An Introduction to Radical Embodied Cognitive Neuroscience

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Introduction

Embodied cognition is no longer a fringe movement in the mind sciences. With few exceptions, embodied cognition is generally relegated to investigating and explaining lower-order cognitive processes involving perception-action and not higher-order cognitive processes such as abstract thinking and imagination. Two major reasons that could explain why those who accept that lower-order cognition could be cases of embodied cognition, but who still resist the idea that higher-order cognition is also embodied are: first, a commitment to the idea that cognition is essentially computational and representational in nature; and second, *smallism*, which is the view that cognitive phenomena are not explained until the account stops at "lower levels" like neurons or molecules.

What follows is an introduction to an embodied approach to investigating and understanding both lower- and higher-order cognition that is not committed to computationalism, representationalism, or smallism: *radical embodied cognitive neuroscience*. Radical embodied cognitive neuroscience treats cognition as systems phenomena that spread across brain, body, and environment. Unlike its predecessor, radical embodied cognitive science, radical embodied cognitive neuroscience explicitly places the brain and central nervous system within its explanatory purview. By utilizing a novel modeling approach (i.e., nested dynamical modeling) and conducting research guided by the search for and application of scale-free principles of activity (e.g., self-organized criticality), radical embodied cognitive neuroscience provides a framework for investigating both lower-order and higher-order cognition. Such a framework can facilitate accounts of phenomena as apparently disparate as single neurons and neural networks, to coordination activities among dyads and larger groups of agents.

In the next section I present a very brief introduction to embodied cognition and draw a distinction between less and more radical forms of embodied cognition. Following, I present radical embodied cognitive neuroscience's direct predecessor and largest influence: radical embodied cognitive science. I then explicate that although radical embodied cognitive science is indeed radical insofar as it rejects the idea that cognition functions via representations and manipulations on those representations, it fails to address issues related to smallism. At that point, I elaborate on the aspects of radical embodied cognitive neuroscience that allow it to reject both the treatment of cognition in terms of computations and representations, *and* explanatory smallism.

Background: Embodied cognition; more or less radical

While the study of cognition typically focuses on the brain, embodied cognition is a non-brain-centric position concerning what causes and is constitutive of cognition (Favela & Chemero, 2016). In light of the fact that there are various forms of "embodied cognition"—not to mention distributed, enactive, extended, situated, etc. cognition—an overview of embodied cognition goes far beyond the scope of the current work. Nevertheless, both adherents and critics agree on some general features. The first general feature is that cognition is based in sensorimotor processes, or perception and motor capacities such as vision and locomotion. What is more, the ability to perceive and act in the world is taken as fundamental to other forms of cognition. The second general feature is the idea that the body both constrains and enables cognition. In other words, whatever capabilities an organism has in relation to cognition are tied to what the body can do. The third general feature is that there is no sharp division between cognition and noncognition in the body, or that cognition often comes in differences of degree from noncognition as opposed to differences in absolute kinds. This final general feature raises an important issue concerning how to define what cognition is.

Both adherents and critics of embodied cognition are faced with the issue of defining what cognition is. Critics of embodied cognition tend to limit their support to a conception of "cognition" defined in terms of computations and representations (e.g., Aizawa, 2015; Shapiro, 2013). Adherents of embodied cognition range in their definition of 'cognition.' The less radical still treat cognition in computational and representational terms. However, the more radical reject the idea that cognition is computational and representational in nature. Instead, cognition is understood as more akin to what William James referred to as "mindedness" (James, 1885), or the meaningful activity exhibited by organisms, which begin with perception and guide action, and is involves their being-in-a-world (Favela & Martin, 2016). This understanding of cognition as mindedness is shared by enactivist conceptions of cognition in terms of the *sense-making* that occurs when meaning is elicited via an organism's engagement with its world (e.g., Thompson, 2007, 2011; Varela, Thompson, & Rosch, 1991).

As noted in the previous paragraph, less radical approaches to embodied cognition have much in common with more brain-centric treatments of cognition as computational and representational in nature. This is because less radical approaches incorporate the body in cognitive processes more so in terms of constraining, regulating, and shaping cognition (Foglia & Wilson, 2013). Such constraining, regulating, and shaping can be merely causally related to cognition, or if constitutive, then the body plays a constitutive role insofar as it serves computational and representational functions. In addition, less radical approaches tend to relegate "embodied cognition" to peripheral cognitive capacities such as perception and action, but not core cognitive capacities such as imagery, planning, and reasoning. On the other hand, more radical approaches tend to support the idea of cognition as fundamentally dynamic and necessarily coupled to the body and world. It is from this fundamentally dynamic and externally coupled nature that motivates many of anti-computational and anti-representational arguments. What then, are the major dividing lines between less and more radical approaches understanding cognition as embodied?

