fundamental questions, but they are poorly understood and remain at the center of intense debates (see Dietrich, 2007). One facet of these debates that is of particular interest here concerns the relevance of neuroscience for the study of representation.

The "cognitive revolution" that came to the forefront in the late 1950s led to the overturning of decades of behaviorism in

North American psychology and returned the study of mind and mental processes to the discipline. However, it became apparent that the dominant model of the mind that arose from the cognitive revolution had serious limitations (Dreyfus, 1972; Searle, 1980). According to Bruner (1990), the original emphasis of the cognitive revolution was founded in the work of Piaget and Chomsky, and it aimed "to discover and to describe formally the meanings that human beings created out of their encounters with the world, and then to propose hypotheses about what meaning-making processes were implicated" (p. 2). However, the cognitivist view of the mind that emerged from the cognitive revolution did not reflect this emphasis. Instead, this predominant conceptualization of the mind had become heavily influenced by the developing discipline of artificial intelligence, through which the mind became seen as an information processor, manipulating subpersonal representations to which meaning had been preassigned rather than constructed (Bruner, 1990). For a number of reasons, this cognitivist, information-processing approach to the mind has also impeded the development of an integrative formulation of the relation between psychology and neuroscience (see Edelman, 1992).

A fundamental criticism of cognitivism is that it encourages a computational view of the mind in which the function of mental processes is paramount, with little or no regard for how those functions might be biologically realized. Indeed, a consequence of the rise of the information-processing view of the mind is that mainstream cognitive psychology has eschewed the study of neuroscience. As noted earlier, the emergence of cognitive psychology was heavily influenced by developments in computing through the belief that if computers could be used to support representations, then mental processes could become transparent rather than hidden (Newell, Shaw, & Simon, 1958). In other words, representation could be transparently studied outside the head through the use of symbol-manipulating algorithms that could be implemented on a computer. The actual makeup of the human brain was not particularly relevant—it was much more important to determine how algorithms could be used to solve problems.

An emphasis on the formal manipulation of representations, without any consideration of the biological context, reflects the historical primacy of the computational theory of mind (CTM) in cognitive science. In traditional versions of the CTM, such as that developed by Fodor (1975), thought consists of formal computational reasoning processes acting on the syntactic, but not the semantic, content of symbolic representations. The classical version of the CTM further suggests that neuroscience cannot make a substantive contribution to the study of mental representations. According to Fodor (1975), this is a consequence of the multiple ways in which functionally identical but physically different mental representations could be realized across a variety of brains or other intelligent systems (see also Putnam, 1975; Pylyshyn, 1984). This notion of multiple realization appeared to place a discontinuity at the intersection of psychology and neuroscience and put an emphasis on the function rather than the form of representations.

The question of whether a computational, representational theory of mind is an adequate model of the mind has been the subject of a very large amount of research and theorizing that can only be touched upon here. One aspect of this debate concerns the similarities between the CTM and the folk psychology underlying everyday discourse, both of which posit that mental states consist of propositional attitudes (e.g., beliefs, desires) being directed toward the content of mental representations. Churchland (1981) proposed that the propositional attitudes of folk psychology are artifacts of natural languages and that, as such, the brain is unlikely to function in a way that mirrors either the CTM or folk psychology. According to Churchland, folk psychology is simply a way for humans to represent the workings of their own and others' minds, and searching for intentionality in the brain (i.e., searching for the neural instantiations of mental states involving beliefs and desires) would be a fruitless enterprise. Churchland further proposed that, as knowledge of brain functioning advances, the primitive constructs of folk psychology would be replaced or eliminated by neuroscientific terms. This proposal sparked much debate among philosophers, but its central eliminative premise has yet to be realized. On the contrary, cognitive neuroscientists are using folk psychological frameworks as the basis for studying brain regions involved in the attribution of beliefs and desires (e.g., Saxe, Carey, & Kanwisher, 2004). Nevertheless, Churchland (2007) retains deep skepticism toward any specific neural basis for the propositional attitudes underlying folk psychology, and he suggests that because his form of eliminative materialism depends on extremely long-term predictions about the progress of neuroscience, this position has essentially been shelved by most philosophers of mind, who await further developments.

INFORMATION PROCESSING AND THE BRAIN: THE COGNITIVE NEUROSCIENCE APPROACH

Fodor and Churchland proposed polar opposite approaches to the question of how the mind creates representations, with this dichotomy being particularly apparent in the relevance of neuroscience to each approach. Fodor supports psychology as a special science that is essentially cut off from neuroscience by a natural discontinuity, whereas Churchland's biological perspective is founded on a deep skepticism of the mental state terms of folk psychology and the CTM, combined with a thorough embrace of neuroscience (for a summary and an alternative approach, see Dennett, 1987). The central question that arises from this dichotomy is whether the study of mental representations can be approached from a neurobiological perspective without moving toward eliminativism. As the study of mental life, how do we place psychology between "brain-less" autonomy and "only-brain" elimination? One possible route is through a cognitive neuroscience approach, which attempts to combine an information-processing perspective with the investigation of brain structure and function.

