Embodiment and grounding in cognitive neuroscience

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Abstract

Research in embodied and grounded cognition is defined by the types of hypotheses researchers pursue, with specific emphasis on the ways in which the body, brain, and environment interact to give rise to intelligent behaviour. In cognitive neuroscience, it is hypothesized that simulations in modality-specific representations, situated and embedded in a behavioral context, underlie our ability to plan actions, discuss our thoughts, and coordinate our activities with each other. In this framework, representations are powerful, predictive constructs, and integrate the brain (i.e. neural networks), body, and immediate environment. Overall, the grounded perspective encourages us to think deeply about our cognitive ontology, cognition's relation to the brain, and the dynamic processes that underlie our most complex behaviors. In this way, embodied and grounded perspectives promise to shape research in cognitive neuroscience in highly productive ways.

Key Terms: grounded cognition; embodied cognition; modality-specific representation; semantic memory; concepts

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Introduction

It is taken for granted that cognition manifests itself as intelligent, goal-directed, and flexible behaviour. But what does it take for a system to be cognitive? Does a single neuron have cognition? Two connected neurons? Of course, two neurons can't communicate electrochemically without an appropriate extracellular milieu, and this milieu needs to be incased in something (otherwise it would just spill outwards); it *needs* a body. Further, neuronal activity can't proceed without some sort of signal from outside the milieu, so it *needs* an environment. Also, since we are talking about intelligent behaviour, a cognitive system must change its behaviours over time; it *needs* to respond. Overall, if neurons, the body, the environment, and behaviour are inseparable in descriptions of cognitive phenomena, are they all *a part* of cognition? Is it possible to identify cognition that is not, in this way, embedded in a context, enacted through action, and grounded in the body, emotions, and situations (see Noë, 2009)?

These questions motivate the embodied and grounded cognition research programs in cognitive science, philosophy, psychology, and neuroscience. Though there is no general theory of embodied or grounded cognition, the program is characterized by a central tenant: The body, brain, and environment interact in inseparably dynamic ways to give rise to intelligent behaviour. According to this view, not only does the environment constrain the types of experiences an organism has, but the sensorimotor capacities of an organism, its body, and the way the body is embedded in the environment, constrain what aspects of the environment can even affect the organism. In general, the embodied and grounded cognitive perspective broadly motivates researchers to identify the mechanisms that underlie the coupling of the environment, body, and brain, and the regularities that arise during behaviour (see Varela et al., 1991; pg 206). This perspective has many consequences for cognitive neuroscience.

In the present chapter, we aim to accomplish six goals in relating embodied and grounded cognition to the research within cognitive neuroscience. First, like many other authors, we take a brief look at the underlying assumptions of a traditional approach to cognition, cognitivism, and contrast this with the embodied or grounded approach, which developed largely from dissatisfaction with the traditional framework. Second, to contextualize our discussion, we briefly discuss a taxonomy of the major hypotheses that have developed within this framework, allowing us to characterize at least four distinct approaches. Third, we focus on the grounded cognition framework within cognitive neuroscience more specifically, highlighting some major predictions, and provide examples of how this framework has influenced research. Fourth, we identify a number of themes that have appeared in grounded cognitive neuroscience, allowing us to highlight major theoretical ideas. Fifth, we discuss the consequences of this perspective for cognitive neuroscience more generally, and discuss how grounding may continue to influence theory and research in specific ways. Finally, we identify major critiques of the framework, and lay out open issues and challenges for the field. Such challenges must be addressed before embodiment, and grounding more specifically, can contribute to a theory that is predictive and generalizable within cognitive neuroscience.

Background Issues

1. Cognitivism vs. embodied and grounded cognitive science

Embodiment and grounding offer complimentary frameworks for studying cognition to the more traditional paradigm. The traditional paradigm, sometimes called cognitivism, has been the dominant approach since the mid twentieth century. Precipitating the decline of behaviourism, McCulloch and Pitts (1943) proposed that neurons perform calculations according to an internal logic and therefore behaved lawfully. Chomsky (1959) articulated a scathing argument against behaviourism, suggesting that human communication is not under simple stimulus control. By this time, Miller was investing heavily in attempts to unite interdisciplinary researchers in psychology, computer science, philosophy, and linguistics into a new field of cognitive science (see Miller 2003). Ultimately, these efforts laid the groundwork for theorists such as Marr (1982), Kosslyn (1984), and Fodor (1983) to develop theories of cognition based on the computer metaphor of the mind. According to this view, cognition arises from computations performed on abstract, amodal, symbols (see Neisser, 1967). In these theories, symbols are amodal in the sense that they are completely cleaved from the input systems and can be manipulated independently of them. Newell (1980) suggested that the brain quite literally is a physical symbol system, that neurons (or networks of them) serve as the physical implementation of symbolic computations, much like how the silicon chips in a computer are the physical implementation of symbolic computations (see Hatfield, 2014, for a thorough history of cognitivism). With the introduction of imaging techniques, including the electroencephalography (EEG) and functional Magnetic Response Imaging (fMRI), researchers sought to identify the neural correlates of the computations underlying cognitivist theories. Overall, the computer metaphor has had a profound effect on cognitive neuroscience, and much of the research in the field is guided, whether explicitly or implicitly, by the notion that the brain implements abstract computations. This approach has yielded tremendous insights into the basic science of how the brain works, how the brain relates to behavioural disorders, and has led to the creation of cognitive technologies.

There are, however, a number of important criticisms of cognitivism, both theoretical and methodological. The first major criticism has been theoretical. Cognitivism has largely treated perception and action as separate entities, and this has left a major lacuna in our understanding of how they interact. According to the cognitivist approach, information comes into the system (is transduced by sensors), the system transforms that information (in the brain), and outputs are sent to effectors to produce an appropriate behavoiur (motor action). In this framework, the phenomena of interest occur in the 'black box', mostly the neo-cortex. However, it has long been recognized that this is an oversimplification (see Hatfield, 2014). Indeed, the lack of attention to action and how it unfolds in the environment was one motivation for the development of ecological psychology (Gibson, 1979), which analyzes behaviour as an environmentally embedded activity. Like its Gibsonion precursor, embodiment and grounding recognize the coupling of perception and action and attempt to account for the relationship between the two.

