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A Theory of Resonance: Towards an Ecological Cognitive Architecture

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Abstract This paper presents a blueprint for an ecological cognitive architecture. Ecological psychology, I contend, must be complemented with a story about the role of the CNS in perception, action, and cognition. To arrive at such a story while staying true to the tenets of ecological psychology, it will be necessary to flesh out the central metaphor according to which the animal perceives its environment by 'resonating' to information in energy patterns: what is needed is a theory of resonance. I offer here the two main elements of such a theory: a framework (Anderson's neural reuse) and a methodology (multi-scale fractal DST).

Keywords Cognitive architecture · Embodied cognition · Ecological psychology · Resonance · Neural computation

1 Introduction

The computational approach to cognitive science, or *computationalism* (Milkowski 2013),[1] lies at the heart of contemporary cognitive science because it offers an operative way to explain cognitive states in a fairly naturalized fashion. Besides its utility in explaining specific cognitive processes such as memory or language, computationalism is widely accepted because of its power to generally account for

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[1] It is important to note that I use the wording "computational approach" or "computationalism" in the broadest possible sense. This means that by these terms I refer both to classic computational approaches (Fodor 1975) and to new computational-like ones (e.g., Clark 2015). If it is more comfortable for the reader, "computational approach" may be understood as "information-processing approach".

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the cognitive states of a system in mechanistic terms. Computation offers a mechanism for the mind.

Given the virtues of the computational approach, it is not surprising that *neural computation* is the preferred cognitive architecture in contemporary neuroscience. Cognitive architecture is to be understood here as “the set of basic operations, resources, functions, principles, etc., …whose domain and range are the representational states of the organism” (Calvo and Symmons 2014, p. 12), and neural computation as the concrete instantiation of the computational approach to cognitive science in the sciences of the brain. One of the most important resources that is offered by computationlaism as a paradigm for these sciences is the ability to arrive at a mechanistic description of the inner states of the system (i.e., a description of the role of the nervous system in cognition).

Along with the rise of the embodied approach to cognition in the last decades (Calvo and Gomila 2008; Shapiro 2014), computationalism and some of its related concepts (e.g., representation, content, information processing) have been highly contested by non-computational, non-representational theories of cognition, such as enactivism (Hutto and Myin 2013), ecological psychology (Chemero 2009), the sensorimotor account of vision (O’Regan and Noë 2001), or the dynamic systems approach to cognition (Beer 1995). Disregarding their success in criticizing the computational approach to cognition, these are on-going paradigms receiving attention by contemporary scholars and researchers. However, they all lack a satisfactory account of the role of the CNS and the peripheral nervous system in cognition. An account neural computation as a cognitive architecture is able to offer. In the case of ecological psychology, the lack of such an account has to do with the focus on the organism-environment system as the correct unit of analysis for the sciences of the mind. The only reference to the activity of the brain and other intra-organismic features is the concept of *resonance*: the CNS does not compute outer stimuli, but resonates to outer information.

The aim of this paper is to offer an operational, naturalistic characterization of resonance that enables ecological psychology to enter into a dialogue with contemporary neuroscience. I outline a cognitive architecture that is based on the principles of ecological psychology, and that therefore offers an alternative to standard computational approaches. In the next section, I briefly introduce some of the central concepts of ecological psychology, including resonance, and I summarize the ecological critique of computational approaches to cognition. In the third section, I claim that a theory of resonance compatible with the main tenets of ecological psychology can be sketched within the framework of Anderson’s *neural reuse* theory (2014), and I offer an operational definition of resonance under this framework. In the fourth section, I give some examples to support both the biological and explanatory plausibility of the theory of resonance I am developing here. In the fifth section, I claim that a suitable methodology for an operative, naturalistic theory of resonance may be based on the tools of dynamic systems theory and fractal analysis. In the last section, I briefly discuss the relation between my proposal and the rising paradigm known as radical embodied cognitive neuroscience.

2 Ecological Psychology and Resonance

2.1 Ecological Psychology

Ecological psychology is an approach to the study of perception and cognition developed by J. J. Gibson across his last two books (1966, 1979).[2] The ecological approach stands in opposition to computationalism and its related concepts. According to ecological psychologists, perception is direct, so no inner processing of information is needed and, therefore, no appeal to computational mechanisms or representations is made. In explanatory terms, all computational approaches share one main feature: psychological explanation consists in accounting for agents' computational mechanisms (Fig. 1). Such a mechanism may be thought as a language-like one (Fodor 1975), as a neural network (Rumelhart et al. 1986), or as a Bayesian brain (see Clark 2015; reviewing Friston's work), for example, but spelling out the mechanism is always the aim of these theories.

Unlike computational approaches, one main tenet of ecological psychology is that psychological explanation remains ecological. That is, psychological processes are explained in terms of the interactions between agents and their environments—what is known as the *ecological scale*. The reason for this essentially *interactive* approach is that Gibson found in *action* (including agents' active exploration of the environment) a way to deal with the *complexity* of the environmental information and the *redundancy* in the abilities an organism can use to face it. Ecological psychologists have developed concepts such as invariants and *coordinative structures* to address the complexity/redundancy issues and, more recently, they have drawn on *dynamic systems theory* (DST) as their preferred explanatory tool for the agent-environment interactions. However, for his theory to work, Gibson had to introduce the notions of *resonance* and *ecological information* as the relevant features of the agent and the environment, respectively, in terms of psychological activity (Fig. 2).

To highlight the difference between ecological and computational explanations of psychological phenomena, the outfielder problem is a classic example (Todd 1981; McBeath et al. 1995; Shaffer et al. 2004; Fink et al. 2009): how is an outfielder of a baseball game able to catch a fly ball? How does she know where to run to in order to be in a position to catch it? From the computational approach to cognition the explanation of the behavior of the outfielder will involve a series of calculations applied to the trajectory of the fly ball which allow the fielder to predict the place of its landing. Such calculations will be carried out by a computational mechanism that will have 2D retinal images as input and behavior as output. The ecological explanation, in contrast, appeals to the regularities in the behavior of the outfielder regarding some specific ecological information. In this case, put simply, if the outfielder moves in order to cancel the lateral motion and vertical acceleration of the fly ball relative to her own movement and changes her own place so as to maintain a homogenous expansion of the ball in her visual field, she will be in the right place to catch it before it lands. The relations between the relative motions and

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[2] See Chemero (2009) for a contemporary account of ecological psychology.