The advent and growth of functional brain imaging technologies in the 1980s and 1990s allowed researchers to access the previously private domain of individuals' brain activity, sparking a period of rapid growth in the fledging discipline of cognitive neuroscience (Kosslyn & Koenig, 1992; Posner & Raichle, 1994). Although these functional imaging technologies joined existing methods such as electroencephalography, as well a long tradition of brain research in neuropsychology, they had a sizeable impact on the study of the human mind. Despite some perceptions to the contrary (e.g., Bennett & Hacker, 2003), the cognitive neuroscience approach does not seek to usurp or misuse the language of psychology, but rather employs functional neuroimaging and related techniques in the same way that a previous generation of cognitive scientists used chronometric behavioral measures such as reaction time: to break apart cognitive processes (Posner, 1978).

As described by Bechtel (2002), the dominant perspective in cognitive neuroscience revolves around two main principles: first, "different brain areas perform different information processing operations" and second, "an explanation of a cognitive performance involves both decomposing an overall task into component information processing activities and determining what brain area performs each" (both from Bechtel, 2002, p. 49). These guiding principles appear to promise a brain-based approach to studying the mind. Indeed, a cognitive neuroscience approach has been proposed as a "promising consilient bridge between psychology and the natural sciences" (Rand & Ilardi, 2005, p. 7). But how are cognitive neuroscientists attempting to realize this promise? I briefly outline the main approaches to each part of Bechtel's definition, as summarized by Henson (2006) and Poldrack (2006).

As indicated by Bechtel (2002), one goal of the cognitive neuroscience approach is to decompose a task into component information processing activities. Using neuroimaging data to elucidate the cognitive processes involved in performance of a particular task relies on a method known as *forward inference* (Henson, 2006). In its most basic form, this method examines whether carrying out related tasks involves similar cognitive processes: If differences in brain activation patterns are found between the performance of two related tasks, a hypothesis that the tasks utilize identical cognitive processes can be rejected. The key function of neuroscience data in this approach is to help distinguish between competing psychological hypotheses that were initially derived from behavioral data (Schall, 2004). When used in this manner, neuroscience measures do not have a privileged status over other measures, representing another dependent variable (along with behavior) for testing competing hypotheses about unseen mental processes. As noted by Henson (2006), "All types of data are observations about the system that we are trying to understand, viz. the mind" (p. 195). In this sense, the forward inference approach is consistent with the view that psychological theories are often the starting point for the application of neuroscience data (Hatfield, 2000).

The other main goal of cognitive neuroscience concerns the determination of the brain regions that subserve the various cognitive functions involved in a performance of a task (Bechtel, 2002). This relates to a second approach known as *reverse inference* (Poldrack, 2006). This approach results in more controversial claims than forward inference, as it involves attempting to leverage information about the specific location of psychological functions in the brain. The reasoning behind reverse inference is that activation of a particular brain region x in a particular task is indicative of the engagement of cognitive process y, based on an association from other studies between activation of brain region x and the inferred cognitive process y. In other words, the activation of a specific cognitive process is inferred through the observed activation of a particular brain region, on the basis of prior evidence linking this cognitive process to this particular pattern of brain activation. As noted by Poldrack (2006), this is a logically problematic sequence, as it involves affirming the consequent, although he further suggests that relations between activation of certain brain regions and cognitive functions can be strengthened in a number of ways, such as the use of Bayesian reasoning to identify commonalities across studies. Meta-analytic approaches that draw on large numbers of datasets and include the parametric manipulation of the activation of a purported cognitive process can also help establish more logically sound associations between brain regions and specific cognitive functions (see Zacks, 2008).

NEUROSCIENCE AS A THREAT TO THE AUTONOMY OF PSYCHOLOGY

In cases in which forward inference is used, the cognitive neuroscience approach is not particularly reductionist; it primarily uses neuroscience methods as tools for testing competing hypotheses that were formulated at the psychological level. In contrast, reverse inference does raise questions about reductionism, as it involves the attempt to localize psychological functions. Assuming there is sufficient evidence to associate a particular cognitive process with the activity of a particular brain region, a strong reductionist argument would be that the cognitive process in question could be described more parsimoniously at the level of neuroscience than at the psychological level. But can psychological constructs be replaced by terms describing patterns of brain activation? This question lies at the heart of a deep philosophical debate over the relation between neuroscience and psychology, a debate that I will briefly sketch out here.