Two major reasons may explain why one would be less or more radical in the extent to which they think cognition is embodied. The first reason is that although the body may constrain, regulate, and shape cognition, it is not constitutive of cognition. Moreover, whether the body is causally or constitutively related to cognition, such relations are fundamentally computational and representational. In other words, cognition is embodied in so far as the body is a conduit for computations and representations, such that in the end, cognition remains computational and representational in nature. A second major reason may be that explanations of cognition are incomplete until the account includes "lower levels" such as neurons and molecules. Such a position can be referred to as a commitment to explanatory *smallism* (cf. Sanches de Oliveira & Chemero, 2015), which places greater value on parts of explanations that include lower level, small stuff. In the next section, I present a response to the first commitment in the form of radical embodied cognitive science, which is the predecessor and largest influence on radical embodied cognitive neuroscience.

Influence: Radical embodied cognitive science

One of the strongest cases against treating cognition as being computational and representational in nature is Chemero's *radical embodied cognitive science* (2009, 2013). Since the current work is not an introduction to radical embodied cognitive science (RECS), I will keep the explication brief. RECS "is an interdisciplinary approach to psychology that combines ideas from the phenomenological tradition with ecological psychology and dynamical systems modeling" (Chemero, 2013, p. 145). It is *radical* in that it is anti-computational and anti-representational in its conception of cognition. It is *embodied* in that it treats cognition as phenomena that should be described in terms of coupled agent-environment dynamics. RECS is guided by the theories of Gibsonian ecological psychology, which began primarily as a theory of perception-action (Gibson, 1979/1986). One of the major changes brought about by ecological psychology in the study of cognitive phenomena was the shift to the animal-environment system as the unit investigation, and not the animal in an environment. Gibson attempted to dissolve dualisms with his treatments of perception and action as continuous and the systems-view of animal-environments. Chemero, like other ecological psychologists (e.g., Kugler, Kelso, & Turvey, 1980), utilizes the methods of dynamical systems theory to describe and explain the activities of agent-environment systems over time.

Dynamical systems theory has tools that are particularly well-suited to capture the dynamics of agent-environment systems, such as differential equations. Take the following coupled differential equations that model an agent-environment system (cf. Beer, 1995; Favela & Chemero, 2016):

$$1.\ \frac{dX_a}{dt} = A(X_a; S(X_e))$$

$$2.\ \frac{dX_e}{dt} = E(X_e; M(X_a))$$

Equation one models the changes over time of an agent (dX_a/dt). Equation two models the changes over time of the environment (dX_e/dt). Note that although there are two equations, the model is one system. This is because the parameters for agent (A) and environment (E) are embedded in each equation such that changes to one parameter affect both equations. In other words, there cannot be changes to the agent or environment in isolation; to change either is to change the whole system. Coupled equations will play an important role in radical embodied cognitive neuroscience.

With dynamical systems as the methods, RECS utilizes ecological psychology's concept of affordances as its primary guide to discovery, or as a source of hypotheses to develop new experiments (Chemero, 2009, 2013). Ecological psychology frames perception in terms of affordances, which are directly perceivable opportunities for behavior. Examples of affordances include a cup being grasp-able, a door being pass-through-able, and a chair being sit-on-able. In this way, affordances emerge at the level of the animal-environment system, such that there is congruence between the animal's perceptual-motor capabilities and features of the environment. For example, a cup affords grasping if the dimensions of the cup and the dimensions of the hand are such that the animal (e.g., human) can grab the cup. This combination of ecological psychology (esp. affordances) and dynamical systems theory (esp. differential equations) has provided RECS with a compelling alternative to treating cognition in terms of computations and representations. Accordingly, RECS addresses the first commitment of less radical approaches to embodied cognition by demonstrating how cognition can be investigated and understood non-computationally and non-representationally (for details see Chemero, 2009, 2013). However, RECS does not win over all of the less radical supporters of embodied cognition because it does not satisfy those who find explanatory smallism compelling.