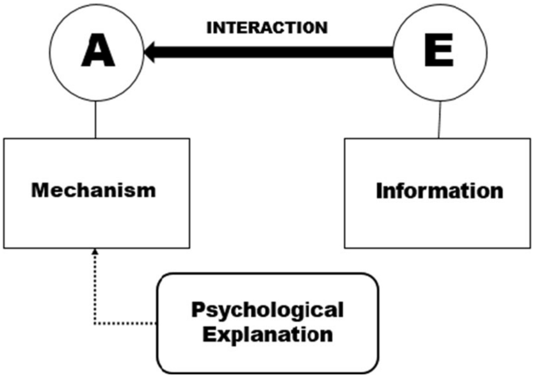

Fig. 1 Psychological explanation in computational approaches. ('*A*' stands for Agent and '*E*' for Environment). The interaction between *E* and *A* is taken to be an internalization of outer E-stimuli by A (*unidirectional arrow*). Such E-stimuli is then processed by an internal computational mechanism in *A*

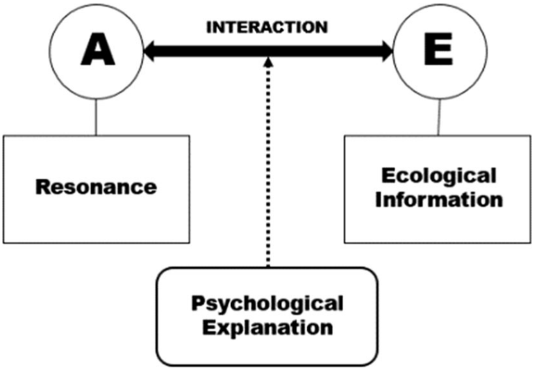

Fig. 2 Psychological explanation and ecological psychology. The *A*–*E* interaction is not an internalization of E-stimuli anymore. The interaction happens at the ecological scale and so it has to be explained (*bidirectional arrow*). The activity of *A* in such an interaction is not the internal computation of E-stimuli, but the resonation to ecological information

accelerations (vertical, lateral, and approaching/expansion) of the fly ball in the visual field of the outfielder constitute the ecological information that specifies both the landing place of the ball and the direction in which the fielder must run in order to successfully accomplish the task.[3] An ecological explanation of the outfielder problem will consist of making explicit the lawful connection between such information and the behavior of the outfielder.

In the last five decades, the notion of ecological information has received plenty of attention, for example, in the descriptions of the behavior of light relevant to visual perception in terms of ecological optics (Michaels and Carello 1981). The case of resonance is different. It has received little attention. The reason, put bluntly, is that, insofar as psychological explanation focuses on the agent-environment interaction itself—e.g., the behavior of the outfielder and ecological information—the details of an agent's ability to resonate are not crucial for the explanation. Nevertheless, I claim that a theory of resonance is needed to complement the ecological explanation of perception and controlled behavior: without such a theory, ecological psychology fails to offer a true alternative to computational explanations.

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[3] The explanation in ecological terms is, of course, more technical and complicated and involves the ecological variable *tau*, for example. I left these details out of the text to avoid technicalities that do not add too much to its purpose. See Todd (1981) for a deeper study of those technicalities.

As in the case of our explanations for ecological information, the system that enables the agent to behave in the way she does must be explained.

2.2 Resonance

The concept of resonance has not been fully developed since Gibson first proposed it in *The Senses Considered as Perceptual Systems* (1966). Actually, neither Gibson himself nor Gibsonians are clear on what resonance is and how it works—i.e., resonance remains a metaphor (e.g., Turvey et al. 1981; Michaels and Carello 1981; Reed 1997; Chemero 2009). The basic idea of resonance, though, appears at the very beginning of Gibson's second book:

> Instead of supposing that the brain constructs or *computes* the objective information from a kaleidoscopic inflow of sensations, we may suppose the orienting of the organs of perception is governed by the brain so that *the whole system of input and output resonates to the external information*. (1966, p. 5; emphasis is mine).

Resonance is characterized as the proper activity of the organism regarding external information, and the brain seems to have a chief role in it. Despite its importance within the ecological framework, however, the quote above is one of the few places where resonance as such is referred to in Gibson's work. It is noteworthy that, although the concept is used in the relevant literature, no further explanation is given. To develop the concept, the first step must be to describe the requirements an operative definition of the notion of resonance has to meet in order to, first, be scientifically addressed, and second, be compatible with the other ecological principles.

I want to claim resonance is *what is going on inside the organism*, especially in the CNS, with regard to *what is going on at the ecological scale*. This broad definition will work for now and grasps the character both of the 'external information' (ecological and constituted by the agent-environment interactions; for instance, the relative accelerations of the fly ball regarding the movements of the outfielder in the example above) and the organismic activity, which along with its relation to the ecological scale is the main *explanandum* of a theory of resonance. Nevertheless, some constraints are needed to make it compatible with other ecological principles. First, we have to make clear the scale at which resonance must be described. There are three possibilities: the agent-CNS interactions, the inner-CNS interactions, and CNS-environment interactions. I will recommend the *agent-CNS interactions*—i.e., the CNS activity in relation with the overall activity of the agent in her environment—as the correct scale for the analysis of resonance because it captures all the relevant features of both the ecological and the intra-organismic scales. There are problems with each of the other two possibilities. On the one hand, if we pick the inner-CNS interactions, the link to the ecological scale is broken. If we focus only on what is going on inside the organism, our explanation will be as non-ecological as the ones criticized by Gibson. On the other hand, if we focus on the CNS-environment interactions, we will misconceive the role of the body in perception and action, so we will violate another set of tenets of ecological psychology.[4]

The second constraint on developing an operative concept of resonance is that it must refer to the relation between the agent-environment and the intra-organismic scales without appealing to computation. To describe resonance in such terms would entail the violation of some of the main tenets of ecological psychology. For example, one tenet is that perception is direct and no neurological processing of information is needed. Obviously, to explain what is going on at the intra-organismic scale with regard to the ecological scale (aka, resonance) in terms of computation would violate this tenet. Let’s analyze this constraint closely.

2.3 Ecological Psychology as Anti-computationalism

An explanation regarding why ecological psychology is an anti-computational approach to cognitive science is noteworthy because prima facie it might not be an obvious claim. Although anti-computationalism is foundational in ecological psychology and held by the vast majority of ecological psychologists,[5] there seems to be no reason, *in principle*, for an ecological explanation and a computational explanation to be incompatible. Actually, they might be seen as two explanations of the same phenomenon at two different scales: the ecological explanation accounts for the changes of the agent-environment system at the agent-environment scale, while the computational explanation unveils the mechanism that makes those changes possible. To keep using the example of the outfielder, the ecological and the computational explanations might be seen as complementary: the ecological explanation unveils the lawful relations between behavior and ecological information, while the computational explanation describes the mechanism that enables the outfielder to behave and deal with such information. However, in the Gibson quote above, it is clear that the brain does not construct or compute outer information. But if computation is not, in principle, incompatible with an ecological explanation, why is it boldly rejected by Gibson and other ecological psychologists? There are, at least, two different but interrelated reasons.[6]

First, probably the best way to understand why ecological psychologists reject computation is to analyze the reasons why any kind of computational process is posited to begin with. According to ecological psychologists, computation is needed

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[4] Gibson (1966) famously introduced the concept of *perceptual system* to capture the role of many parts of organisms and their very action as constitutive elements of perceptual processes. The visual system, for example, is constituted by the CNS, but also by the peripheral nervous system, and the eyes placed in a movable head, which at the same time is placed in a movable body, etc. All these elements are relevant to explain visual perception, and a theory of resonance based just on the CNS-environment interactions will be inadequate for grasping its complexity.

