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Embodiment and cognitive neuroscience: the forgotten tales

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Abstract
In this paper, I suggest that some tales (or narratives) developed in the literature of embodied and radical embodied cognitive science can contribute to the solution of two longstanding issues in the cognitive neuroscience of perception and action. The two issues are (i) the fundamental problem of perception, or how to bridge the gap between sensations and the environment, and (ii) the fundamental problem of motor control, or how to better characterize the relationship between brain activity and behavior. In both cases, I am going to propose that cognitive neuroscience could incorporate embodied insights—coming from the sensorimotor approach to perception and action, and from ecological psychology—to advance the solution for each issue without the need for abandoning or undergoing a substantial revision of its core assumptions. Namely, cognitive neuroscience could incorporate the forgotten tales of embodiment without undergoing through a complete revolution. In this sense, I am proposing not a call but a farewell to arms.

Keywords Cognitive neuroscience · Embodied cognition · Ecological psychology · Sensorimotor approach

1 Introduction

One fundamental issue in cognitive neuroscience, at least regarding perception[1] and action, is illustrated by the very first paragraph of David Marr's seminal work *Vision*:

> What does it mean, to see? The plain man's answer (and Aristotle's, too) would be, to know what is where by looking. In other words, vision is the *process* of

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[1] I will focus on vision for the sake of simplicity, but what follows can be applied to any perceptual system.

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> discovering from images what is present in the world, and where it is. (Marr 1982/2010, p. 3; emphasis in the original).

The part of this quote I want to highlight is 'in other words'. It might seem peripheral, but indeed it points out one of the core assumptions in the cognitive neuroscience of vision: looking is the same as the process of discovering the world from images. The latter is the former said *in other words*. Such an assumption underlies Marr's work but also the general information-processing approaches to vision (Stone 2012) and contemporary approaches based on Bayesian inference, such as predictive processing (Dayan and Abbott 2001; Friston 2005, 2010). The general idea is that the 'visual' brain is in the business of bridging the gap between what it gets (i.e., retinal image, sensory stimuli) and what causes it (i.e., the environment, the world). This is*, in other words*, the aim of visual perception as far as the dominant narrative in cognitive neuroscience is concerned. Embodiment is, to an important extent, a reaction to this narrative.[2] In the case of vision, embodiment is a reaction to the assumption that brain activity is responsible for bridging the gap between sensations and a world that is, in principle, inaccessible. Embodiment is also a reaction to the idea that *looking* can be fully understood in terms of image processing. There are resources and events beyond the brain, so the embodied story goes, that allow looking to be redefined without assuming the need for images, the need for the processing of information, or the epistemological seclusion from the world. These are, however, somewhat *forgotten tales* in cognitive neuroscience.[3]

The best-known tales or narratives of embodiment in cognitive neuroscience are the influence of bodily metaphors or activities in different (and higher) cognitive functions (Carney et al. 2010; Hughes 2018; Lakoff and Johnson 1999; Williams and Bargh 2008; Zhong and Liljenquist 2006) and the different aspects of the embodiment of objects and tools (Schettler et al. 2019). These tales are easily accommodated by contemporary cognitive neuroscience as they open interesting research paths while challenging none of the fundamental assumptions of the field. The forgotten tales of embodiment, however, are inspired by advances in the study of perception (Lee 2009; Warren 1998), the control of action (Kelso 1995; Warren 2006), learning (Jacobs and Michaels 2007; Thelen and Smith 1994), and social cognition (Marsh et al. 2009), along with several theoretical developments in the cognitive sciences (Chemero 2009; Di Paolo et al. 2017; Gallagher 2017; Gibson 1966, 1979; Thelen and Smith 1994; O'Regan and Noë 2001; Varela et al. 1991). These tales could undermine the core assumptions of cognitive neuroscience leading to either a substantial revision or to a paradigm shift in the field (Anderson 2014; Cisek 2007; de Wit et al. 2017; Favela

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[2] In the rest of the article, I will use 'embodiment' as an umbrella term despite the plurality of notions that refer to the influence of body and environment in cognitive activities—embodied, embedded, situated, enactive, ecological, 3E cognition, 4E cognition, etc. If differences between these notions are relevant at any point, I will make them explicit and will use more concrete wording.