Questions of reductionism are by no means restricted to discussions of the relations between psychology and neuroscience—they are relevant to understanding across all branches of science (for an introductory summary, see Klee, 1997). Historically, an assumption of classical reductionism in neopositivist philosophy of science in the mid-20th century was that any higher level theory could be deduced from (and thus reduced to) lower level theories, with the concepts from each level being connected by “bridge laws” (e.g., Nagel, 1961). Problems with the derivation of such laws resulted in variations on this reductive theme that attempted to explain the relations between different branches of science. For instance, Oppenheim and Putnam (1958) developed the Unity of Science concept, the central idea of which was that there was a reductive continuity in nature, meaning that sciences dealing with higher level constructs (e.g., psychology) could be reduced to sciences dealing with smaller levels of organization (e.g., physiology, which could then be reduced to chemistry, then physics).

Many philosophers of science have noted that the neopositivist approach to reduction exemplified by Nagel (1961) and Oppenheim and Putnam (1958) suffered from a fatal flaw. In its emphasis on epistemic systematization, this approach did not facilitate an understanding of causation—a fundamental problem that contributed to the demise of the concepts of universal bridge laws and uniformity in nature. Despite this failure, reductionism has recently returned as a possible solution to integrating psychology and neuroscience. The eliminative materialism of Churchland (1981) represented one form of reductionism; although, as noted earlier, Churchland’s prediction of the reduction of folk psychology to neuroscientific terms has not been realized. A more recent approach in the philosophy of mind proposes a different route toward the explicit goal of eliminating psychological concepts. Instead of becoming tangled in traditional arguments about causation, the *ruthless reductionism* of Bickle (2003) puts aside the prior emphasis on deduction and bridge laws, instead proposing a more direct relation between neurophysiological and psychological phenomena.

Using the molecular biology of long-term potentiation (LTP) as an example, Bickle (2003) attempts to show that functional constructs used by behavioral neuroscientists to explain the consolidation of long-term memories can be more parsimoniously described at the biochemical level, and that this bottom–up approach negates the need for bridge laws. Although Bickle focuses on LTP and long-term memory, he suggests that a similar elimination can occur across much of psychology. This eliminativist approach should be of interest to those working at the intersection of neuroscience and psychology, partly because it relates to the dominant approach in the life sciences in which explanations are provided through descriptions of low-level biochemical mechanisms (Bechtel & Abrahamsen, 2005).

Bickle’s approach certainly has elements that are not particularly palatable to most psychologists—in his reductive approach, there is only biochemistry, which echoes the logical positivist stance that science consists of surface, not depth. But, surely, Bickle’s approach merits more discussion within psychology, in part because he dismisses the rumination inherent in the philosophy of mind, casting scorn on thought experiments about the mind–body problem that are also anathema to the empirical approach that characterizes psychology (see Chemero, 2007). That said, it seems unlikely that pursuing Bickle’s form of reductionism will lead to useful neurobiological redescriptions of mental life (see de Jong & Schouten, 2005). But it should at least provoke us to prepare a clear explication of the following problem: Assuming that neuroscience has an important role in the study of psychological questions, why couldn’t psychological terms be adequately replaced by the language of neuroscience? Within psychology, one popular approach to this question frames neuroscience as a separate level of implementation that realizes cognitive processes. Although it may be convenient, various emerging themes within contemporary cognitive science suggest that, ultimately, this approach is not entirely satisfactory.

PRESERVING AUTONOMY: LEVELS-BASED APPROACHES AND THE CONCEPT OF MECHANISM

Within psychology, the conceptualization of the role of neuroscience data in addressing questions of a psychological nature frequently reveals a framework that could be broadly characterized as the “different levels of analysis” approach. For example, in their influential discussion of the emerging framework of social cognitive neuroscience, Ochsner and Lieberman (2001) identify three such levels of analysis: A motivational level, a cognitive (i.e., information processing) level, and a “neural level, which is concerned with the brain mechanisms that instantiate cognitive-level processes” (p. 717). Similar distinctions are common, and they usually make reference to the benefits of studying processes at different levels, with the notion that a multilevel approach promotes a deeper understanding of the phenomenon at hand (e.g., Ozonoff, Pennington, & Solomon, 2006).

The conceptual attractiveness of a multilevel approach is noted by de Jong (2002), who sees “interlevel synchronous investigation” as an asset, as it allows “both top–down and bottom–up influences on theorizing” (p. 457). From this perspective, studying interactions between different levels is considered to be a productive and worthwhile enterprise (Machamer & Sytsma, 2007), a notion that perhaps drives much of the interplay between psychology and neuroscience (Cacioppo, 2002). However, much work in this area seems to avoid a particularly well-specified account of the relations between the various levels. This omission is problematic, and it leads to two important questions. First, how are we to arrive at a satisfactory classification of levels? Second, how should we conceptualize the specific relations between levels and the relative explanatory power of each level? As these questions are examined further, it can be seen that a tidy framework of separate levels becomes increasingly untenable and that a much revised conceptualization is needed.