[5] Both Gibson’s main books (1966, 1979) and classic texts on ecological psychology (Turvey et al. 1981; Michaels and Carello 1981; Lombardo 1987; Reed 1997) offer arguments against computation. Such arguments may be also found in the contemporary ecological psychology literature (e.g., Richardson et al. 2008; Chemero 2009; Michaels and Palatinus 2014).

[6] Other reasons such as the necessity of a *homunculus* (Turvey et al. 1981, 1982) or the appeal to *loans of intelligence* (Dennett 1978; Kugler and Turvey 1987) to any computational theory to work have been described in the literature as well. I will not review them here due to the lack of space.

because cognitive science acritically assumes the Chomskyan argument of the *poverty of stimulus*.[7] Put bluntly, the defenders of the argument of the poverty of stimulus claim that the stimuli arriving to the sensory receptors of agents are unspecific, ambiguous, and generally insufficient to support any cognitive task. This fact entails that an internal processing of such stimuli must be taking place in order to enrich and disambiguate them and make them suitable for the task.[8] For example, think about perception of size and distance. Although two cars are of the same size in the 3D environment, if they are at different distances from the sensory receptors of an agent, they will be different in size in her 2D retinal image—i.e., the stimulus is unspecific regarding the state of affairs. Thus, a construction of a model of the 3D environment is needed for the agent to be able to recognize the correct state of affairs, namely, that the two cars are equal in size and they are merely at different distances. Such a model-construction requires some kind of information-processing in terms of computational mechanisms.[9]

Contrary to the argument of the poverty of stimulus, one of the foundational claims of ecological psychology is the idea of the *richness of stimulus* (Gibson 1966; Michaels and Carello 1981). Ecological information is specific and unambiguous, so it is sufficient enough as to support the different cognitive tasks an agent develops in her environment without the need for any processing, enrichment, or construction of an internal model. As Reed (1997) states:

> Standard theories of information processing in both neurophysiology and psychology take for granted that there is no meaningful information [i.e., unspecific, ambiguous] available to an observer except what the observer's brain can construct out of sensory inputs. But if ecological information exists, *then the observer's job is not to create information but to find it*. (p. 65; emphasis is mine).

Ecological psychologists view as a dogmatic assumption the idea that stimulation is poor and that it must be enriched by computation before it can serve in cognitive tasks. Ecological psychologists reject the dogma. If computation is posited only to solve the problem of the poverty of stimulus, and if stimulus poverty is in fact a non-problem, then computation is not needed after all. Information need not to be computed, it can simply be detected.

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[7] See Chomsky (1980) or Fodor (1981) for the argument. See Michaels and Carello (1981), for a critique from ecological psychology.

[8] In his influential textbook Cognitive Psychology (1967), Neisser claims: "These patterns of light at the retina are… one-sided in their perspective, shifting radically several times each second, unique and novel every moment… bear little resemblance to either the real object that gave rise to them or to the object of experience that the perceiver will construct… Visual cognition, then, deals with the process by which a perceived, remembered, and thought-about world is brought into being from as unpromising a beginning as the retinal patterns." (pp. 7–8).

[9] Marr (1982), for instance, famously offered a mechanism for the construction of a 3D image from a 2D one, going through an intermediate step known as $2D^{1/2}$.

The second reason for the rejection of compuationalism by ecological psychologists is based on the idea many of them hold regarding cognitive systems. Namely, that cognitive systems are just a specific kind of *physical system*:

> In my opinion, the search for mental mechanisms (of either the symbolic or sub-symbolic kind) is overvalued. The challenges facing cognitive theory are considerably more profound, having to do with laws and principles formative of the functional order characterizing nature's ecological scale—the scale at which animals and their environments are defined. I believe that *the major concepts needed to address cognition will not be found in the concepts provided by formal logics, computational languages, or network architectures*. Rather, *the kinds of concepts needed will be developed in the context of an emerging ecological physics and must include a physical notion of information* that satisfies the conditions of information about, in the sense of specificity to, and a notion of intentionality suited to the task of particularizing very general principles. (Turvey 1992, p. 85–86).

In this context, "physical" is used in terms of the science of physics, or ecological physics, and not in terms of ontology. The vast majority of cognitive scientists agree that cognitive systems are physical in ontological terms. Namely, that cognitive systems are of the same kind as bodies, trees, or sand; so they reject ontological dualism. However, what ecological psychologists mean when they claim that cognitive systems are physical systems is that cognitive systems must be explained by the appeal to the laws of physics and that no special explanatory strategy is needed (see, for example, Turvey et al. 1981, 1982; Tuller et al. 1982). This is, primarily, the *ecological stance*; namely, the idea that the psychological explanation must be developed at the ecological scale (see Fig. 2). But also, by this claim, ecological psychologists exemplify within psychology one of the philosophical maneuvers originated in the beginnings of the scientific revolution regarding scientific explanation: explanations must appeal to laws of interaction between entities and not to intrinsic/inner features of those entities as the realizers of the target *explanandum* (Raja et al. 2017). For example, in Aristotelian physics, the behavior of a falling stone was explained in terms of its *substantial form*. Namely, in terms of an intrinsic/inner feature that made the stone to fall. In Newtonian physics, however, such a falling was explained in terms of a law (the Law of Universal Gravitation) that related the stone with another body (say, the Earth) under some conditions. Ecological psychology favors this second general explanatory strategy for psychology and rejects an explanation that posits an intrinsic/inner feature, a computational mechanism plus representations in our case, as the realizer of the psychological process.

Chemero (2009) puts this explanatory preference for the ecological scale and ecological physics in a very illuminating way. Suppose, for instance, a visual event. In a classic computational interpretation, there is some causal chain that brings light reflected from some object (or surface) to the retina of the observer. From this moment, light gets into the system in form of stimulus and a chain of computational operations is applied to it. The last link of that chain of computational operations is a representation of the external object. Then, explanation of that visual event appeals to an internal mechanism and a representation. Following Chemero, ecological psychologists reject this kind of interpretation of a visual event because they think nothing special happens in the retina, which is nothing more than another way to state the ecological stance. That is, there is no reason to change from a purely physical explanation of the event when we refer to the causal chain in the environment to a chain of computational operations after the light gets to the retina. An ecological psychologist would say: “Nothing magical happens in the retina! It’s just one causal chain and physical causation all the way down!”. This position is reinforced by the afore discussed idea of the richness of stimulus: there is no reason to posit computational processes if there is no need for information processing.