[3] I choose to call them *tales*, as opposed to theories, hypotheses, or conjectures, for the same reason Stephen Jay Gould defends a *narrative* approach to evolutionary biology in *Wonderful Life* (1989): because explanations of complex events sometimes require tools of history (p. 277). Here I convey a story about perception-action events and the role of the brain (along with body and environment) in them founded on some developments of embodied cognitive science. In this sense, I provide a new *tale* that may work both as a framework and as a source of new theories, hypotheses, and conjectures in cognitive neuroscience. Currie and Sterelny (2017) have provided a similar take on story-telling and scientific explanations.

2014; Kelso et al. 2013; Kiverstein and Miller 2015; Raja 2018, 2019a, 2020; Raja and Anderson 2019; van Dijk et al. 2008). For instance, if Anderson's (2014) theory of neural reuse is right, the localization of cognitive functions in the brain—e.g., the idea that vision is localized somewhere in the occipital cortex or language is localized in Broca's area—would not only be superfluous but intrinsically misguided as brain regions are used and re-used in different cognitive functions. In this sense, neural reuse would lead to a substantial revision of the localization assumption in contemporary cognitive science.

In this paper, I will call neither for a substantial revision nor for a paradigm shift in cognitive neuroscience. On the contrary, my main aim is to show how contemporary cognitive neuroscience may benefit from some of the radical insights of embodiment without completely rebuilding itself. In other words, contemporary cognitive neuroscience can incorporate the forgotten tales of embodiment into its canon for the sake of its own development. To support my claim, I will focus on two of these forgotten tales: (i) the tale of what is there to be perceived and (ii) the tale of how to control our movements in the world.

The first forgotten tale targets one well-known issue within the cognitive sciences that follows from the assumption that perceiving is the process of moving from sensory stimuli to the actual states of the world: that the relationship between actual states of the world and stimuli is nonlinear, irreversible, and generally intractable (Friston 2002, 2003, 2005; Gibson 1960; Marr 1982/2010; Stone 2012). The manifestation of this problem in cognitive neuroscience ranges from a general ambiguity in the notion of what counts as stimuli to issues in the characterization of naturalistic stimuli (Rieke et al. 1995; Sonkusare et al. 2019). I will show the way in which embodied approaches based on sensorimotor contingencies (O'Regan and Noë 2001) and ecological information (Gibson 1966, 1979; Warren 1998; Segundo-Ortín et al. 2019) could equip cognitive neuroscience in facing these issues.

The second forgotten tale offers resources to account for the relationship between brain activity and behavior, which constitutes an open question in cognitive neuroscience (Krakauer et al. 2017; Gomez-Marin and Ghazanfar 2019). This tale relates both to the general control of action and to specific issues such as what kinds of resources are used in *looking*. Generally speaking, these issues involve the possibility that complex behavior is organized solely by using neural resources (Meijer 2001; Warren 2006). Particular cases have to do with concrete assessments of the control of specific behaviors given our current knowledge of different neural systems (Pillai and Jirsa 2017). As in the case of the previous forgotten tale, I will show how embodied approaches to the control of action based on a deep exploration of behavioral dynamics at a proper scale (e.g., Cappuccio 2019; Cappuccio et al. 2020; Haken et al. 1985; Fajen and Warren 2003; Schneider et al. 1989; Newell et al. 2001) can provide additional resources to the framework from which cognitive neuroscience addresses these issues.

Overall, the aims of this paper are to explore those forgotten tales of embodiment that remain somewhat alien to mainstream cognitive neuroscience and to show the benefits of integrating them into the current dominant framework in the field. To do so, in Section 2, I start with a word on the main aspects of the current relationship between embodiment and cognitive neuroscience. Then, in Section 3, I provide a detailed analysis of the two forgotten tales introduced above and of the beneficial role they might play in cognitive neuroscience. I also point to some studies in contemporary cognitive neuroscience that already incorporate some of these insights. Finally, in Section 4, I provide some concluding remarks.

2 From embodiment to cognitive neuroscience or there and back again

Perhaps the most fundamental insight of the set of theories I am labelling *embodiment* is that cognitive functions are not the product of brain activity simpliciter, but that resources beyond the brain contribute to their constitution. The way this insight is interpreted in the different flavors of embodiment varies from allowing for a little contribution of the body to cognitive states to endorsing a full-fledged explanation of cognition as an event that occurs, to an important extent, outside the brain. The common thread of these flavors of embodiment, however, may be captured by the idea of delocalization: the idea that cognitive functions are not localized in different regions of the brain and, therefore, we cannot attribute those functions to those regions. As early as 1935, one of the precursors of cybernetics, Pyotr Anokhin, was already conveying this idea in a powerful manner:

> If extirpation of, say, the visual region of an animal leads to complete or partial loss of vision, then this does not mean at all that we excluded the 'visual center.' Bethe correctly observes that, although the optic function is completely eliminated when the optic nerve is cut, it would never occur to anyone to say that the 'visual center' is placed in the optic nerve, but most physiologists make this conclusion in relation to the visual region of the cortex. (Anokhin 1935; translation is mine).