The second major theoretical criticism is that cognitivist theories rely on the notion of abstract representations (e.g. amodal calculations). Here, amodal is used to indicate that the representations and computations of the cognitive system are arbitrarily tied to entities in the world. In what is most commonly discussed as the symbol grounding problem (see Searle, 1980), it is argued that cognitivism provides no way of grounding the meaning of representations; that is, abstract representations cannot be defined by their relationship to other abstract symbols (see Kashak et al., 2014; Glenberg & Robertson, 2000). The symbol grounding problem suggests that meaningful intelligent behaviour cannot arise from the manipulation of symbols that are defined by the relationship they have to each other (Harnad, 1990). To counter this, embodiment and grounding propose that the meaning of any given process is defined by its relevance to action, the body, and/or situated experience. As we will discuss later, there are a number ways different theories address this issue. For instance, meaning might be grounded in the sensorimotor processes of the organism-- in the systems that interface with the environment. In this framework, the way information is taken into the system shapes what is represented. Conversely, meaning might be defined by the actual relationship of the organism to the environment as it behaves. In this case, meaning is manifest at the moment of a given behaviour, and is actually not stored or represented anywhere. Over all, embodiment and grounding address the symbol grounding problem left by the cognitivist paradigm.

A third criticism of traditional approaches is mostly methodological. Cognitivism, as a framework, is merely implied in most cognitive neuroscience research, and rarely do researchers make explicit commitments to the entailments of cognitivism (or the computer metaphor more specifically). When a paradigm of research takes for granted major philosophical and theoretical assumptions, it ignores relationships that exist between brain and behaviour that are not predicted from the implicit theory. One major consequence of this (to be elaborated later) is that certain phenomena or variables of interest are ignored. For instance, what may be a confound under one framework (e.g. size in a visual experiment under the implicit assumptions of the computer metaphor) may be reconstrued as a variable of interest in the other (e.g. graspability under the assumptions of embodiment). These methodological considerations have obvious consequences for experimental design, implementation, and interpretation. Embodiment and grounding attempt to identify and explain phenomena that the cognitivist paradigm tends to ignore.

Although embodiment and grounding are largely a response to cognitivism, they do not aim to *replace* it. In many cases, pitting cognitivism against embodiment or grounding is artificial and contrived (in fact, approaches within the embodied literature are often more at odds with each other than they are with cognitivism). It is not necessarily the case that these approaches are mutually exclusive, and is more likely that they provide complimentary perspectives on a given phenomena (e.g. by analogy, the phenomena of light is described as waves or particles, depending on how it's investigated; see also Zwaan, 2014). In the end, theories with the most predictive power become dominant, but embodiment and grounding have the potential to reveal unique information about our activity in, and experience of, the world.

2. A taxonomy of embodied and grounded approaches

As interest in embodied and grounded cognition has grown, many theoretical and empirical reviews have followed, in books (Varela, Thompson, Rosch, 1991; Shapiro, 2010; Lakoff & Johnson, 1999), edited volumes (Shapiro, 2014; Gibbs Jr., 2005; Pecher, & Zwaan, 2005), numerous journal articles (e.g. Wilson, 2002; Barsalou, 2008; Meteyard, 2012; Körner, Topolinski and Strack, 2015), and special issues (e.g. Lupker, 2015; Borghi & Pecher, 2012). Together, these contributions describe the heritage of embodiment and grounding, and provide examples of cognitive research that has evolved from these ideas.

Despite these efforts, no single theory exists. Furthermore, an over-arching theory of embodied and grounded cognition is unlikely. This is largely because the basic ideas have emerged in different ways in philosophy (e.g. phenomenology; see Gallagher, 2014), artificial intelligence (Brooks, 1991), linguistics (Johnson & Lakoff, 1997), cognitive science (Varela et al., 1991), psychology (e.g. Allport, 1985; Barsalou, 1999), musicology (e.g. Leman & Maes, 2014), evolution and ethology (see MacIver, 2009), and even literature studies (e.g. Johnson et al., 2014) and religious philosophy (e.g. Buddhism, see Varela et al, 1991; Confucianism, see Seck, 2013).

Thus, embodiment and grounding are heterogeneous concepts. They are better defined by the type of hypothesis that researchers use to investigate them than by any single theoretical proposal. To deal with the variety of embodied and grounded approaches, Shapiro (2011) has suggested that three types of hypotheses define research, and we would like to explicate a fourth. While other authors have compared and contrasted different theoretical ideas and offered taxonomic suggestions (e.g. with respect to the relationship between perception and action, Riener & Stefanucci, 2014; the relationship of the body to computations; see Kiverstein, 2012; see also the six versions proposed by Wilson, 2002), we find the following taxonomy is the most useful in characterizing and understanding any given research program.

Shapiro has defined a) the replacement hypothesis, b) the constitution hypothesis, and c) the conceptualization hypothesis, and we will suggest d) the influence hypothesis. Each is discussed below.

The replacement hypotheses. In some embodied cognitive frameworks, representations are discarded. In this domain, it is argued that behaviour is mediated not by incoming sensory information activating different representations, but by sensorimotor contingencies (i.e. the statistical regularity) that the organism experiences as it moves through the environment (see Myin & Degenaar, 2014; O'Regan & Noë, 2001). According to this view, the brain ‘picks up’ on these contingencies and exploits them to direct behaviour. In this approach, there is no need to model cognition with symbolic representations and algorithmic computations. Support for these notions comes from robots that perform tasks with an embodied architecture (Brooks, 1991). This approach is extended by radical embodied cognition in which organism-environment interactions are described in mathematically succinct ways using dynamic systems theory (e.g. Chemero, 2011). The replacement hypothesis accounts, in general, for the approach taken by ecological psychologists who study cognition in the Gibsonian tradition (see also Wilson & Golonka, 2013), and represents a significant departure from cognitivist approaches.

The constitution hypothesis. Stemming from arguments in the philosophy of mind, some researchers argue that cognitive systems do not exist in the brain alone, but extend to the body and the environment (i.e. the environment is a part of cognitive processing; see Clark and Chalmers, 1998). For instance, the use of a grocery list to remember which items to pick up on the way home is constitutively part of the process of 'remembering', and therefore can be modeled as a part of the memory system. In this framework, behaviour requires an analysis of the ways in which the environment is coopted to perform cognitive acts. Here, representation may or may not be central to how cognition is modeled; the main interest is in describing the ways in which the environment scaffolds cognition (see Clark, 2008; see also Hutchins, 2000, 2010, for an introduction).

The influence hypothesis. Though other authors have previously identified this perspective on embodied research (e.g. Wilson & Golonka, 2013), we wish to formalize it as the influence hypothesis. According to this hypothesis, the state of the body influences cognition. In many cases, the mechanisms of this influence are not specified, and the prediction is only that bodily states bias cognition in predictable ways (e.g. Witt, 2011). For instance, it has been shown that the probability of a judge giving a favarouable parole decision depends on whether they are hungry or not (Danziger et al., 2011). The influence is bi-directional. Much research on mental imagery has shown that voluntarily imagining events can improve behavioural performance, a case of cognition affecting the body. For instance, imaging running performance improves running ability (e.g. Burhans et al., 1988), imaging piano performance improves piano playing (e.g. Bernardi et al., 2013), and mentally rehearsing specific surgical procedures improves surgery (Arora et al., 2011; Louridas et al., 2015). Such effects are relevant clinically as well, in which imagery can lead to the maintenance of disorders such as depression and anxiety and the physiological consequences of them (vasodilation, sweating; see Pearson et al., 2015). However, because this research is often vague with respect to its theoretical commitments, the conceptual interpretation of many of these results is not straightforward. We identify the influence hypothesis in cases where there are no strong commitments about the mechanisms underlying the relationship between the body and cognitive performance. In many of these cases, cognitivist theories might best explain the results, and they are embodied only insofar as they describe an influence of the body on cognition.