What this example highlights is that ecological psychologists reject the assumption that inner states of the organism must play a preferred role in the explanation of a visual event or any other perceptual event. In other words, they hold an ecological explanatory strategy. There is only one causal chain (the whole chain of the animal-environment system), and to explain, say, a visual event, is to explain the whole chain by the appeal to physical laws. To explain the whole chain requires the explanation at the ecological scale, and to understand cognitive systems as purely physical systems requires anti-computationalism. It requires the rejection of any kind of inner feature as the realizer of the target phenomenon—nothing special happens inside! Thus, thinking in terms of a chain of computational events after the retina is forbidden in the ecological worldview.[10]

It is important to note, however, that these ideas regarding the status of cognitive systems and the understanding of cognitive processes such as perception do not block the possibility of a description of the role of the CNS or other inner states of the agent in those processes. In other words, we are allowed to explain resonance. The only constraint posited by these considerations is that when we explain resonance, we have to do it having two caveats in mind. First, that resonance is just a part of the chain, so it only makes sense regarding the rest of the chain. And second, that it is a physical chain, so no matter if we explain the whole or a part, we have to appeal to physical tools to do it. In the rest of the paper, I will try to develop an ecological cognitive architecture in which resonance can be explain while all the constraints posited in this section are met.

3 A Framework: Neural Reuse

Due to the constraints for an operative definition of resonance set out in the previous section, the great majority of contemporary models of cognitive architecture cannot serve as a basis for a notion of resonance compatible with other ecological principles. A review of some of the contemporary approaches to CNS behavior,

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[10] Chemero’s example can be further reinforced. In the classical interpretation of the visual event, perception happens at the end of the inner computational chain: we perceive the representation of the of outer object, and such a representation is at the last link of the chain. According to most ecological psychologists, *perception is the whole chain*. Perception is a state of the whole animal-environment system as a physical system. The inner end of the chain is not special in any regard. This is another way in which the idea of computation is incompatible with the main tenets of ecological psychology.

brain dynamics, and the like, that neuroscientists have used during the last few decades (e.g., computational neuroscience, ACT-R, neural network theory, dynamic systems theory, Eliasmith's semantic pointer architecture (2013), Clark's Bayesian predictive coding (2015) and so on) shows their failure to meet at least one of the constraints identified above, either because of the scale of analysis, which is fully internal and not ecological, or because of the appeal to computation, which is forbidden under the Gibsonian proposal.

Given this situation, a completely new cognitive architecture is necessary to account for resonance. The first element of such an architecture is a framework compatible with the main features of ecological psychology. I want to propose Michael Anderson's version of *neural reuse* (2014) as the best framework, regarding the activities of the CNS, for a theory of resonance. There are two main reasons for this choice. First, neural reuse allows for a degree of delocalization regarding cognitive functions that meets the requirements of an ecologically oriented psychology. And second, as a theory, neural reuse shows a strong structural and theoretical parallelism with ecological psychology although their scales of description are different. This fact allows for explanations at different scales—e.g., ecological scale and resonance scale—from the same general strategies, as required by most ecological psychologists. In the following, I take a closer look at neural reuse and I examine these advantages.

Neural reuse is an organizational principle for the functions of the brain. Its core tenet is that different parts of the CNS (at different scales: neural networks, individual neurons, etc.) are used and reused to accomplish different functions, and that this phenomenon is achieved by the soft-assembling of different parts in different functional systems as required by the cognitive task:

> Neural reuse theories generally accept… that, rather than developing new structures de novo, resource constraints and efficiency considerations dictate that whenever possible neural, behavioral, and environmental resources should have been reused and redeployed in support of any newly emerging cognitive capacities. (Anderson 2014, p. 7).

As an organizational principle, neural reuse stands explicitly against componential (aka modular) accounts of the functional organization of the brain. According to Anderson (2010, 2014), contemporary cognitive neuroscience is based on a strongly componential version of the computational approach to cognitive science (see Edelman 2008; Gallistel and King 2009) and so it is entangled with the idea of the brain as a group of different components or modules, each one of them devoted to performing a specific function (see Anderson 2014, p. xix–xx; see also Fig. 3).

Contrary to modular accounts of brain functions, neural reuse argues in favor of a plastic functional organization for the brain in which different neural networks combine differently to perform different functions depending on the constrains of the cognitive task (Fig. 3). Such an organization allows for a highly delocalized account of the different brain functions: they are not realized by specific components (e.g., specific neural networks) of the brain, but by different neural networks interacting in novel ways and finding new patterns of functional connectivity depending on the demands of each task.

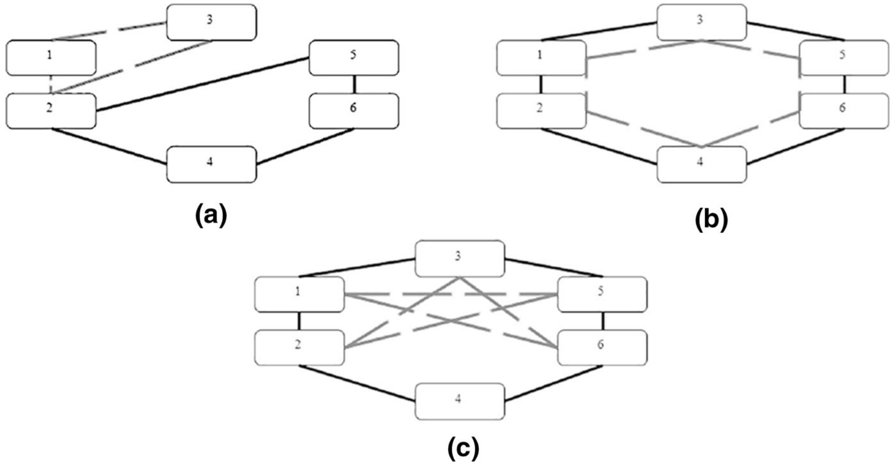

Fig. 3 Comparison between three different functional organizations in the brain. In all cases, there are 6 structures (*boxes* 1–6) and two different functions represented by the *two lines* (*solid* and *dashed*). The first organization (**a**) is modularity. Structures 1, 2, and 3 combine to support one task and 2, 3, 4, 5, and 6 to support another task. Both combinations have a residual if not a non-existent interaction, though. This is an organization based on segregated modules as proposed by the componential version of computation. The second organization (**b**) is holism, which is typical of connectionist models, for example. In this organization, all the structures participate in both tasks, but their pattern of connectivity is always the same. Finally, the third organization (**c**) is neural reuse. Here, most of the structures participate in both tasks (4 does not participate in the *solid line* task), but what changes dramatically is their pattern of (functional) connectivity depending on the task. (from Anderson 2014, p. 8, Fig. 1.1)