As stated above, smallism refers to the idea that an explanation of a phenomenon is incomplete until the account includes the lowest relevant levels. In terms of cognition, mammalian memory is not explained until the account stops at the scale of molecules at the synaptic junctions of neurons (Bickle, 2006). RECS is explicitly centered on the investigation of affordances as its guide to discovery. So, an adherent of RECS has a reasonable response to an objection motivated by smallism: “Insofar as an affordance is not directly affected by molecules at the synaptic junctions of neurons, or if the effect is inconsequential, RECS does not have to incorporate that scale into its research and explanations of its targets of inquiry.” Such a response may save RECS as a viable scientific framework, but couched in such terms it is viable only at a limited scale of investigation. The reason investigations of affordances need not be concerned with “small/lower scales” like neurons and molecules (though, see Cisek, 2007 and Favela, 2016 for another perspective) is because affordances *disappear* at those scales. Within RECS, affordances happen at the scale of animal-environment interactions. The affordance grasp-able happens at the scale where an animal can see the cup, which is a limited range spatial and temporal scale, and disappears at lower (e.g., cellular) and higher (e.g., city) scales. Thus, as RECS conceives of them, affordances cannot be a complete guide to discovery concerning all things cognition.

Chemero is aware of this limitation of RECS and the need to incorporate other scales, such as the neural, into more complete accounts of cognition. As Chemero states, “it is perfectly respectable... for radical embodied cognitive scientists to acknowledge that brains are important, but insist that they are far from whole story” (2009, p. 181). Chemero speculates that RECS may need to integrate with enactive cognitive science (e.g., Thompson, 2007; Varela et al., 1991), which includes research on the neural scale: “much more work is required to genuinely integrate ecological and enactive cognitive science under the banner of radical embodied cognitive science” (2009, p. 154). This is where Chemero and I part ways: Although I think RECS addresses the commitment of some less radical supporters of embodied cognition who still treat cognition as essentially computational and representational in nature, RECS cannot sway those who are compelled by smallist considerations. However, I disagree that much more work needs to be done before a radical *and* embodied framework can satisfactorily address both challenges. In the next section I present such a framework, which I claim treats cognition as not necessarily computational and representational in nature, and provides a scope of inquiry into cognition that can include the small stuff.

An introduction to radical embodied cognitive neuroscience

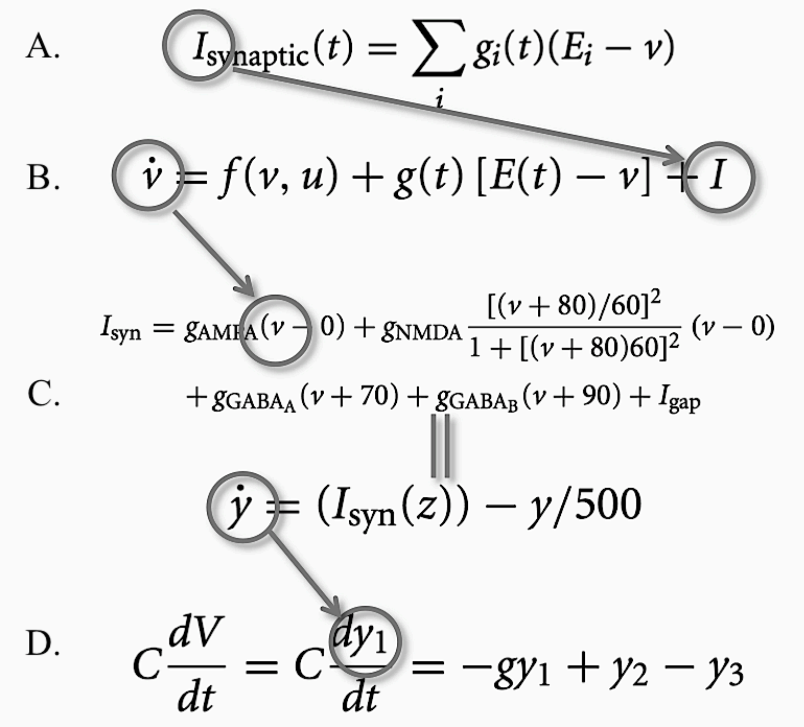
Radical embodied cognitive neuroscience (RECN; Favela, 2014) has much in common with RECS: both are *radical* in their rejection of treating cognition as necessarily computational and representational in nature, and both are *embodied* in that the body (and world) are understood as being both causally related to and constitutive of cognition. Moreover, both utilize the tools of dynamical systems theory. However, RECN is not committed to ecological psychology as a theoretical framework or affordances as its guide to discovery. As discussed in the previous section, RECS is explicit about its explanatory purview: the scale at which affordances emerge, namely, the scale of animal-environment interactions. RECN provides a more expansive framework to investigate and understand scales ranging from the "lower" (e.g., synapses) to the "higher" (e.g., social group interactions). Because cognition is a systems-phenomenon and embodiment truly spans body and world, then the brain and nervous system ought to play a more prominent role when investigating and explaining cognition even from an embodied approach. Consequently, the neural scale is explicitly within RECN's purview of investigation, which may earn the approval of supporters of smallism. In the following two subsections, I will elaborate on RECN's methods (esp. nested dynamical modeling) and theory (i.e., universality classes).