One influential different-levels approach comes from the work of the vision scientist David Marr (1982). In brief, Marr proposed that the study of a particular task could be approached at three levels: (a) a *computational* level, which refers to a general analysis of the requirements of the task and the formulation of a strategy to solve the problem; (b) an *algorithmic* level, which describes a series of mechanical steps that would solve the problem; and (c) a level of *implementation*, which refers to a description of the physical hardware needed to carry out the sequence of steps that was specified at the algorithmic level. Marr's own theorizing put a heavy emphasis on the relations between the computational and the algorithmic levels, with the assumption that the optimum level of explanation involved translating task requirements into an algorithmic solution. According to Marr (1982), the actual hardware that was used to implement the algorithm was less important than the method by which the problem was solved.

Despite the neglect of neuroscience in his own functionalist theorizing, Marr's three levels have provided a useful conceptual framework for a number of discussions concerning the relations between psychological constructs and neuroscience (e.g., Clark, 2000; Gold & Stoljar, 1999; Kitcher, 1988; Mitchell, 2006; van Eck, de Jong, & Schouten, 2006). One reason for the attractiveness of Marr's framework is that it avoids questions of mechanism, as it invites the nonreductive notion that neuroscientific and cognitive approaches are different ways of looking at the same system. Craver (2008) notes that Marr's levels of analysis are levels of realization, such that the computational level is realized by the algorithmic level, which in turn is realized by the implementational level. From this perspective, Marr's levels "are all properties of the same thing" (Craver, 2007, p. 218), with no one level having particular causal status.

Although the notion of cognition being implemented or realized through neurobiology is an attractive one (see Miller & Keller, 2000), it still leaves too many open questions concerning the specific relations between levels, and it exposes a contradiction in the literature. Approaches that implicitly place psychology and neuroscience as different levels of realization also often include an appeal to neural mechanisms with some implication of causality—a notion that does not mesh with the more neutral stance of a realization-based account. Indeed, one does not have to look too far into the literature to find references to neural mechanisms of psychological phenomena, although the construct of mechanism is rarely unpacked. To assist with this problem, a number of philosophers have recently made attempts to conceptualize the notion of mechanism within psychology and, more specifically, within cognitive neuroscience (see Thagard, 2007). William Bechtel, Carl Craver, and others have provided insightful analyses of the concept of mechanism in explicating the relations between psychology and neuroscience (e.g., Bechtel, 2007, 2008; Craver, 2005, 2007; McCauley & Bechtel, 2001; Wright & Bechtel, 2007).

In the approach of the "new mechanists" such as Bechtel and Craver, mechanisms are described through specifying the activities of component parts of a system, with the overall specification of these components forming an explanation of a particular phenomenon. From this perspective, explanation is achieved through addressing questions of mechanism ("how" questions) in which "the component parts and their operations and organization are themselves what do the explaining" (Wright & Bechtel, 2007, p. 49). Following an elegant summary of levels-based approaches, Craver (2007) advances the notion of levels of mechanisms, which are not necessarily levels of objects (e.g., societies, organisms, cells, molecules, atoms), but instead are levels of "behaving components" that often "fail to correspond to paradigmatic entities with clear spatial boundaries" (p. 190). In this approach, items are unified into a component through their organized behavior toward a particular activity. An account such as Craver's may certainly help us conceptualize the elusive intertheoretic propositions that would link psychology and neuroscience. However, I do not wish to further explore his suggestions here. Instead, I wish to turn to emerging perspectives in cognitive science that also recognize the difficulty of placing neuroscience in a separate, implementional level of analysis.

EMBODIED COGNITION: BEYOND THE DIFFERENT-LEVELS CONCEPT OF PSYCHOLOGY AND NEUROSCIENCE

As noted above, one implicitly popular levels-based framework sees neuroscience as a level of implementation that realizes cognitive phenomena on a (separate) level of information processing. However, it is suggested here that the basic premise of neuroscience as a separate level of implementation has been undermined by recent developments that have taken place under the umbrella of embodied cognition.