It is noteworthy that neural reuse as presented by Anderson since, at least, *After Phrenology* (2014), is allegedly anti-computational.[11] Also, the role of the brain is described in terms that strongly recall Gibson's position:

> Here I try to develop a picture of the brain as a complex causal mediator of the relationship between body and environment… What emerges in the course of these chapters is that the brain is best understood as first and foremost an action controller, responsible for managing the values of salient organism-environment relationships. (p. xxii).[12]

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[11] I will not deny the possibility of finding a way to interpret Anderson's proposals in *After Phrenology* as computational. However, I think there are unambiguous claims explicitly pointing to anti-computationalism, such as: "[I]t is worth an initial if brief reflection on an important disanalogy between the brain and a computer: whereas a computer is typically understood as a device that carries out a specific instruction set on (and in response to) inputs, brain responses to stimuli are characterized instead by specific deviations from intrinsic dynamics." (Anderson 2014, p. xx). Or: "My current approach to this problem… is to quantify the functional properties of neural assemblies in a multidimensional manner, in terms of their tendency to respond across a range of circumstances—that is, in terms of their *dispositional tendencies*—rather than trying to characterize their activities in terms of computational or information-processing operations." (Anderson 2014, p. xxii–xxii).

[12] Interestingly enough, it is possible that Gibson also had in mind an idea similar to neural reuse for the functional organization of the brain. In his Gibson biography, Reed (1988) refers and quotes some unpublished works in the Gibson archive at Cornell University. He writes: "Considering the capacity of the nervous system to adjust to stimulation in many different ways, Gibson hypothesized that '*a given set of neurons is equipotential for various different functions in perception and behavior*. The same neuron

As to what matters for resonance, thanks to the focus on functions, delocalization, and the high sensitivity of patterns of functional connectivity to the demands of different cognitive tasks, neural reuse as proposed by Anderson offers a way to explain the intra-organismic scale in the same terms (i.e., with the same language[13]) ecological psychology uses to explain the ecological scale. When the focuses are functions and not mechanisms, and soft-assembled structures and not concrete areas of the brain enabling the agent to perform a concrete action, the activity of the CNS becomes easier to explain in terms compatible with the main tenets of the Gibsonian theory. As we have seen, in ecological psychology, the primacy of the ecological scale in psychological explanation and the rejection of computation are crucial, and neural reuse is fully compatible with both. Moreover, neural reuse and ecological psychology show a strong structural and theoretical parallelism, as noted above. As a framework for the neurocognitive architecture—just like ecological psychology as a framework for agent-environment interactions—neural reuse is *interactive* and concerned with the *redundancy* problem (the brain offers many different ways to soft-assemble a functional system to accomplish a task). Also, it takes active search (a kind of *action*) to be a central element of the paradigm and suggests functional systems (or patterns or structures) that are similar to *coordinative structures*. Finally, it takes DST as the correct tool to analyze the intra-organismic interactions. Thus, both theories fit perfectly with each other.

Choosing neural reuse as the framework to study the activity at the intra-organismic scale has two main consequences. First, it allows for the elaboration of a description of different scales relevant for the cognitive phenomena—ecological and neural scales—under completely compatible tenets. Second, it allows for a re-definition of resonance in more precise terms. Given the structural and theoretical parallels between ecological psychology and neural reuse, and given that both the ecological and the CNS scales are proposed to be explained by using DST, we can understand resonance by describing the relationship between the dynamic system at the intra-organismic scale and the dynamic system at the ecological scale. In other words, because both ecological psychology and neural reuse use DST as an explanatory tool, the dynamics of a given agent-environment interaction is captured by a dynamic system, and the respective intra-organismic interaction in the same event is captured by another dynamic system. In this sense, what is going on at the intra-organismic scale is captured by the latter. But resonance is what is going on at the intra-organismic scale with regard to the ecological scale, so a complete explanation of resonance also requires showing the specific kind of relation between the two dynamic systems. In other words, a model to explain resonance must explain how the dynamic systems at the two scales are coupled.

Footnote 12 continued
may be excited for different uses at different times. [Therefore] neurons, nerves, and parts of the brain have a vicarious function. *A nerve cell is not the same unit in a different combination of nerve cells.*' (Ibid.)" (Reed 1988, p. 224; emphasis is mine). The similarity with neural reuse is, again, astonishing and reinforces the parallelism between both theories I am defending here.

[13] This aspect is crucial regarding NSF's grand challenges for the sciences of the mind. More on this in the last section.

My core claim regarding the coupling between the dynamic systems at the two scales is that the ecological variable we take to be the main variable of our dynamic systems model at the ecological scale (i.e., the *collective variable* in DST jargon) is also the main variable of the dynamic systems model at the intra-organismic scale. So, for example, if the interaction at the ecological scale is described by using the variable for the time-to-contact (τ), the momentum of inertia, or the relative phase of two oscillatory components of a system (ϕ), the interaction at the intra-organismic scale must be explained by appealing to the same variable. This can be re-stated in several ways: the two dynamic systems are constrained by the same ecological variable, the dynamic system at the intra-organismic scale reverberates to the ecological variable, the ecological variable defines the coupling between the two dynamic systems, etc. The idea is a simple one, though, and allows the final conceptualization of the study of resonance: *to explain resonance is to account for the coupling of the dynamic systems at the ecological and intra-organismic scales in terms of the ecological variable that constrains a given agent-environment interaction.*

This conception of resonance may be exemplified in terms of an abstract model for the sake of clarity and precision. Suppose a system performing some (psychological) task. We can define the dynamics of such a system at two different scales:

A–E; the agent-environment (aka ecological) scale.

N; the intra-ogranismic (CNS) scale.

The dynamics at these two scales (i.e., their change over time) may be defined as two functions of some variable:

$$\mathrm{A{-}E_D} = f(\psi, \mathrm{t})$$

$$\mathrm{N_D} = f(\chi, \mathrm{t})$$

where ψ is the ecological variable and χ is the variable that defines the intra-organismic dynamics. Now, as when N resonates to A–E these two functions are coupled in terms of the ecological variable, so χ may be defined as:

$$\chi = k\psi$$

where k is a linear constant. Given that, our abstract model of resonance for some (psychological) task would be:

$$\mathrm{A{-}E_D} = f(\psi, \mathrm{t})$$

$$\mathrm{N_D} = f(k\psi, \mathrm{t})$$

Now both functions—i.e., both dynamic systems—are linearly coupled in terms of the ecological variable. Or course, this is an abstract model, so it does not refer to any concrete or empirical situation. However, some consequences follow from it. One of them is that ecological variables must be found in CNS dynamics if the model is plausible. I address this consequence in the next section.