Of course, Anokhin was still concerned about the nervous system and not about other aspects of the body or the environment, but his move illustrates a trend that will be typical in embodied approaches.

As noted before, there is a variety of interpretations and implementations of this central insight of embodiment in cognitive science. Shaun Gallagher (2017) suggests such a variety ranges from what he labels as weak embodiment to what he labels as radical embodiment. On the one hand, weak embodiment refers to the kind of embodied theories that depict the influence of the body in cognitive events in terms of its role in representations, as in the case of B-formatted representations (Glenberg 2010; Goldman 2012, 2014; Goldman and de Vignemont 2009; Prinz 2002, 2005). These theories are pretty much an extension of the dominant information-processing paradigm in cognitive science. For instance, B-formatted representations are just good old-fashioned representations that "represent states of the subject's own body, indeed, represent them from an internal perspective" (Goldman 2012, p. 73). On the other hand, radical embodiment refers to some proposals, usually within the coordinates of ecological psychology and enactivism, that can be characterized by the postulation of the inadequacy of computational mechanisms and representations to pursue explanations in cognitive science (e.g., Chemero 2009; Di Paolo et al. 2017; Gallagher 2017; Gibson 1979).[4] These proposals take cognitive systems to be dynamical, complex

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[4] Further details of this characterization of radical embodiment may be found in Chemero (2009, pp. 28 & ff.) and Gallagher (2017, pp. 26 & ff.).

systems that must be understood in terms of brain-body-environment interactions (e.g., van Gelder 1998; Walmsley 2008; Raja 2018, 2020). Of course, a gradation of embodiment between the weak and the radical may be found in the literature.

The focus of this paper, however, is not cognitive science at large but cognitive neuroscience in particular. How is embodiment incorporated into cognitive neuroscience research? A complete review of the different ways embodiment is made part of cognitive neuroscience would be a task for a different project, but it is possible to point out two of these ways that properly reflect the state of the art in the field. One of them is the work on the embodiment of objects in terms of sensory processing developed by Luke E. Miller et al. (2018, 2019). The other one is the work by Paul Cisek and colleagues on the affordance competition hypothesis (Cisek 2007; Cisek and Kalaska 2010; Pezzulo and Cisek 2016). Both start as legitimate attempts to incorporate embodied insights into cognitive neuroscience. However, both are, at the same time, like Bilbo Baggins' trip in *The Hobbit*: a there-and-back-again adventure. An adventure from cognitive neuroscience to embodiment, only to end up back at the starting point.

In a series of experiments, Miller et al. (2018, 2019) studied the possibility of sensory information processing outside of the nervous system in human beings. The idea of sensory information processing through non-neural elements is common in a variety of species (Burton 1993). For instance, spider webs and rodent whiskers are commonly described as non-neural intermediaries that participate in sensory processing (Bagdasarian et al. 2013; Japyassú and Laland 2017). The studies by Miller et al. show the similar intermediary role that tools can play in the case of human beings. Concretely, Miller et al. (2018) shows that humans wielding a wooden rod can sense the location in which an object contacts the rod as accurately as they sense the location in which the same object contacts their own arm. Moreover, their analysis of the way the contact upon the rod is encoded reveals a modal response akin to the one found in whiskers and webs; a response that, as suggested by the computational model they develop, may be re-encoded into neuronal spiking through a familiar process in cognitive neuroscience.