Although approaches that stress mind–body–environment interactions (e.g., gesalt and ecological approaches) have coexisted with the classical, cognitivist model of representation for some time (Clark, 1998), the challenge raised by alternative approaches in cognitive science has gained a good deal of momentum in recent years (e.g., Barsalou, 2008b; Calvo & Gomila, 2008; Clark, 1998; Damasio, 1994; Gibbs, 2006; Glenberg, 1997; Overton, Müller, & Newman, 2008; Semin & Smith, 2008; Thompson, 2007; Varela, Thompson, & Rosch, 1991; Wallace, Ross, Davies, & Anderson, 2007; Wheeler, 2005; Wilson, 2002). Although this challenge has deeper historical and philosophical roots (Overton, 2006), it dramatically increased in visibility through certain developments in cognitive science in the mid-1980s and early 1990s. Beer (in press) traces the recent history of these developments through the emergence of three related approaches to studying the mind: Situated cognition (Agre & Chapman, 1987), embodied robotics (Brooks, 1991), and developmental dynamic systems (Oyama, 2000; Thelen &

Smith, 1994; van Gelder, 1997). Although there are key differences between these approaches (Beer, in press), the convergence of certain aspects of these threads into a overarching paradigm (e.g., a "metatheory of embodiment"; Overton, 2006, 2008) puts intense pressure on the cognitivist notion of the mind as a disembodied computational engine (see Edelman, 1992).

One important criticism of cognitivism has come from the failure of the classical computational account to significantly advance the field of artificial intelligence. In the views of various critics (e.g., Dreyfus, 1972; Searle, 1980), any early expectations for progress in artificial intelligence through a cognitivist framework were misguided. According to these critics, such expectations could never realized because of the fundamental problem faced by an isolated computational system "needing to impose a meaning on a meaningless Given" (Dreyfus, 2006, p. 45). A related criticism stems from the observation that the emphasis on formal aspects of information processing and the rejection of a role for the construction of meaning on the part of an embodied organism has significantly impaired the development of an integrative cognitive science (Bruner, 1990; Overton, 1994). My premise here, which builds on this, is that various facets of the cognitivist model of the mind—including the disembodied nature of the mind and the emphasis on function over form—have also prevented an integrative approach to relating psychology and neuroscience (see Damasio, 1994; Edelman, 1992). To move forward in this respect, a more integrative paradigm is needed for relating brain and mind. I suggest here that *embodiment* constitutes such a metatheoretical paradigm (see Overton, 2006; Thelen, 2000).

As noted previously, the historical focus of cognitive science has been on the mind as a representational, computational system for the manipulation of symbolic representations. This worldview is characterized by divisions between perception, cognition, and action such that modular, cognitively impenetrable sensory input is transduced into an amodal, symbolic form that is manipulated by a representational system, with responses being mediated by a separate action system (Fodor, 1983). However, the notion that detailed, discrete central representations of the external world are formed and processed by a cognitive reasoning engine that then guides action has faced challenges from embodied approaches in which perception and action are seen as overlapping, tightly linked systems. These approaches deemphasize the necessity of detailed central representations for embodied, embedded agents who can instead "use the world as its own best model" (Brooks, 1990, p. 5).

From an embodied perspective, representation is seen "less like a passive data structure and more like . . . a recipe for action" (Clark, 2001, p. 8). Attention is primarily directed toward relevant features of the environment, with a constant view toward acting on the world. As Clark (2000) puts it, "Perception is often tangled up with possibilities for action, and is continuously influenced by cognitive, contextual, and motor factors" (p. 95). This broad challenge to a representational, computational theory of mind has sometimes been associated with a tendency to severely diminish or even dissolve the concept of mental representation (e.g., Nöe, 2004). However, Anderson (2003) stresses that although the "central argument of embodied cognition . . . strikes at the nature and foundation" (p. 100) of representation, the key to progress is not the elimination of representations from cognitive science, but a renewed emphasis on their linkage to "moving and acting in a dynamic environment" (p. 100).

How does an embodied view of the mind, which posits close links between perception and action, relate to the comparatively tidy view of psychology and neuroscience exemplified by Marr's levels of realization? The implications for such levels-based frameworks have been eloquently described by the philosopher Andy Clark (1998, 2000), who sees embodied cognition as presenting a threat to the entire conceptualization of neuroscience as a separate level of implementation. One cogent piece of evidence here concerns the extremely dense functional connectivity within the brain. For instance, the primate visual system is not a feed-forward, hierarchical system, but instead involves highly complex bidirectional pathways involving extensive back-projections from deep inside the brain to early sensory-processing centers (Felleman & van Essen, 1991). Edelman (e.g., Edelman, 1992; Edelman & Tononi, 2000) has proposed that all brain networks are characterized by complex bidirectional connections between outputs and inputs, as well as a lack of specialization of individual pathways. These notions lead to dynamic models of the brain that move away from the linear perception–cognition–action sequence characterized by a classical information-processing account (see Thelen & Smith, 1994).