4 On Plausibility

The idea of an ecological variable constraining the behavior of an intra-organismic system might be a pretty picturesque one for some readers, both from the computational and the ecological traditions. Thus, a justification of its plausibility is needed. Such plausibility may be addressed in two ways: regarding neural dynamics themselves and regarding the models we use to explain them. Put simply, an ecological variable that already constrains the agent-environment interaction also constrains the behavior of an intra-organismic system when the dynamics of the latter are modulated by the influence of the former. On the one hand, such a modulation may be found at the neural scale when the variation in the recorded activity of single neurons or populations of neurons is strongly correlated with the variation of the ecological variable at the ecological scale. This fact would account for the *biological plausibility*. On the other hand, the modulation may be found in a more abstract scale when the models used to explain neural dynamics include the ecological variable as one of their parameters and are successful at predicting the behavior of the target neural system. This fact would account for the *explanatory plausibility*. Both biological and explanatory plausibility are equally relevant for an ecological cognitive architecture. Resonance must be, first, possible at the neurophysiological scale. That is, the CNS must be capable of exhibiting such a behavior—i.e., we have to be able to *measure* changes in the target behavior compatible with our depiction of resonance. And second, our models for the behavior of intra-organismic systems must be able to include the relevant ecological variable that constrains the target behavior. These models may hold a degree of abstraction such that their biological plausibility may be brought into question. However, they are the tools we currently have, and as such they should offer resources for developing an account of resonance.

Both plausibility requirements set out above would be met if examples of CNS dynamics and models which are constrained or depend upon an ecological variable are found.

4.1 Biological Plausibility

Two examples point to the biological plausibility of resonance. First, some studies show that *tau* (τ), the ecological variable that specifies the time-to-contact between an approaching object and the visual system (Lee 2009) is found in the neural activity when it is operating at the ecological scale (van der Weel and van der Meer 2009; see Fig. 4). In their study, van der Weel and van der Meer analyze the theta rhythm oscillatory behavior of babies' visual cortex—which is related to cognitive and anticipatory attentional processes (Orekhova et al. 1999)—during a looming danger situation. They found that such oscillatory behavior is tau-coupled, that is, the change in rhythm's temporal structure is linearly correlated with (modulated by) the value of tau at the ecological scale. In Fig. 4c, they show how the value of tau of the waveform of the neural activity of babies' visual cortex (black dots) matches the value of tau of the loom over time (blue dots)—starting roughly at 0.10 s. This fact

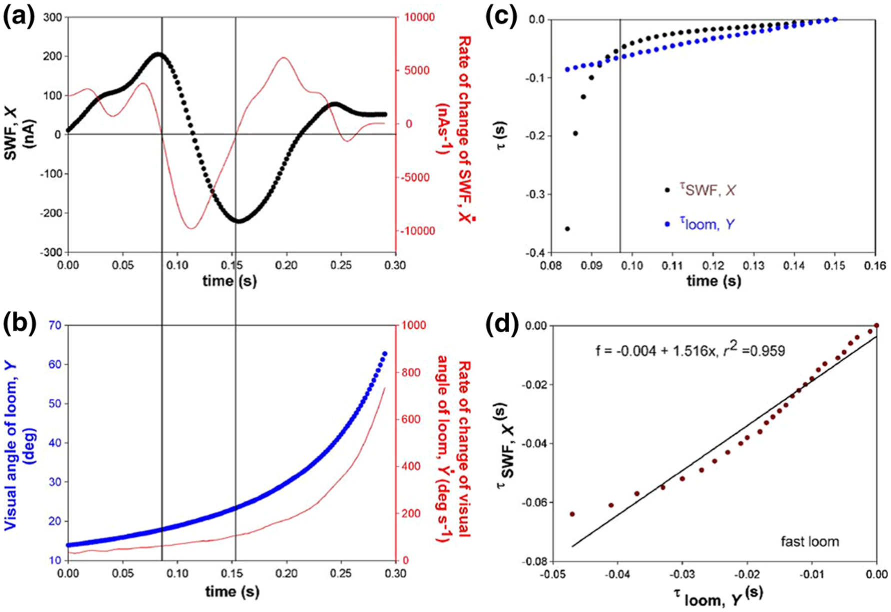

Fig. 4 This figure shows the tau-coupling analysis between the two relevant scales: the ecological scale (variable Y) and the neural scale (variable X). **a** and **b** show the change over time of the neural activity (source waveform [SWF]) and the visual angle, respectively, along with their rates of change during a looming situation. **c** plots the *tau* value of SWF and the corresponding *tau* value of the loom over time. Finally, **d**, represents the tau value of SWF against the tau value of looming to check if they are coupled. The figure shows a strong coupling between them, $r^2 = 0.959$. (Image from van der Weel and van der Meer 2009, Fig. 4, p. 189)

shows, I contend, a process of resonance in which the dynamic systems at the intra-organismic and the ecological scales are coupled in terms of the ecological variable for a given task. Such a coupling is quantified in linear terms in Fig. 4c, what fits the abstract model I presented in last section where the coupling between the two dynamic systems as a linear relation between the main variables at each scale was described ($\chi = k\psi$).

Second, some studies show that phi (ϕ), the variable that specifies the relative phase between two oscillatory components of a system at different scales,[14] is also found in the neural activity (Kelso and Tognoli 2007). In this case, the high-order (in fact, ecological) variable that accounts for a wide range of coordinative behaviors (e.g., tapping, gait, or inter-personal coordination) also accounts for coordination in neural oscillatory synchronization, namely, that both scales are constrained by the same variable. Again, it points to the biological plausibility of resonance.

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[14] This is the collective variable of the HKB model, one of the most famous instantiations of the explanation of a behavior by the appeal to an ecological variable (Haken et al. 1985).

4.2 Explanatory Plausibility

I will consider three studies that exemplify the explanatory plausibility of resonance. First, Port et al. (2001; see also Merchant et al. 2004) proposed a model to account for the dynamics of the motor cortex during an interception-of-a-moving-target behavior. In the model that accounts for both single-neuron and population scale dynamics, *tau* (τ) is one of the main parameters. Thus, the ecological variable is present in the model of brain activity. Another interesting feature of this study is that, although it is a perceptual variable, tau appears in motor control activity. This fact is fully compatible with the idea of perception-action loop and the intimate relation between perception and action as proposed by ecological psychology (Turvey et al. 1981).

In another example, some studies on musical perception of rhythm and tonality (Large 2008; Large et al. 2016) show that the dynamics at the ecological scale match the dynamics at the intra-organismic scale guided by the same variable. Put simply, the perception of rhythm, for instance, depends on the influence of the metric structure of the music over the CNS's intrinsic oscillatory dynamics. In other words, perception of rhythm depends on the intra-organismic dynamics being modulated by the ecological interaction—they exhibit the same rhythm, which is the ecological variable in this case. Large (2008) proposed an abstract dynamical model to account for this phenomenon. It is worth noting that in these studies the appeal to resonance is explicit. The intra-organismic dynamics resonate to the ecological information.