The conceptualization hypothesis. This hypothesis posits a causal, functional role of the body and sensorimotor systems in generating intelligent behaviour. Specifically, this hypothesis suggest that simulations/reactivations in these sensorimotor systems serve as the fundamental building blocks of cognition, and therefore, cognitive processes are supported by simulations, either retroactively (as in simulations of past experiences) or proactively (as in planning, or creative problem solving). According to this view, to know that the object lying on the table is a hammer, we must reactivate our experiences with a hammer— a network connecting visual, auditory, and sensory-motor information. Additionally, in the future, when thinking about a hammer, we use similar reactivations as the basis of our cognitive operations. Indeed, all of our thoughts about hammers will rely on these modality-derived simulations in some way.

Importantly, the conceptualization hypothesis has attracted the most attention in cognitive neuroscience, especially under descriptions of grounded cognition (Barsalou, 2008), and will be the major focus of the rest of the chapter. Grounded hypotheses maintain some form of the representationalist doctrine inherited from cognitivism (see Barsalou, in press). Below, we discuss the conceptualization hypothesis in more detail, elaborating on the major theoretical proposals as well as reviewing some of the basic evidence supporting its major predictions.

3. The conceptualization hypothesis in cognitive neuroscience.

The conceptualization hypothesis is the basis of much research in cognitive neuroscience and cognitive psychology. It is discussed in detail in reviews of grounded cognition (see Barsalou, 1999; 2008), situated conceptualization (see Barsalou, in press; 2009), the convergence framework (Damasio, 1989; Meyer & Damasio, 2003) and more generally in the literature on modality-specific semantic memory (see Slotnick, 2004; Martin, 2007; Thompson-Schill, 2003; Meteyard et al., 2012). Fundamentally, the conceptualization hypothesis is about how an organism forms and uses concepts. Here, a concept is broadly defined as states (or sets of states) that elicit similar responses, and are cognitive structures that underlie almost all of our intelligent behaviour. However, unlike previous accounts of concepts (e.g. i.e. traditional views of semantic memory; Tulving, 1972; see Smith, 1978), conceptualization attempts to demonstrate that an organism's sensorimotor systems ground how concepts are formed and how the organism makes inferences about possible routes of action, the affordances of different stimuli, and, in the case of humans, how we communicate experiences and plans with each other through language. In this way, the conceptualization hypothesis makes predictions about the primitives, or building blocks, of all of cognitive processing.

What are the building blocks of cognition? From a grounded cognition perspective, the building blocks of cognition develop in the modalities and the motor system, constrained biologically by the neural systems that have evolved to interface with the environment (see Barsalou, 1999; Barsalou et al., 2003; and Meyer & Damasio, 2003, for detailed reviews). Each modality responds selectively to a particular type of stimulation (electromagnetic in the visual modality, density of air molecules in the auditory, etc.), with its associated neural networks parsing that information (e.g. line orientation or pitch) in a hierarchical processing stream (see also, Thompson-Schill, 2003). Additionally, neural networks support motor actions that are constrained by the body an organism has (e.g. a neural network can support an arm swing if there is an arm). These neural networks are organized in a reciprocal, hierarchical manner, such that co-occurrences of particular types of physical stimulation (e.g. concurrences of lines that form edges, of pitches that come form animals or people; see the parallel distributed processing model of Farah & McClelland, 1991) become potentiated via a mechanism such as Hebbian associative learning, or by the weight adjustments that occur in distributive, connectionist networks (e.g. McClelland & Rumelhard, 1985). For instance, in encountering a hammer repeatedly, neural ensembles that respond to different features in each of the modalities (the general shape in visual modality, the sounds it makes in the auditory modality, the way it is held in the motor modality, etc.) are reliably co-activated. The regularities in these co-occurrences serve to establish strong, functional, associations between the different types of features, distributed across the brain. These associative relationships between the features define the distributed network that represents the concept of a hammer (Martin, 2007; also see Barsalou, 1999; Pulvermuller and Fadiga, 2010 for related discussion). Critically, to support ongoing cognition, feature information is retroactively activated via reciprocal connections (Damasio, 1989; Barsalou, 1999). These retro activations are a type of simulation of past experience, and they inform an organism's ongoing behaviour and its plans for future action. Thus, an organism may simulate the features of the hammer (it's visual shape, the sounds it makes, the way it is held, etc., as encoded its sensorimotor systems) when information about that class of stimulus is needed during a cognitive task (e.g. when talking about how to use a hammer). Importantly, in most accounts, simulations are not conscious nor are they complete (see Barsalou, 2005; Barsalou et al., 2003).

In this way, simulation is a critical construct in the conceptualization hypotheses (see also Anderson, 2010; Hesslow, 2002). Below we review a number of predictions of this construct and the evidence that supports these predictions. For simplicity, we will focus only on studies that have explicitly related brain activity to behaviour, as it is in these areas the theory of grounded cognition has had the greatest impact on cognitive neuroscience.

Prediction 1: Modality specific information is activated during cognitive tasks. One obvious prediction, and one that has received abundant support, is that the brain regions activated during perception and action should be active when performing cognitive tasks (a prediction that doesn't necessarily fall out of cognitivist theories *a priori*). Initial support for this idea comes from the literature on visual imagery. It has been known for some time that mental imagery depends on the same (or overlapping; see Rugg and Thompson-Schill, 2013) neural substrates as perception (e.g. Kosslyn, 1996; see Moulton & Kosslyn, 2009) or motor activity (e.g. Jeannerod & Frak, 1999). Under grounded cognition, however, this prediction extends to all modalities under all types of conceptual processing, whether conscious imagery is explicitly experienced or not (e.g., during unconscious simulations). For instance, when identifying a hammer, regions involved in grasping actions, as well as visual and motion areas associated with seeing a hammer in use, should be active. Importantly, because we use conceptual representations dynamically, we might expect that not all information is activated equally (see Lebois, Wilson-Mendenhall, & Barsalou, 2015). This prediction has been supported in a number of cognitive tasks (e.g. Chao & Martin, 2000; Fernandino et al., 2015a, 2015b; see Martin, 2007 and Binder et al., 2009, for reviews). Similar findings have been widely reported in language, in which reading verbs corresponding to hands (e.g. pick) and feet (e.g. kick) activates the motor cortex in a somatotopic manner (Hauk, Johnsrude, & Pulvermüller, 2004; see Pulvermüller 2005 for a review). Similarly, research on low-level perception has shown that colour sensitive regions in the occipitotemporal lobe are active when verifying that a word (e.g. taxi) matches a particular colour (e.g. yellow; Simmons et al., 2007; see also Hsu et al., 2011; Hsu, Frankland, & Thompson-Schill, 2012). Additionally, viewing someone performing a particular action activates the same neural regions that are implicated in producing that action (Iacoboni et al., 1999; see Rizzolatti & Craighero, 2004 for a review of the 'human mirror neuron system'). Finally, verifying a gustatory property of a noun (e.g. that something is sweet) activates orbitofrontal areas implicated in taste (Goldberg et al., 2006). Overall, a great deal of neuroimaging research supports the notion that modality specific information is activated during cognitive processing of words, actions, and objects (see Fischer and Zwaan, 2008; Kiefer and Pulvermüller, 2012; Slotnick, 2004; Thompson-Schill, 2003; Meteyard et al., 2012 for reviews).