In such dynamic models, perception and action are naturally linked through the interconnectivity of the brain: The back-projections in the visual system play a key role in attention to relevant events, as the individual moves its eyes, head, and body to better characterize things in its environment that have been captured by low-level perceptual processes (Clark, 1998). From this perspective, the distinctions between Marr's three levels are severely undermined, as "our notions of what top-level task needs to be performed, and what kinds of algorithms are adequate to perform it, are thus deeply informed by reflection of details of bodily implementation, current needs, and action-taking potential" (Clark, 2000, p. 96). These ideas underline the fundamental implication of embodiment for Marr's levels-based framework: The algorithmic and implementational level cannot be considered in isolation. However, they also invite a stronger suggestion, which is that the way in which a representation is supported or an algorithm is implemented cannot be placed in separate levels to begin with (Clark, 2000).

One consequence of situating the mind in an active organism and the grounding of this embodied mind through perception-action linkages is that another key aspect of the cognitivist view of the mind is challenged: The belief that representations are privatized mental structures that only exist internally to the individual. In contrast, the embodiment paradigm suggests the radical notion of mind as encompassing the transactional, transformational situation of an organism that is deeply embedded in its environment. Through this embedding, the embodied mind is extended beyond a manipulator of internal representations to which meaning has been preassigned. If taken to its conclusion, this extension has the potential to not only to transform our view of the mind, but also our understanding of the relations between psychology and neuroscience.

THE PROBLEM OF THE EXTENDED MIND

The ascent of cognitivism depended on making the mind more transparent by using computers to model mental processes (Newell et al., 1958), which also contributed to the focus within cognitive science on an algorithmic level of analysis. As noted above, the Cartesian foundation of this approach has inspired a rising tide of criticism over the last three decades, mainly centered around the problem that the computational mind of cognitivism lacks a brain, a body, and a culture. One approach to the former omission has been the development of connectionist approaches that attempt to model mental processes in a more neurobiologically realistic manner (Rumelhart & McClelland, 1986). Although the advances of cognitive neuroscience have also been tremendously important in putting the brain back into cognitive science, these approaches primarily assume that representations are internal to the individual (i.e., within the head, or as Fodor has put it, "north of the neck"). My suggestion here is that this internalist focus has also constrained the development of integrative conceptualizations of the neuroscience–psychology relation.

Over the last two decades or so, intriguing (and controversial) questions have been raised from alternative perspectives within cognitive science about the extent to which representations can be considered to be partly external to the individual, rather than being solely internal, central representations (e.g., Clark & Chalmers, 1998). This perspective partly concerns the embedding of minds within a cultural environment where written language and other props are forms of representation in themselves. For instance, as part of an innovative research program, Hutchins (1995) considered the nature of representation in the cockpit of commercial airliners—specifically the representation of the required landing speed, which is a function of various physical characteristics of the plane as well as environmental conditions. Hutchins' analysis points to this representation being distributed: It exists partly within the heads of the pilot and copilot, partly in artifacts throughout the cockpit (e.g., visual reference cards as well as "speed bug" markers that are set by the crew on the aircraft instrumentation), and partly in the interactions between the crew members. According to Hutchins, a complete description of this representation would not be reached through adoption of a solely internalist perspective.

A related challenge to an internalist approach to representation comes from the notion that individuals are participants in cultures and that any account of representation must view mental life in relation to this cultural participation (Bruner, 1990; Cole, 1988). This challenge originates in what Harré (1992) termed the "second revolution" of psychology, which focused a lens on meaning, discourse, and narrative (Vygotsky, 1962). Cahan and White (1992) traced the history of arguments for two psychologies, a bottom-up (cognitive, perceptual, neuroscientific) and a top-down (social, cultural) "second" psychology. Although the precursors of this second psychology began much earlier, an emphasis on social and cultural influences was slow to appear, but it developed rapidly in the 1960s and 1970s (White, 2004).

Although some may argue that the ensuing subfield of cultural psychology has had too many associations with the directionless relativism of postmodernism (see Held, 2007; Slingerland, 2008), the study of the interface of mind and culture cannot be ignored as a challenge to the internalist approach that dominates cognitive science (Bruner, 2008). Developmental psychology is particularly illustrative in this respect, as the development of representational thought is perhaps the most central problem in this discipline (Piaget, 1952). It remains a matter of intense debate how (and when) the primarily procedural, perceptual world of the infant is transformed into the world of the child in which conceptual representations are flexibly and readily available (Mandler, 2004; Meltzoff & Moore, 1998; Quinn, 2004; Rakison, 2007). Any coherent account of this transformation clearly needs to deeply embed the infant in its world as an active participant and thus has to move beyond views of the infant either as a passive observer or as a vehicle for a highly adapted, computational mind (for discussion, see Newcombe, 2002). In this respect, embodied developmentalists have drawn on Piaget to present accounts that stress the self-organizing nature of the developing mind and the construction of representation through the self-transforming actions of the infant as an embodied agent (e.g., Bickhard, 2001; Müller & Overton, 1998). In placing the embodied mind within an active organism, such accounts provide an integrative picture of individual development within a sociocultural context. But they also present difficult questions in terms of locating representations in the conventional, cognitivist sense.