In the last example, a study (de Rugy et al. 2002) shows that a model in which the intra-organismic activity is constrained by an ecological variable—a transformation of tau—correctly describes participants' foot-pointing dynamics when walking. In this last example, the model is not concerned with neural activity as such, so it cannot be claimed that the biological requirement is met (see Fig. 5). However, the example is interesting because it shows how a classic inverse-pendulum model of gait, modified to include assumptions similar to what my theory of resonance proposes, is successful in explaining human behavior. The model itself aims to describe neither the ecological nor the neural scale, but it is targeted to an intermediate scale of behavioral kinematics.

All these examples account for plausibility of resonance at the explanatory level: they fit the abstract model I proposed in Sect. 3 and show that we are able to develop concrete models that grasp the coupling between the two scales relevant to account for cognitive phenomena in terms of resonance.

5 A Methodology: Multi-scale Fractal DST

The other required element to complete a successful account of an ecological cognitive architecture is a general methodology for the study of resonance. I propose such a methodology based on dynamic systems theory (DST), with special attention to the possibilities of multi-scale and fractal analyses. On the one hand, by multi-scale analysis, I refer to the ability of looking for the influence of relevant

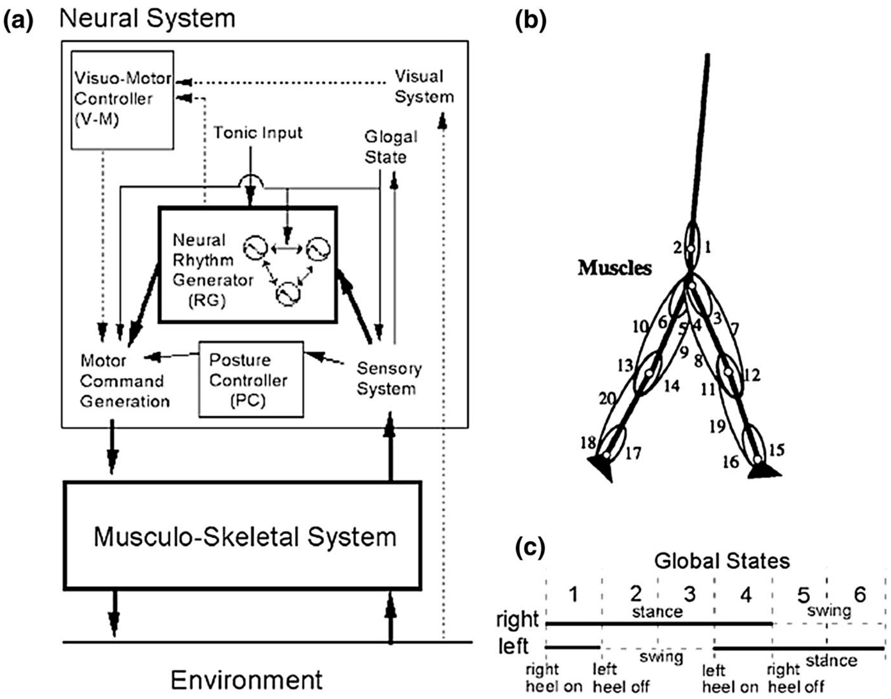

Fig. 5 The model used by de Rugy et al. is based on a model of bipedal locomotion developed by Taga (1998). It incorporates a neural rhythm generator (**a**) and a musculoskeletal system (**b**). The behavior emerges by the modulation between these two systems that happens during action (**c**). What de Rugy et al. include is a transformation of *tau* to that modulation to see if it helps the prediction of foot-pointing dynamics during walking. The enhanced model actually predicts foot-pointing dynamics better that Taga's one. (Image from de Rugy et al. 2002, Fig. 2, p. 143)

ecological variables at many different scales (e.g., ecological, behavioral, CNS, population of neurons, or single neurons, among others). Such a multi-scale approach has already been defended in psychology and behavioral sciences (Ibáñez-Gijón et al. 2016), but also in many other disciplines such as economics (Ouyang et al. 2015) or engineering (Lamarque et al. 2012). The approach is not essentially different from the classic single-scale DST ones. Classic DST approaches account for the change of a system through time by means of differential equations that describe and quantify such change. The only novel feature that comes with multi-scale DST is the specific treatment of the coupling dynamics between dynamic models at different scales. By fractal analysis, meanwhile, I refer to the tool that opens the possibility of addressing the relation between relevant scales in terms of fractals—i.e., how structural properties at higher scales are found at smaller scales as well. Fractal structures are found in many different physical and biological systems, and fractal analysis is a mathematical tool that has been successfully applied in many disciplines (Moreau et al. 2009; Bizzarri et al. 2011), also including psychology and behavioral sciences (Van Orden et al. 2003).

The reason I propose what I will name *multi-scale fractal DST* as the right methodology for this kind of study has to do with the ontological relation between the two scales involved in the explanation. In the case of resonance, the two sides relevant for explanation (agent-environment and intra-organismic scales) are nested. Specifically, the intra-organismic scale accounts for a sub-system of the system that exists at the ecological scale. For this reason, we cannot assume that the two dynamic systems that describe their activity are decoupled. In fact, they are always intrinsically coupled and may be understood as two different scales of the same phenomenon. This kind of relation, I contend, is better grasped by the methodology of multi-scale fractal DST. However, it is noteworthy to mention that I am not proposing a revolutionary methodology. As I have noted above, multi-scale fractal DST stands for a combination of two well-known, already in use, methodologies in psychology and cognitive sciences—DST and fractal analysis. My emphasis in their combination is due to the very nature of the phenomenon of resonance and the way such a combination will help our understanding of it. Otherwise, the technical details of multi-scale fractal DST are not dramatically different from standard DST and fractal analysis.[15] Different variants of this kind of methodology—there is no exact matching between multi-scale dynamics and fractal dynamics—have been applied to research within ecological and DST approaches (e.g., Van Orden et al. 2003; Riley and Van Orden 2005; Kelso and Tognoli 2007; Van Orden, Hollis, and Wallot 2012; Tognoli and Kelso 2014). These applications go from different ranges of behavioral and neural scales to different levels of coordinative structures. For example, an ecological variable could be playing a role in neural dynamics, or in kinematic relations between different parts of the body, or both. Thus, as researchers we must be able to address the phenomenon of resonance at these different scales—but priming the agent-CNS interactions as suggested in Sect. 2. The coupling between dynamic systems is a well-known phenomenon and there are different methodologies to account for it. In other words, to approach an event from a multi-scale DST perspective is not a challenge in mathematical or technical terms. The challenge resides in the right selection of the framework, the scales, and the collective variable to be working with.