While these findings are well supported, more recent research has explored their specificity. Indeed, according to one version of the conceptualization hypothesis, representation of a concept will depend on whether particular sensorimotor features exist in a person's repertoire. To investigate this, Calvo-Merino et al. (2006) studied male and female ballet dancers. Because there are gender specific movements in ballet, each gender is a motoric expert in executing a particular class of actions. These authors showed that regions implicated in action planning, including the cerebellum and premotor cortex, are more active in male ballet dancers viewing videos of male movements vs. female movements, and visa versa. This finding suggests that action simulations are grounded in specific ways as the result of experience. Similarly, in language comprehension, Beilock et al. (2008) showed that hockey players reliably activate regions implicated in action planning, namely the left premotor cortex, when making decisions about sentences that described hockey actions; in contrast, novices activated primary motor regions. This suggests that experts simulate higher-order action plans, whereas novices are left to simulate the primitive, isolated, actions in an attempt to comprehend the sentences (see also Lyons et al., 2010). Overall, not only is there evidence for simulation of action in different cognitive tasks, but the types of simulations depend on the quality of our embodied experience (see Beilock, 2009, for a review of expertise effects in memory and preference judgments).

Prediction 2: Modality specific information plays a functional role during cognitive tasks. The finding that modality-specific information is activated during cognitive tasks supports the minimal prediction of grounded cognition that modality specific information is activated during cognitive tasks. However, one strong criticism of this literature is that these findings merely demonstrate that modality-specific activity is correlated with cognitive performance but not necessarily fundamental to it (i.e. activity might simply cascade from amodal representations to modality-specific features; see Mahon & Caramazza, 2008). While concomitant activity is predicted *a priori* by grounded approaches, most correlational fMRI studies cannot rule out an amodal account. It is relevant to the theory of grounded cognition whether the activation of modality specific information plays a causal role in cognitive performance.

Cognitive neuroscientific investigations of the functional role of modality-specific information have used both neuropsychological patients and transcranial magnetic stimulation (TMS) to determine whether disruption (or activation) of sensory-motor information impairs or facilitates cognitive performance. The conceptualization hypothesis makes a specific prediction: interfering with (or facilitating) a simulation should causally interfere (or facilitate) cognitive processing. Supporting this stringent prediction of the conceptualization hypothesis, research has shown that TMS over hand-related premotor cortex facilitates lexical decisions of action words performed with the dominant hand (e.g. “to throw”) but not non-hand action words (e.g. “to wander”) (Willems et al., 2011; see also Buccino et al., 2005). Similarly, Parkinson’s patients, in which abnormalities to the motor system result in motor deficits, show selective impairment comprehending sentences with hand and arm actions words but not other, non-action words (Fernandino, et al., 2013).

More demonstrations are needed before strong conclusions are justified. We note that, according to the grounded hypothesis, conceptual performance may be supported by different degrees of activation across the modalities. This suggests that interfering with one modality (e.g. motor) may not result in disruptions of performance if information from the other modalities can support the task. For instance, in a task in which visual information is strong enough to support performance, interfering with the motor system may not affect it (see Matheson et al., 2014). A goal of future research is to determine the extent to which different modalities contribute to the performance of different tasks. However, despite this challenge, current findings do support the hypothesis that modality-specific information plays a functional role in cognitive performance.

Expanding on this, more recent research has investigated the specificity of modality-specific activity and its contribution to cognition. For instance, Repetto et al. (2013) used repetitive TMS to disrupt functioning of the primary motor region in either the left or right hemisphere of right-handed participants. They showed that after stimulation of the left hemisphere (which controls the right hand), participants were impaired at judging the concreteness of verbs that could be performed with the right hand (e.g. to draw) but not other, non-hand related verbs (e.g. to settle); this effect was not present after right hemisphere stimulation (and therefore the disruption of left-hand simulations). This suggests that a specific simulation of right-hand action (and not hand action in general) contributes causally to verb comprehension.

Another way in which researchers have addressed the causality of neural simulations is to investigate their timing. It is argued that if a simulation occurs early enough, this is evidence that it plays a causal role in organizing behaviour (e.g. Boulenger et al., 2006; see Hauk, Shtyrov, & Pulvermüller, 2008, for a review). For instance, using magnetoencephalagraphy (MEG), Pulvermüller et al. (2005) showed divergent activity at about 200 ms for face and leg related words, localized in a somatotopic manner along the central sulcus. Because word recognition (identifying that a stimulus is a word) occurs earlier than this and many semantic effects occur later, this finding led the authors to propose that this somatotopic activity contributes causally to the semantic processing of the word. Future research should investigate the timing of activations in detail to determine their role in cognitive performance. However, overall, there is evidence of a causal relationship between specific modality-specific simulations and cognitive performance.

Prediction 3: Modality specific information is situated. Recently, researchers have focused on investigating the dynamics of modality-specific simulations (e.g. see Tomasino & Rumiati, 2013). A major tenant of grounded cognition is that simulations should depend on the task that is performed (i.e. the type of conceptualization that is needed), reflecting the fact that a simulation takes place in a particular cognitive or social context (see Barsalou, in press; Willems, & Francken, 2013; see Lebois et al., for a review of context sensitivity effects). The context (i.e. everything that determines what is needed to perform a given behaviour) should guide, in predictable ways, the activation of modality-specific representations. The general idea is that a history of co-occurrences sets the limits on the simulations (what aspects of an experience are simulated). For instance, in encountering a hammer in a tool shed, aspects of the tool shed might serve as situational cues that activate a rather specific action, such as swinging the hammer to put a nail into wood. These situated cues would make available the modality specific information relevant to that action (motor information about swinging, visual shape information about the motion trajectories of the hammer, auditory information about the sounds it makes, etc.). Under these circumstances, the simulated activity should contribute to cognitive tasks, such as describing what a hammer is. In contrast, in encountering the hammer in a hospital, aspects of the hospital might make available only a subset of simulated information (e.g. how to pick it up and carry it). In this way, modality-specific simulations are constrained by information in all of the systems of the brain.