The results of Miller et al. (2018) may be seen as direct evidence for what, in the relevant literature, would be labelled as the 'embodiment of the rod' (Schettler et al. 2019). The rod is embodied by the person insofar as it acts as a part of her own body in terms of sensory information processing (sense of ownership; see de Vignemont 2011). In this sense, Miller et al. (2018) offers a compelling example of how research can transit the way from cognitive neuroscience to embodiment and can be permeated by ideas of the delocalization of cognitive functions: non-neural resources such as the rod may be taken to be integral parts of a cognitive system. However, a follow-up study by Miller et al. (2019) exemplifies the there-and-back-again scenario in which, after being permeated by embodied ideas, cognitive neuroscience folds back on itself and provides an unmistakably brain-centric explanation of the phenomenon. In the same experimental setup they described in the previous paper, Miller et al. (2019) used electroencephalography (EEG) to test the way the brain deals with the embodied rod. They reported several similarities of processing—e.g., location and dynamics of the EEG activity—both when an object impacted the rod and when the same object impacted the arm of the participants. They interpret this finding as evidence that the "elementary strategy the human brain uses to sense with tools is to recruit primary somatosensory dynamics otherwise devoted to the body" (p. 4276). So, at the end of the day, they explain the phenomenon in terms of the activity of the brain that may account for the embodiment of the rod. Namely, they offer a highly localized explanation where the brain-body-environment dynamics play no role. And the move from cognitive neuroscience to embodiment and back again is complete.

A similar there-and-back-again story may be found in the work on the *affordance competition hypothesis* developed by Paul Cisel and colleagues (Cisek 2007; Cisek and Kalaska 2010; Pezzulo and Cisek 2007). In this work, they incorporate the markedly embodied concept of affordance into cognitive neuroscience. The concept of affordance, originated in J. J. Gibson's works on ecological psychology (1966, 1979), refers to the opportunities for action organisms find in their environment. For instance, a mug affords 'grasp-ability' to some organisms (e.g., to most adult human beings), a wall affords 'walk-ability' to other organisms (e.g., to spiders or flights), and water affords locomotion to others (e.g., to fishes or octopuses). These opportunities for action are different affordances for different organisms and Gibson introduced them as the fundamental objects of perception. Namely, according to Gibson, instead of colors, shapes, or objects, perception is primarily of affordances. Importantly, these affordances were taken to be intrinsically meaningful properties of the environment and not the product of any kind of 'mental gymnastics' (see also Turvey et al. 1981; Chemero 2003, 2009; Segundo-Ortín et al. 2019). In this sense, affordances were proposed within ecological psychology as a means to explain psychology in terms of organism-environment dynamics and not in terms of the internal, cognitive activities of the organism.

The ecological character of affordances makes them relevant resources for embodied explanations as they take brain-body-environment interactions to be the core of the explanatory activity for the sciences of the mind—that's the case, for instance, of embodied approaches different from ecological psychology, like enactivism (Di Paolo et al. 2017; Gallagher 2017) or less-radical, mainstream embodied cognitive science (Clark 2015; Ramstead et al. 2016). In this context, the fact that Paul Cisek and colleagues use the notion of affordance signals a clear intention to incorporate some aspects of embodiment into cognitive neuroscience. However, akin to the works of Miller et al. (2018, 2019), such an intention crystalizes in another instance of a there-and-back-again move. Paul Cisek and colleagues incorporate affordances into cognitive neuroscience by stripping them away from any embodied connotations. The perception of affordances is depicted in terms of classic brain-centric models based on an information-processing paradigm (Cisek 2007), describing specific neural mechanisms for the selection of specific actions between competing alternatives (Cisek and Kalaska 2010) within a landscape of affordances (Pezzulo and Cisek 2016). In this sense, although Paul Cisek and colleagues incorporate the notion of affordance into cognitive neuroscience, they depict affordances only in terms of the activity of the brain. In other words, they offer a highly localized explanation of affordances and not the explanation based on brain-body-environment interactions for which the concept was originally conceived. And, again, the move from cognitive neuroscience to embodiment and back again is complete.

These two examples are not presented to offer an exhaustive review of the embodied approaches to cognitive neuroscience. As we will see in the next section, there are some other works that are able to bring more substantive notions of embodiment to the field. However, what these two examples highlight is how little of a mark embodiment leaves in cognitive neuroscience due to the there-and-back-again moves that allow for shallow conceptual incorporations but not for deep effects in methodology or explanatory strategy. In this sense, the tales of embodiment incorporated into cognitive neuroscience neither challenge the fundamental assumptions nor contribute to solving the pressing issues of the field. There are, nevertheless, *forgotten tales of embodiment* that may challenge those assumptions and, more importantly for the aims of this article, may contribute to solving those issues. We turn to such forgotten tales now.