The features of this multi-scale fractal DST, thanks to fractal analysis, also allow for the detection of structural similarities between the different scales of the system (fractals; scale-free patterns of behavior)—these scales may be behavioral, sub-behavioral, neural, etc. The fractal analysis as proposed by some researchers in ecological psychology and complex systems (e.g., Liebovitch and Shehadeh 2005; Aks 2005) can trace relations between these different scales. A useful concept here is the idea that intentional or psychological systems exhibit *self-organized criticality* (Bak 1996; Juarrero 1999; Van Orden et al. 2003), that is, that intentional or psychological systems endogenously organize themselves in such a state as to be

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[15] Any kind of comprehensive account of such details is completely out of the scope of this work. However, the NSF's *Tutorial in Contemporary Non-Linear Methods for the Behavioral Sciences* (edited by Guy van Orden and Michael Riley) is a good introduction to the field. See: https://www.nsf.gov/sbe/bcs/pac/nmbs/nmbs.jsp.

able to rapidly change from a behavioral pattern to another. Self-organized criticality entails that different scales are related. Specifically, if the dynamics of a higher scale (say, the ecological or the intentional scale) constrain the dynamics of a smaller one (say, the muscular or neural scale), as it is stipulated in the theory of resonance being outlined here, from self-organized critically it is predicted that what in a psychological experiment is usually taken as unsystematic random variability (error, noise) due to mind and body dynamics is actually a source of information, and that a fractal analysis will find 1/*f* noise (pink noise) in its temporal distribution. For example, suppose an experiment in which a participant is asked to grasp a glass with her right hand. Every time the participant does that, she will perform basically the same behavior, the same movement. However, there will always be some variability from time to time. If we analyze these variations as a temporal distribution, we will find a fractal structure (1/*f* or pink noise) in the distribution. This is the mark that a higher scale (e.g., the personal/intentional scale; the intention to grasp the glass) is constraining a lower one (e.g., the muscular or the neural scale). Following this logic, if neural dynamics are temporally constrained by some ecological interaction, as established by my account of resonance, their temporal variability will exhibit a fractal pattern (1/*f* or a pink noise pattern). This kind of analysis is exactly what is needed for scientific inquiry of resonance.

It is important to note one implication of fractal analysis applied in the cognitive context, in general, and in this ecological cognitive architecture, in particular. The 1/*f* noise predicted by the fractal theory is a mark of a scalar relation, namely, a relation in which a higher scale constrains a lower one. Thus, a fractal analysis of this kind offers directionality to the coupling between two scales: the higher scale always constrains the lower one and not the other way around. The particular significance of such an implication of fractal analysis for the ecological cognitive architecture is that the ecological scale is modulating the CNS scale and not the other way around. This fact entails the primacy of the ecological scale regarding any psychological and cognitive investigation: the ecological scale will always be the source of the collective variables that, subsequently, will be used to account for different scales of the system. In this way, my proposal avoids any interpretation based on internalism and, at the same time, is compatible with the primacy of ecological explanation that, as we have already noted, is one of the main tenets of ecological psychology.

A further advantage of multi-scale fractal DST is that by some of its inherent conceptual features the framework we are using may be both refined and further developed. For example, according to Anderson's neural reuse, the postulation of *active search* (i.e., the active selectivity of different neural configurations—patters of functional connectivity—in order to respond to different functional requirements even while each brain region has some specific functional tendencies) as one of the main mechanisms for his paradigm is, in the current state of neuroscience, primarily speculative:

> All of this [some evidence reviewed by Anderson] suggests to me that the mechanisms of interactive differentiation underlying functional development (early as well as late skill acquisition) must also include a process of *active*

> *search*: the rapid testing of multiple neural partnerships to identify functionally adequate options… Obviously, this is highly speculative, and establishing the existence of some such process will take significant research effort, but it is far from clear to me how a more passive process (such as the "unmasking" of latent inputs) could account for both the variety of things that can be learned (what manner and degree of latent connections would need to remain in place?) and the apparent ability (at least in some cases) to rapidly shift the functionally relevant neural bases for a given skill. (Anderson 2014, p. 58–59).

Namely, although some evidence points to the idea of active search, we do not yet have a way to fully characterize it. However, a multi-scale analysis such as the one proposed by Kelso and Tognoli (2007) entails metastability as one of the main features of the CNS dynamics—in general, it is a feature of most dynamic systems. And, as they claim,

> … [m]etastable coordination dynamics reconciles the well-known tendencies of specialized brain regions to express their autonomy, with the tendencies for those regions to work together as a synergy. (p. 40).

Otherwise, as already noted, Juarrero (1999) describes self-organized criticality (see also Van Orden et al. 2003) as living systems' endogenous activity by which the systems are able to self-organize near critical states, namely, in such a state that might rapidly change towards a more adaptive one with a little change in the surrounding conditions. The combination of metastability and self-organized criticality may offer a way to scientifically account for active search. It would explain the endogenous activity of finding novel patterns of functional connectivity between neural networks and their rapid change due to environmental conditions, while avoiding denying the intrinsic dynamics—the dispositional tendencies, in Anderson's wording—of each individual one.[16] Thus, although neural regions have their own tendencies, these are tools that, at least theoretically, could help in the explanation of how neural systems rapidly test possibilities and change from one configuration to another.

6 Radical Embodied Cognitive Neuroscience

As a last note, I want to point out the place of the ecological cognitive architecture I am proposing here within what has been termed *radical embodied cognitive neuroscience* (RECN). RECN is an approach to neuroscientific inquiry, inspired by radical embodied cognitive science (Chemero 2009), that tries to integrate some of the insights of embodied cognitive science with research in neuroscience (Kiverstein and Miller 2015). Specifically, as Favela (2014) points out, RECN tries to face what "[the] National Science Foundation recently identified "grand

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[16] A full account of active search is out of the scope of this paper, but the idea is that once the CNS system is described in terms of metastability and self-organized criticality, active search becomes a phenomenon easy to explain.

challenges" in brain mapping" (p. 1): the need for a common theoretical approach across multiple scales of inquiry and the reduction of big data to small data.

My suggestion is that the theory of resonance I have proposed here is fully compatible with the aims of RECN and that it offers a solution for the two grand challenges. On the one hand, when resonance is depicted in the way I have depicted it here, the language regarding the ecological and the CNS scales is symmetrical: the same variables are integrated in coupled dynamic systems at different scales. As noted in Sect. 3, ecological psychology and neural reuse allow researchers to explain different scales of cognitive phenomena using the same language. Namely, as far as both paradigms share basic principles (e.g., interactivity, focus on action, complexity/redundancy dilemma, coordinative structures, DST, etc.), the descriptions at both scales are easy to match. On the other hand, a description based on multi-scale fractal DSTs reduces the amount of data processing needed to unveil the behavior of cognitive systems at different scales: ecological variables work as collective variables for systems at different scales, which reduces the degrees of freedom regarding our explanations. Thus, the ecological cognitive architecture based on a theory of resonance I have developed here may be taken as being one instance of a possible paradigm for RECN and a promising way to face the grand challenges of the mind sciences.

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