Currently, situatedness is not often studied explicitly. However, recent research has shown that context determines the extent of modality-specific activation that occurs during cognitive performance. For instance, van Dam et al. (2012) showed that modality-specific activation of the inferior parietal lobe in response to a word (e.g. a tennis ball) was greater than abstract words when participants made judgments about action qualities (e.g. can this be used with a foot?) but not colour qualities (e.g. is this green?), suggesting that the cognitive context shapes the extent to which action information is activated to action words.

Situatedness should also shape the functional relationships between neural regions that code for different modality specific features of the world. Such changes would constitute strong evidence for the idea that conceptual representations are constrained by the ways in which an organism is embedded in its environment. Importantly, recent research has shown that context modulates the functional connectivity between modality specific brain regions. For instance, in an extension of the previous study, van Dam et al. (2012) showed that, when making action related judgments about auditorily presented words (e.g. can you use a tennis ball with your feet), functional connectivity increased between auditory regions and a host of regions associated with action planning and execution, including the motor cortex, the premotor cortex, and the cerebellum. In contrast, when making colour related judgments (e.g. is a tennis ball green?), the functional connectivity increased between auditory areas and visual areas implicated in visual processing tasks, including the precuneus (see also Ghio & Tettamanti, 2010 for the role of concrete vs. abstract contexts; Tomasino et al., 2013; for the role of athletic expertise). Though much more research is required, these initial attempts support the general view that the relationship between brain, body and behaviour is determined by situatedness.

Recent/Emerging Trends

4. Major themes arising in grounded cognitive research

In reviewing the large number of theoretical and empirical discussions of grounding in cognitive neuroscience, a number of consistent themes emerge. Identifying these themes is an important step towards specifying in more detail the hypotheses relevant to cognitive neuroscience. In particular, we focus on the models of grounded cognition that allow for mechanistic predictions about the relationship between brain and behaviour and environment. Identifying these mechanisms will help distill the large number of theoretical and empirical discussions into a few unified principles that can guide grounded cognitive neuroscience. Below we highlight at least three major themes that have arisen, and identify relevant theoretical and empirical results.

Major theme 1: Associative processes. Almost all accounts of grounding posit that a fundamental principle underlying brain organization is associative processing (of the form posited by Hebb, 1949). Indeed, in the two most influential accounts, Barsalou (1999) and Damasio (1989) propose that distributed representations are formed as the co-occurrences of different features are captured by higher order neural centers (also see Simmons & Barsalou, 2003). Such a mechanism is a necessary component of the conceptualization hypothesis, and it is difficult to understand how simulations of sensorimotor or situated content could occur without associative processes guiding the modality-specific activations that are active in any given context.

Importantly, much basic neuroscientific research demonstrates Hebbian learning within neural networks (see Brown et al., 1990; Bi & Poo, 2001; Caporale & Dan, 2008), and such a mechanism is thought to underlie aspects of learning and memory since the discovery of long-term potentiation. However, Hebbian learning has a broader application in grounded cognitive neuroscience and, reflecting this, many influential proposals about the representation of concepts include explicit descriptions of the role of Hebbian learning (e.g. Keysers & Perret, 2004; Pulvermuller, 1999; Barsalou, 1999, and the commentary by Schwartz et al., 1999). Hebbian-like associative processes are also implicated in controlling situated simulations (e.g. Spivy and Huette, 2014), and in flexibly activating different responses in different contexts (e.g. Miller and Cohen, 2001). Importantly, evidence for predictive coding (a general proposal about neural functioning; see Clark, 2013), is consistent with the proposal that the brain uses bidirectional feedback, formed through associative processes, to self-generate predictions (i.e. simulations) in a probabilistic fashion (see also Grush, 2004).

The importance of associative processes for grounding is clearly demonstrated in both the convergence zone framework (Damasio, 1989) and the perceptual symbols system framework (Barsalou, 1999; Simmons & Barsalou, 2003), both explicit models of grounded cognition. Both of these accounts suggest that, in the brain, different regions are ‘maps’, coding for sensorimotor features of experience (or conjunctions of features), and some are ‘controllers’, which capture the co-occurrences and can retroactivate them as needed (see Damasio, 2012). Maps and controllers are both formed and activated based on associative weights that are established as experience accumulates. Interestingly, this description aligns with results concerning the relationship between the resting state network and its deactivation. Specifically, the medial resting state network (and the network implicated in semantic processing more generally; see Binder et al., 2009) may reflect the activity of controllers that trade off activity with maps within the primary sensory areas during perceptual tasks (see Binder et al., 1999), or at the very least, bimodal, trimodal, and heteromotal convergence zones that represent important information derived predictably from the modalities (e.g. convergence of visual, somatosensory and motor information in the case of manipulation knowledge; see Fernandino et al., 2015). While this notion of maps and controllers is surely a simplification of how simulations take place, it is highly likely that the most successful form of grounded theory will determine the ways associative processes coordinate activity between maps and controllers to give rise to intelligent behaviour (Binder, 2016).

Major theme 2: Network dynamics: Associative processes are also fundamental to understanding dynamics. For the grounded cognitive neuroscience, dynamics (in particular, changes in brain dynamics during task performance) is critical to understanding how concepts are activated. Indeed, according to this view, concepts are not static entities in the brain, but are activated in an ad hoc, distributed, and dynamic, fashion (see Casasanto & Lupyan, 2015; Barsalou, in press). Network approaches in cognitive neuroscience are increasingly popular (e.g. Medaglia et al., 2015) and are becoming necessary to understand brain function (see Kiverstein, 2015). While network dynamics is studied as a phenomenon of interest in its own right (Sporns, 2011), its application to grounded cognitive neuroscience is particularly important. Given some of the *a priori* predictions these approaches make about the brain, the approach of network dynamics will contribute to the computational formalization context dependent, modality-specific simulations.

There are a number of emerging findings from network neuroscience that are consistent with the predictions of the conceptualization hypothesis. First, analysis of connectivity within the human brain, using both structural and functional methods, reveals a large number of highly interconnected clusters (i.e. nodes), supporting the idea that cognitive functions are neither strictly localized (modular), nor equipotential (see Sporns, 2011). However, in the current state of knowledge, it is not clear what each node contributes to a cognitive task. Simulation theories (e.g. Barsalou, 1999; Simmons & Barsalou 2003; Meyers and Damasio, 2003) predict a network structure in with nodes representing modality specific information in the visual, auditory, somatosensory and motor domains, converge onto higher-order conjunction or convergence nodes. Additionally, functional connectivity between modality specific nodes and convergence nodes should change with the task (e.g. more connectivity between visual and auditory nodes when this information is relevant to the task).