An influential sociocultural perspective on the development of representation has been offered by Nelson (1996, 2007). She notes that despite a sharp increase in the capacity for expressive communication in the second year of life, infants remain locked into a pragmatic focus on current activities, with self, other, context, and past events not being bound together into a coherent fashion. She proposes that much of children's conceptual development occurs through exposure to (and participation in) cultural narratives in early childhood. Relatedly, Tomasello (Tomasello, 1999; Tomasello & Carpenter, 2007) has done much to further the concept of "shared representations" between infants and caregivers that emerge in the second year of life in the context of coordinated, intersubjective joint attention. Although the work of Tomasello and Nelson has been influential in current thinking about the development of intentionality and representation, it presents problems for the study of cognitive development from a neurobiological perspective, as it does not locate representations as developing entirely within the head. As Nicolopoulou and Weintraub (1998) suggest, "development must be understood as a genuinely dialectical process that includes the active appropriation of collective representations through various modes of socially structured symbolic action" (p. 215; see also Overton, 2004).

The point here is that focusing only on individual's internal cognitive structures presents an incomplete picture, as representations may also have an external, intersubjective component. But how do we approach this issue without yielding to a framework that would "dissolve the individual in his or her sociocultural context" (Nicolopoulou & Weintraub, 1998)? This question clearly has broad implications for psychology as a discipline, and it has been suggested that the widespread adoption of the relational metatheory of embodiment is the key to addressing it (Overton, 1997, 2006). From this perspective, embodiment refers to both the physical body and "the body as a form of lived experience, actively engaged in and with the world of sociocultural and physical objects" (Overton, 2008, p. 3). This definition of embodiment, which draws on the phenomenological traditions of Heidegger and Merleau-Ponty, also presents a potential solution to the problem of how to conceptualize the relations between psychology and neuroscience, as it automatically provides an integration of brain, body, and mind (Overton, 2008).

The potential for moving cognitive neuroscience toward a more integrative, embodied conceptualization has received increasing support from the biological community (Damasio, 1994; Edelman & Tononi, 2000; Gallese, 2005). The time also seems ripe for theorists working in embodied cognition to draw on recent insights from developmental biology (particularly embryology), many of which are very consistent with the notion of embodiment (e.g., Gilbert & Borish, 1997). Within psychology, it might also be argued that the emergence of social neuroscience (Cacioppo, 2002) and social cognitive neuroscience (Ochsner & Lieberman, 2001) will be further steps in an integrative direction. However, in framing social cognition mainly in terms of internal representations of others, much work within these subdisciplines comes from an information processing perspective in which a cognitive/sociocultural dichotomy is maintained (see Osbeck, Malone, & Nersessian, 2007; Semin & Cacioppo, 2008).

Some recent approaches have attempted to place individuals' brain activity in a sociocultural context (see Han & Northoff, 2008), although for a more integrative relation, perhaps adopting a more radical stance—a paradigm shift toward metatheoretical principles of embodiment—is required (Overton, 2008). Such an endeavor should not merely tack on social considerations to an internalist information-processing perspective. Instead, it should be able to push us away from the purely syntactic manipulations of internal representations by an isolated mind that characterizes the cognitivist approach and should move us toward an approach in which the mind is thoroughly embodied and the body is thoroughly embedded in the world (Wheeler, 2005).

One illustration of an embodied research program in which neuroscience data play a key role comes from Barsalou's (1999) theory of perceptual symbol systems, which is a form of concept empiricism (or "neo-empiricism") in which mental concepts are seen as being grounded in perceptual simulations (see also Damasio, 1999; Prinz, 2002). The paradigm of *grounded cognition* (Barsalou, 2008b) has emerged from this theory and aligns itself against the disembodied cognitivist approach in that it sees mental concepts as having a modal component that closely links them to perceptual experience. Evidence for this premise comes from a variety of sources, including behavioral studies of feature listings (e.g., Solomon & Barsalou, 2004), neuropsychological findings of category-specific impairments in semantic memory (e.g., Warrington & Shallice, 1984) and neuroimaging evidence that semantic processing activates brain regions also involved in perception (for review, see Martin, 2007; Martin, Ungerleider, & Haxby, 2000).