RECN's methods. Like RECS, RECN utilizes the methods of dynamical systems theory. As discussed above, dynamical systems theory provides powerful tools for the investigation and explanation of systems-phenomena that change over time. However, RECN utilizes a novel kind of dynamical systems modeling that is well-suited to investigating and explaining phenomena at any scale relevant to cognition, namely, *nested dynamical modeling* (NDM). The main idea behind NDM is that dynamical models at one scale of inquiry can be embedded within models at other scales. This kind of modeling can facilitate the comprehensibility of large data sets derived from multiple scales by eliminating irrelevant degrees of freedom of that system in relation to the target phenomenon being investigated. Without such dimension reduction, explanations of complex systems phenomena can quickly become incomprehensible. Thus, NDM maintains explanatory virtues such as control of target phenomena, prediction, and simplicity without the loss of biological realism. The concepts "order parameters" and "control parameters" are central to NDM, particularly in relation to dimension reduction and model nesting.

An *order parameter* is a variable in a model that captures the global-state of a particular system under investigation (Haken, 1988/2006; Van Rooij & Favela, 2016). For example, if the target of investigation is the transitions between phases of synchronization of two fingers moving (Haken, Kelso, & Bunz, 1985), then the order parameter is the value that captures the shifting phases over time. *Control parameters* are the variables that guide a system's dynamics. In the case of finger movements, the control parameters are the frequencies of the fingers moving. When modeling in terms of order and control parameters, there are no absolute macro-, meso-, or microscales. Scales are relative to targets of inquiry. One consequence of this lack of absolute scales is that a variable that served as a control parameter at one scale may be an order parameter at another scale. Consider the above example again: The order parameter is the transition phases of two fingers moving and the two control parameters are the two fingers. It is possible that the order parameter in the above becomes a control parameter of a model of a different global behavior. In short, the behavior of two fingers moving could play a role in a model of two sets of hands across two people carrying out a task. Conversely, the control parameter of a single finger's movement frequency may become an order parameter where the control parameters may be the tendons of the fingers. This is what I mean by the ability of models to nest: What is considered global behavior at one scale of inquiry may be a local variable nested at a higher scale of inquiry.

The following is a shortened version of a proof of concept of NDM presented in Favela 2014. We begin with the following models: (A) individual synapse activity (Izhikevich, 2010, p. 5067), (B) single neuron activity (Izhikevich, 2010, p. 5068), (C) total synaptic activity for all neurons within a voxel (Izhikevich & Edelman, 2008, appendix, pp. 11-12), and (D) networks of neurons (Rubinov, Sporns, Thivierge, & Breakspear, 2011, supplementary information, p. 3). The global state behavior captured by an order parameter in (A) is the total activity of an individual synapse. The activity captured by (A) becomes a control parameter in another model (B), which has an order parameter that captures the global state activity of a single neuron. The activity captured by model (B) becomes a control parameter in another model (C), which has as the order parameter the activity of total synaptic activity for all neurons within a voxel. This activity becomes a control parameter in (D), which is a model of the global state behavior that is a network of neurons.

This proof of concept demonstrates how an order parameter at one scale can become a control parameter and become *nested* within a model of an order parameter at a higher scale (see Figure 1). By treating the products of the models at one scale as an order parameter (e.g., *I* in a model of individual synapse activity), which can become a control parameter in a model at a higher scale (e.g., nesting *I* within a model of single neuron activity), NDM is able to maintain biological realism without compromising comprehensibility of the target phenomena. Moreover, the proof of concept demonstrates that NDM plays a role in RECN being non-smallist, in the sense that lower scales are not causally or explanatorily privileged. Remember, evaluations such as macro-, meso-, and microscales, as well as order and control parameters, are strongly contextual, namely, they depend on the target of investigation. Now that the methods of RECN have been presented, it is time to move on to the theory.