Second, there are emerging ideas about how dynamics are constrained within particular tasks. For instance, much evidence supports the notion that early sensory modalities do not simply respond to features of the environment in a bottom up fashion, but respond by calculating the difference of the incoming signal to an expected, predicted signal (see Clark, 2013). This idea provides a way in which situatedness can influence network dynamics by altering the brain’s predictions in different contexts. In particular, because higher order regions within sensorimotor systems can influence what is expected in any given situation, they can shape the activity within the modalities in a context sensitive manner, one that is dependent on personal the experiences of the organism bound by a body with a particular form. While still nascent, research on network dynamics will be instrumental to developing the theory of grounded cognitive neuroscience.

Major theme 3: Representation. Some forms of embodied cognition completely discard the notion of representation, especially the radical embodied framework (e.g. Chemero, 2011). Conversely, representations are the central element of any current cognitivist model. Grounded cognition is a middle ground between these two extremes, recognizing the importance of brain, body, environment interactions, but still positing representational power to the brain. However, it denies full-fledged, picture-like representations of the world or symbolic representations taking an amodal form. Whether representations are needed for cognition, and whether there is only one type of representational capacity in the brain, remains an ongoing debate (see Dietrich & Markman, 2003). However, we argue that there are a number of reasons cognitive neuroscience is not ready (and should not be ready) to discard the concept (see Barsalou, in press, b).

First, cognitive neuroscience inherits a large number of theoretical constructs from its cognitivist progenitors in psychology and cognitive science more generally. Many of the models built from these constructs are representational, and the fact that some behaviours are predictable some of the time is prima facie evidence that representation, as a scientific construct, has predictive power (for example, consider the visuo-spatial scratchpad of Baddeley and Hitch, 1974). Despite cognitivism's limitations, it seems disadvantageous to disregard its rich history of predictive power in this domain. What is at stake, in terms of grounded cognitive neuroscience, is what is represented during cognitive tasks.

Second, there are a number of reasons to suppose that the brain's activity does indeed reflect representation of some aspects of experience. We argue that representation occurs when two conditions are met (see Barsalou, in press b): a) when variable A possesses information about variable B, allowing us to interact effectively with B by using A; and b) when variable A (and its relationship to B) was established to serve a function (i.e. when it was established to achieve a goal). For example, though cells within the occipital region are modulated by feedback from the rest of the brain, and though this feedback can modulate activity in this region in response to stimulation (e.g. Murray et al., 2002), there is enough consistency in the activity to isolate receptive fields and tuning curves. Consequently, researchers can rely on this consistency to make predictions about events in the world (e.g. a bar of light in a particular spatial location). We argue that this type of relationship is indicative of representation. In these cases, whether we are discussing bottom-up activity clearly elicited from a sensory event or 'top-down' modulations associated with predictive coding (e.g. Muckli and Petro, 2013; see also Petro, Vizioli, & Muckli, 2014), brain states represent a particular relationship between the body, brain and environment, and do so because they serve the function of guiding adaptive behaviour. It seems likely that the future of grounded cognitive neuroscience will benefit from modeling representations.

We emphasize that, in the context of the conceptualization hypothesis, representations are neither full-fledged reproductions of objects, places, or people in the environment, nor are they amodal or implementable in just any physical system (see Prinz & Barsalou, 2000). Instead, representations are highly constrained by the physical system they find themselves in. Because of this, representations can be thought of as subsymbolic (Varela et al, 1991). One major goal of grounded research is to determine what features (e.g., primary sensory and motor) and conjunctions (e.g., multimodal) are represented in the brain's 'maps' and how their activation is constrained by the situatedness of the organism. Importantly, unlike traditional cognitivist accounts of cognition, which are free to assign any type of symbolic content to representations, the conceptualization hypothesis makes predictions about what sorts of information should be represented by the brain, given the bodies we inhabit, the anatomical architecture of our brains, and the situations we find ourselves in.

Future Directions

5. Consequences of grounding for cognitive neuroscience

Grounded cognition has a number of consequences for cognitive neuroscience, some theoretical and some methodological. While grounded approaches attempt to address some of the critical issues with traditional cognitivist approaches there are a number of more profound entailments. We identify a few of them below.

Consequence 1: Redefining ontology. Cognitive science, regardless of approach, attempts to identify the mechanisms underlying intelligent behaviour. Cognitivist approaches have largely assumed that there is a set of mechanisms that take input from the environment and then transform it into meaningful output. In cognitive neuroscience, researchers attempt to correlate these proposed mechanisms with activity patterns in the brain. Thus, major research programs are aimed at defining the neural 'basis' of many cognitive constructs, such as attention (e.g. Posner & Rothbart, 2007), decision making (e.g. Gold & Shadlen, 2007), and memory (e.g. Squire & Wixted, 2011). Modern textbooks on cognitive neuroscience are often organized around these postulated functions, maintaining a strict separation of action from the rest of psychological functioning (see Gazzaniga et al., 2013; Ward, 2015). However, grounded cognitive neuroscience, by reorienting us to the relationship between brain, body, and environment, suggests that all of these things are codetermined, and consequently, intelligent behaviour will not be explained by identifying neural correlates of our traditional constructs for cognitive mechanisms. In this framework, the world is not simply 'out there' for a nervous system to adapt to and learn about, with separate systems for perception, attention, and memory; rather, different environments, different nervous systems and bodies, lead to different behaviours that or more or less specialized (Varela et al., 1991) by virtue of shaping the sensorimotor representations of the organism. Because of this, classically held constructs such as memory or attention are better construed as dynamic processes that unfold as the brain, body, and environment codetermine one another. Thus, for some constructs like attention and memory, it might not make sense to look for neural 'basis' at all, and it certainly doesn't' make sense to identify the neural correlates of these constructs as separate processes from those that determine action.

Importantly, grounded perspectives are not the only ones that question our current cognitive ontology. The ways in which brain data can inform classical cognitive theories has been questioned before (see Coltheart, 2013; Mather et al., 2013), and other authors have challenged the ontological status of some of our most beloved concepts (e.g. attention; Anderson, 2011; Cisek, 2007; see Price & Friston, 2005 for an overview). This suggests that some classically derived constructs might not have the same ontological status in a grounded cognitive neuroscience.

Consequence 2: Redefining methods. Because ontology is defined differently, the methods used to study cognition are different as well. For instance, under the cognitivist framework, we might search for a stage in processing in which object recognition occurs, which is has methodological consequences for how we design an experiment. In contrast, grounding perspectives assert that, because of the dynamic interdependent nature of body, environment, and brain, there is no *single* stage at which recognition occurs; rather, recognition is instantiated at by the overall state of affairs of the body, brain, and environment. One consequence of this is that recognition, rather than being a specific state in a series of brain activations (e.g. a recognition stage), is a process that manifests a particular behaviour (e.g. saying the word 'hammer' in response to the visual presentation of the image of a hammer). In this case, the methodological procedures for studying recognition (i.e. the generation of the word hammer) will depend on the expectations about whether it is a state (in which neural processing at a particular moment reflects recognition), or a process (in which no single moment of neural, body, environment interaction is identifiably 'recognition').