There have certainly been challenges to Barsalou's approach, in part related to methodological weaknesses of the behavioral and neuropsychological evidence (see Caramazza & Shelton, 1998; Machery, 2007) and to the difficulty of producing abstract concepts out of perceptual simulations. Regarding the latter, although grounded cognition appears best suited for "concepts of things we can see, touch, and manipulate" (Gallese & Lakoff, 2005, p. 469), much recent work has been devoted to theories of how simulations could be the basis of more abstract concepts (e.g., Barsalou, 1999, 2008c; Gallese & Lakoff, 2005; Grush, 2004; Pecher & Zwaan, 2005; Pezzulo & Castelfranchi, 2007; Prinz, 2002). This endeavor is not without its critics: It has also been suggested that no one kind of representation is going to fully explain the mind, and that theorists need to be open to a form of "representational pluralism" in which different kinds of representations (or different conceptualizations of the nature of representation) may be more or less helpful in addressing a given question (Markman & Dietrich, 2000). Another challenge relates to the neuroscience aspect of Barsalou's theory, which relies on the method of forward inference, in which neuropsychological and/or neuroimaging data are used to support one model of mental concepts (embodied, grounded, modal) over another (disembodied, ungrounded, amodal). In this respect, it should be noted that theorists from both sides of the debate have pointed out that the opponent theories are currently quite underdetermined by the extant data (Machery, 2007; Martin, 2007), an issue that future work will hopefully overcome.

Although there remain a number of important challenges, Barsalou's grounded approach to cognition is taken here as a contemporary example of a nonreductive approach that attempts to build a bridge between neuroscience and cognitive psychology as part of an embodied contribution to a truly fundamental debate in psychology concerning the nature of concepts (Barsalou, 2008a). Although contemporary aspects of this debate reflect an age-old conflict between empiricism and rationalism, the study of concepts represents a contemporary arena in which neuroscience tools can play a particularly important role in furthering our understanding of the mind. Barsalou's concept empiricism is particularly interesting in this respect, as, in some ways, it harnesses the methods of cognitive neuroscience to address questions that may mark a return for a role of meaning in the study of mind.

CONCLUSION

The premise in this review has been that our understanding of the relation between psychology and neuroscience has been hindered by the way in which the mind has been construed within mainstream cognitive psychology. Although not explicitly discussed here, it could also be argued that our understanding has also not been helped by the related conceptualization of the brain as "a passive container for the storage of memories, rather than as an active, malleable mechanism involved in the experience-dependent production and integration of thought and behavior" (Dalton & Bergenn, 2007, p. 206; see also Gottfried, Gelman, & Schultz, 1999). This is an area for further exploration, but the primary message here is that the historical model of mind as a disembodied computational engine and the resulting emphasis on function over form was associated with a neglect of neuroscience that has had lasting consequences. Cognitive neuroscience has clearly changed the landscape in a dramatic way, but it has also inherited certain aspects of the cognitivist approach that continue to obscure the relations between psychology and neuroscience. Although it clearly invokes a role for biology in addressing psychological questions, the cognitive neuroscience approach often tends to frame the brain as a processor of information to which meaning has been preassigned rather than constructed by the organism (cf. Bruner, 1990).

A reconceptualization of psychology–neuroscience relations through the relational metatheory of embodiment (Overton, 2008) promises to return the study of meaning to the study of mind and can supersede superficially convenient but ultimately benign approaches that place neurobiology as a level of implementation. This is not to say that a levels-based framework needs to be dispensed with altogether: Significant progress may come through a reframing of the levels of analysis approach from a developmental dynamic systems perspective (Overton, 2006; Oyama, 2000; Thelen & Smith, 1994). Beer (2008) discusses how to approach the study of the "coupled brain-body-environment system" (p. 112), in which dynamical analyses can be applied at multiple levels from the entire system down to the level of neural interactions. Although the complexity of this enterprise is daunting, the notion of brain, body, and environment as dynamically coupled, nonautonomous systems provides an empirical direction that operates under the umbrella of embodiment in a potentially extremely powerful manner. In coupling these systems, embodied approaches also provide a key line of defense against the attempted reduction of psychology by eliminativists such as Bickle (2003), as they preclude the notion that the subject matter of neuroscience is the same as that of psychology (see also Chemero, 2007). From an embodied perspective, neuroscience is not a reductive force, but rather a way to relate internal and external aspects of representations through the sensorimotor interface of an organism that is deeply embedded in the world. There are certainly important challenges that need to be met. These include facing the criticism that embodied approaches lack a truly specific framework (Wright, 2008), as well as the challenge of creating clearly testable hypotheses regarding the consequences of embodiment (Ibanez & Cosmelli, 2008). But the hope here is that pursuing this intriguing approach to reuniting the study of mind, brain, body, and culture will move us toward a more integrative, and hence more collaborative, approach to the relations between psychology and neuroscience.

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