A. $I_{\text{synaptic}}(t) = \sum_i g_i(t)(E_i - v)$

B. $\dot{v} = f(v, u) + g(t)\,[E(t) - v] + I$

C.
$$I_{\text{syn}} = g_{\text{AMPA}}(v - 0) + g_{\text{NMDA}}\frac{[(v+80)/60]^2}{1+[(v+80)60]^2}(v - 0) + g_{\text{GABA}_{\text{A}}}(v+70) + g_{\text{GABA}_{\text{B}}}(v+90) + I_{\text{gap}}$$

$$\Vert$$

$$\dot{y} = (I_{\text{syn}}(z)) - y/500$$

D. $$C\frac{dV}{dt} = C\frac{dy_1}{dt} = -gy_1 + y_2 - y_3$$

Figure 1. Nested dynamical modeling proof of concept. (A) Model of individual synapse activity with product *I*; nested in (B) model of single neuron with product *v̇*; nested in (C) model of total synaptic activity for all neurons in voxel, which is then compressed into simpler model with product *ẏ*; nested in (D) model of networks of neurons.

RECN's theory and guide to discovery. The theoretical framework of RECN is the notion of *universality classes*. "Universality" refers to the idea that particular kinds of behaviors of systems are determined by a few characteristics, and that those behaviors occur across a variety of spatial and temporal scales (Pruessner, 2012). Moreover, these behaviors are substrate neutral, in that the same behaviors occur in a variety of mediums. Since there is purported to be a restricted number of universality classes, research guided by universality classes allows for the development of simplified models for a wide range of phenomena. This approach to understanding is particularly useful regarding complex systems that exhibit features such as chaos, emergence, multiple spatial and temporal scales, and nonlinearity.

The universality class that serves as RECN's guide to discovery is *self-organized criticality*. Self-organized criticality is exhibited when behaviors of a system at different spatial and/or temporal scales tend to organize near critical states. A system is at a *critical state* when it is balanced between two qualitatively different types of behavior (Hesse & Gross, 2014). Neuron pre-spiking, for example, is such a critical state, for it is inactive, builds up, and eventually fires. A system is *self-organized* when a process occurs without the direction of a central controller. Thus, when a system exhibits self-organized criticality, it is ordered enough to maintain spatial and/or temporal structure, but disordered enough to be adaptable to varying dynamics, and it is able to do this without programming, explicit direction, etc. Self-organized criticality has been investigated in the nervous system, for example, brain networks (Chialvo, 2004), nervous system health (Massobrio, de Arcangelis, Pasquale, Jensen, & Plenz, 2015), mental image rotation (Gilden, 2001), and single-neuron activity (Favela, Coey, Griff, & Richardson, 2016), just to name a few. This is a small sample of the increasing evidence of self-organized criticality in cognition and related physiology, which further supports it as a worthwhile guide to discovery for RECN. Moreover, such evidence for self-organized criticality bolsters the case for the application of universality classes in research on cognition. Lastly, the fact that cognition and related phenomena are complex systems that can produce large amounts of data, universality classes like self-organized criticality and methods like NDM are especially appropriate given their ability to simplify even radically complex phenomena (e.g., via dimension reduction) into comprehensible frameworks, while not compromising biological realism.

Conclusion

This paper presented an introduction to radical embodied cognitive neuroscience (RECN). In summary, I began by stating two primary reasons that may prevent more radical versions of embodied cognition from taking hold: first, the belief that although cognition is embodied, it is still computational and representational in nature; and second, explanatory smallism, which is the view that cognitive phenomena are not explained until the account stops at "lower levels" like neurons or molecules. Although I think radical embodied cognitive science (RECS) makes a strong case against treating cognition as computational or representational in nature, it does not address the challenge form smallism. This is chiefly due to the fact that its primary guide to discovery—affordances—disappears at scales lower or higher than those where animal-environment interactions occur.

RECN attempts to incorporate some of the best that RECS has to offer (i.e., an emphasis on systems as the targets of investigations and the methods of dynamical systems theory). RECN then modifies RECS's theory (from ecological psychology to universality classes), guide to discovery (from affordances to self-organized criticality), and methods (a novel kind of dynamical systems modeling: nested dynamical modeling). Via a proof of concept, I attempted to make the case that lower scales can be incorporated into systems-based explanations of cognition and related phenomena. Moreover, I attempted to do this without privileging lower scale phenomena or compromising biological realism, and while maintaining comprehensibility of potentially incomprehensible complex systems.

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