A more significant consequence of this methodological change may be that new analytic procedures can be used to understand cognition. While nothing is prohibiting new analytic procedures from illuminating more traditional cognitivist hypotheses, developments in dynamic systems theory, Bayesian inference, multivariate analysis, and network neural science promise to be particularly useful in grounded cognitive neuroscience. Indeed, because these approaches propose that cognition arises during dynamic interactions between brain, body, and behaviour, and/or simulations in distributed representational networks that are activated in probabilistic ways, these analytical techniques will be indispensible.

Consequence 3: Redefining variables. Kousta et al. (2011) showed that words are not best described as a variable with levels 'abstract' and 'concrete', as is typically discussed in cognitivist literature, but as a variable with levels 'emotional' and 'non-emotional' (high or low valence). These authors propose that simulations of interoceptive states partially underlie our ability to use abstract concepts. This is just one example how a grounded perspective can redefine a variable in such a way that is not predicted by cognitivist frameworks. Such redefinitions lead to new insights about behaviour. For instance, in a visual paradigm, object size might describe levels of a variable (e.g. large vs. small), something that is very important to the cognitivist construal of vision. However, grounded approaches encourage us to consider the entire brain, environment, and body, and may redefine an object size variable as a graspability variable (e.g. small = graspable, large = not graspable). This allows for unique predictions that do not necessarily fall out of a strict view of size as a visual variable, such as interactions between the presence of the hand in the visual field and the proximity of the object (i.e. object affordances; e.g. Linkenauger et al., 2010). Regardless of whether these two examples reshape the entire body of research on abstract words or object size, the general point is that grounding can redefine variables and lead to unique findings.

Independent variables are not the only thing that gets redefined. Grounding encourages measurements of new dependent variables as well. Again, a traditional framework might overlook these dependent measures. For instance, because of the bi-directional nature of perception and action, some authors have begun using kinematic measurements to have led to the discovery of novel phenomena. Till et al. (2014) showed that the presence of a graspable object in the visual field influences the 3-D trajectory of the hand as it reaches for an irrelevant object, suggesting that even while the hand is in motion, processing objects with incompatible actions influences the reach. This relationship could not be revealed with traditional verbal or button press responses, or with imaging tasks in which no action is measured. Importantly, this finding is not predicted by traditional cognitivist frameworks, as the motor response is viewed as merely the output of cognitive processing, not central to it. How such measurements relate to brain activity remains to be determined, but developing new dependent measures remains an exciting avenue for future research.

Consequence 4: Redefining applications. Ultimately, a framework within cognitive neuroscience that focuses on grounded predictions will lead to unique applications in many areas of psychology (see Barsalou, in press), and to the development of novel cognitive technologies.

For instance, grounding has much to offer education and cognitive training. Again, much current research in these areas is based on traditional accounts of cognition in which input and output are incidental to the processes of learning. Thus, most applications tend to be computer based, either on desktops or tablets. Research is beginning to show, however, that such learning contexts are limiting. For instance, people are better at reporting the details of a narrative if they experience reading the text in a book than on a tablet (Mangen & Kuiken, 2014). While reading a book, there is ample embodied experience (e.g., holding the pages in your hand, moving your eyes down a page, flipping pages, etc.); conversely, much of the sensorimotor changes that occur along with the narrative are abolished on an electronic tablet. In this case, the embodied experience covaries with the narrative, and this offers clear advantages for the retrieval of the narrative structure. Related to this, much current western curriculum is based on abstract analyses of language (grammar, words) or mathematics (symbols, operations), with little if any emphasis on the role of grounded simulations and action. For instance, though algebra is considered a quintessential symbolic operation, unrelated visual variables (e.g. the physical layout of elements of the equation) influence the likelihood a problem is solved (e.g. Landy and Goldstone, 2007), and overt eye movement behaviour systematically predicts arithmetic performance (see Goldstone, Landy, and Son, 2010, for a review). Recently, intervention programs that encourage young children to physically or mentally simulate actions and events result in large increases in reading comprehension and retention of simple texts, as well as improvements in scientific reasoning (e.g. the identification of experimental confounds; see Glenberg, 2008; 2011;

Kiefer and Trumpp, 2012). Together, these findings suggest that by exploiting the relationship between action and concepts we can improve educational initiatives and enhance learning.

Additional applications of grounded cognitive neuroscience have been identified in law (see Davis et al., 2012). Indeed, in the current western model, judicial decisions are thought to rely on the careful weighing of facts, and eyewitness testimony is thought to rely on memories that are recorded with relatively high fidelity. These ideas are heavily reinforced by traditional cognitivism. However, recent research has shown a host of seemingly irrelevant bodily or grounded information could affect decisions of jurors and judges and reports made by eye-witnesses. For instance, an interviewer's gestures may influence an eye-witness report by unconsciously activating aspects of a concept through action (e.g. gesturing a heavy object when asked "What was the man carrying?" could elicit false information about a heavy suitcase; see Broaders & Goldin-Meadow, 2010). This is another way in which grounding orients us towards variables that would otherwise go unexamined and suggests ways in which we could alter the structure of judicial proceedings and interrogation to eliminate unwanted, embodied, effects.

Another application that grounded cognitive neuroscience is changing is artificial intelligence. It has been argued for some time that embodiment, broadly construed, has the potential to transform robotics, and evidence has amassed supporting this (see Brooks, 1991; Metta et al., 2010). But because grounding redefines how an organism comes to categorize its environment, any artificial architecture that can adapt to environments in flexible ways is likely to be useful (e.g. in space exploration). Further, within the specific context of cognitive neuroscience, grounding suggests a different structure of intelligence than traditional approaches (i.e. grounded simulations in modality specific processors vs. abstract, amodal computations). This clearly has consequences for how we build artificially intelligent systems, along with significant consequences for the types of information we can expect to learn from them. Future research will determine whether one approach is more powerful than the other, but in the meantime, researchers are working on formalizing the computational architecture to support grounded learning in artificial systems (e.g. Pezzulo & Calvi, 2011; see Pezzulo et al., 2013)

Finally, grounding will have major consequences for clinical applications within clinical psychology and psychiatry. Already, much interest has developed in simulation accounts of disorders such as autism spectrum disorder. One hypothesis is that disruptions in the ability to simulate other peoples' actions (or emotions, or viewpoints) underlie the core deficits of the disorder (Eigsti, 2013). Such theoretical insights will contribute to shaping how such disorders are screened and could result in effective individualized treatment programs, for instance, by targeting specific simulation deficits in one domain or another (e.g. emotion vs. action), or targeting early motor deficits to improve imitative movement (see Gallagher & Varga, 2015). Research in grounded cognitive neuroscience may lead to novel insights of wide variety of currently defined disorders in the Diagnostic Statistics Manual (DSM; see also Fuchs & Schlimme, 2009).

6. Major critiques.

As this chapter demonstrates, grounded cognition has much to offer cognitive neuroscience, and much evidence has accumulated supporting some of its main hypotheses. However, the conceptualization hypothesis is not without criticism and there are a number of issues that need addressing (Barsalou, 2010).

First, there are a small number of commonly raised issues that have yet to be sufficiently dealt with. For instance, Mahon and Caramaza (2008) have adamantly argued that there is no evidence from neuroimaging research that modality specific activations are anything more than simple co-activations; they serve no functional role and are merely incidental to the processes that do the computational work. While we have shown that some research has addressed this issue, much more causal evidence needs to be amassed, perhaps through interference paradigms (e.g. Yee et al., 2011). Despite this, it is clear that modality-specific activations do occur and we feel it is unlikely that they play no functional role in cognitive tasks. Thus, the more specific challenge for grounded approaches is not to account for all of cognition by appealing to modality-specific representations, but to show how grounded processes contribute to and influence cognitive processing.

Another common criticism is that grounded perspectives cannot account for the acquisition of abstract concepts or the creation of novel concepts that have not been experienced and therefore cannot be simulated (see Dove, 2012). The most common responses to this are that a) abstract concepts are grounded by a metaphorical mapping of an abstract domain (e.g. love) to a concrete one (e.g. a journey; see Lakoff & Johnson, 1999) or b) abstract concepts are grounded by emotional or interoceptive states (see Vigliocco et al., 2014), or c) abstract concepts are grounded in events and situations and therefore are more temporally spread out than their concrete counterparts (see Barsalou & Wiemer-Hastings, 2005). Of course, abstract concepts could be grounded in all three of these ways, perhaps weighted differently depending on the particular concept. Importantly, we argue that abstract thought might rely on neural regions that processes abstract information (i.e. information that is abstracted across instances), but it does not follow that these regions are amodal (i.e. arbitrarily defined, independent of the modalities) neural processes. Indeed, grounded cognitive theories recognize that modality-specific information converges in different neural regions (convergence zones). The kind of information that converges in any given region will be highly constrained by the structural anatomy of the region. Functionally, these convergence regions capture co-occurrences of information across different modalities. Thus, the activity of a convergence zone in cognitive tasks reflects multimodal information about conjunctions of features in the world or situation that an organism is in, but they are not at all arbitrarily related to information in the world. Future research needs to provide a precise mechanistic account of how conjunctive information is used during tasks in which we produce abstract concepts.

A final common criticism is that formal computational models are lacking (see Barsalou, 2010). While attention to this area is increasing (see Pezzulo et al., 2013), grounded perspectives will not become a powerful paradigm in cognitive neuroscience until ideas like perceptual symbol systems (Barsalou, 1999) or convergence-divergence zone architectures (Damasio, 1989) are formalized in computational structures. Efforts are increasing in this area. In one attempt Pezzulo and Calvi, (2011), created an artificial agent in an environment filled with different 'insects'. They modeled perceptual schemas (e.g. components that tracked size, colour, shape) and connected them to action schemas (follow size, colour, shape). While each perceptual and action schema alone did not produce meaningful behaviour, associative links (formed through Hebbian learning) between them could, allowing the agent to categorize the different types of insects. Importantly, as predicted by perceptual symbol systems, no single layer or schema decided the agent's behaviour. More explicit models attempting to capture the critical features of perceptual symbols systems (i.e. hierarchical integration of information from modality specific regions based, hebbian associations, etc) have shown that cell assemblies of the type shown in fMRI spontaneously form, with distributed motor related regions representing action words and visual related regions representing object words (Garagnani and Pulvermüller, 2016; Pulvermüller and Garagnani, 2014; Pulvermüller, Garagnani, and Wennekers, 2014; Garagnani, Wennekers, and Pulvermüller, 2009). This type of computational research promises to formalize many aspects of the conceptualization hypothesis (see also Caligiore et al., 2010; Schrodt et al., 2015).

There are a few other technical issues that need to be addressed. For instance, though a number of studies have shown that modality-specific information is activated during cognitive tasks, different studies make incompatible assumptions about whether this activity should facilitate or interfere with an ongoing cognitive task. Indeed, much behavioural research reports either facilitation or interference effects, and both findings are argued to support grounded theories (see Matheson et al., 2014). This is problematic, because without strong hypotheses about the role of activated modality specific representations in any given cognitive task, any effect could support grounded cognition. This leads to a lack of empirical specificity and would disqualify grounded cognition as a theory. We need more precise predictions about the role of these activations in specific cognitive tasks. One idea is that timing is important. We hypothesize that the timing of modality specific activations during cognitive performance will determine its role in producing any given behaviour. Additionally, meta-analytical techniques will be indispensible in establishing the direction of grounded effects.

Finally, some theorists have criticized grounded or embodied research as being 'old hat', and not really the revolutionary new paradigm it is often touted as (Dennett, 1993; see also Wheeler, 2014). We think it is a safe to say that radical embodied cognition of that proposed by the replacement hypothesis is in fact a significant departure from traditional cognitive science. Such an approach discards representation and completely changes the methods used to study cognitive phenomena. However, researchers interested in the conceptualization hypothesis retain core concepts from cognitivism, like that of representation. At the very least, the entire enterprise of embodied and grounded cognition, theoretical and empirical, does serve to reorient traditional cognitivist approaches to something that might be considered ‘experientially-coded’ cognition, where the representations and computations that are used in cognition are of/about/oriented towards the body, modalities, and situations (cf. Goldman, 2012). Thus, even for cognitive neuroscientific researchers who have no interest in abandoning current conceptions of cognitive ontology or architecture, the grounded perspective still promises to uncover new phenomena and result in exciting cognitive models.

Conclusion

Research in embodied and grounded cognition is defined by the types of hypotheses researchers pursue, but all investigations are interested in the ways in which the body, brain, and environment interact to give rise to intelligent behaviour. The philosophical heritage of embodied and grounded cognition has resulted in many different theoretical and empirical approaches. For cognitive neuroscience, theories of grounded cognition have principally shaped the conceptualization hypothesis, in which it is hypothesized that simulations in modality-specific representations, situated and embedded in a behavioral context, underlie our ability to plan actions, discuss our thoughts, and coordinate our activities with each other. In such a framework, representations are powerful, predictive constructs. Overall, the grounded perspective encourages us to think deeply about our cognitive ontology, cognition’s relation to the brain, and the dynamic processes that underlie our most complex behaviors. In this way, embodied and grounded perspectives promise to continue shaping research in cognitive neuroscience in highly productive ways.

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