3 The forgotten tales: on what is there and how to get it

Some embodied theories of perception and action call for an insurrection in the cognitive sciences. And, if such an embodied insurrection finds success, there will be a revolution in the field that will specifically affect the way cognitive neuroscience is carried out. At least some forms of embodiment require a re-conceptualization of cognitive systems in terms of brain-body-environment dynamics that may be interpreted as downplaying the role of the brain in perception, action, and cognition.[5] In this context, it is far from surprising that some of the tales or narratives of embodiment are somewhat forgotten in cognitive neuroscience as they may be regarded as direct attacks to the very foundations of the field. However, as I have already noted, the aim of this article is not to feed the fire of the insurrection. On the contrary, I want to show that some of the forgotten tales of embodiment can provide new avenues for solving some long-lasting issues in cognitive neuroscience. In the following sections, I present two of these issues and suggest possible contributions of embodiment to the advancement of their solutions.

3.1 The tale of what is there

The first forgotten tale of embodiment has to do with what is there to be perceived and relates to the *central problem of perception*. The quote by David Marr that opens this article is a simple statement of this problem: namely, how to bridge the gap between sensations and their causes. Marr (1982/2010) himself makes this point more explicit later when he claims that bridging the gap between the retinal image (the sensation) and the environment (the cause of the sensation) is the purpose of vision with regard to the shape of environmental surfaces:

> The main stepping stone toward this goal is describing the geometry of the visible surfaces, since the information encoded in [retinal] images, for example by stereopsis, shading, texture, contours, or visual motion, is due to a shape's local surface properties. The objective of many early visual computations is to extract this information. (p. 36).

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[5] This does not have to be the case though. Indeed, many of the proposals that can be considered as part of the embodied insurrection attribute an important role to the brain in perception, action, and cognition (see, e.g., Anderson 2014; de Wit et al. 2017; Favela 2014; Kelso et al. 2013; Raja 2018, 2019a, 2020; Raja and Anderson 2019). The role of the brain in these theories is just *different* from its role as it is understood by mainstream cognitive neuroscience.

The problem of perception is, therefore, one of closing an epistemological gap between what is there—e.g., surfaces of the environment—and what we get from it—e.g., the different aspects of the retinal images we get from those surfaces. The bad news is that solving this problem is way more difficult that it might seem.

Imagine a green square over a white background and a perceiver looking at it. Depending on the position of the perceiver in relation to the green square, the retinal image in the eye of the perceiver will be different—e.g., wider, narrower, diamond-like, etc. Moreover, two green squares of different size can project the same retinal image in the eye of the perceiver if they are placed at different distances from her. The consequences of the phenomenon illustrated by these two situations are deep: given the indeterminacy of the relation between sensations (e.g., retinal images) and the environmental events that cause them (e.g., green squares), the problem of perception is generally intractable when it is framed in inferential terms—i.e., there are some unsolvable steps of the inference. In other words, as one environmental event may generate an infinite set of different sensations and one sensation may be generated by an infinite set of different environmental events, bridging the gap between sensations and their associated environmental events seems to be impossible without postulating resources for different (usually non-perceptual) knowledge about that gap and the way to bridge it.

This fundamental problem is what led Helmholtz to postulate the necessity of an ‘unconscious *inference’* to explain perception and is what drove Marr to develop his three-leveled, information-processing approach to visual perception. However, the problem is not a past issue and contemporary cognitive neuroscientists acknowledge it. Karl Friston (2005), for instance, explicitly stated the problem in his early works on predictive processing and the free-energy principle when he claimed that “[t]he problem the brain has to contend with is to find a function of the [sensory] inputs that recognizes the underlying causes” (p. 820). Right after this, Friston identifies the problem with the indeterminacy of the relation between the mentioned sensations and causes, noting its intractability because such a relation “may not be invertible and that the estimation of causes from input may be fundamentally ill-posed” (Ibid.). Similarly, James V. Stone (2012) acknowledges the central problem of vision (sic) when he claims that “[t]he brain is constantly doing its best to find out what in the world is responsible for the image on the retina” (p. 2). After that, he immediately compares such a task of the brain with the one of a detective in a murder scene.

Both Friston and Stone proceed from the acknowledgement of the problem to offering Helmholtz-like, inferential solutions to it. On the one hand, Stone (2012) favors the *efficient coding hypothesis* according to which, in visual perception, the brain is able to properly and effectively encode and decode the input in the retina as to gather information about its causes. On the other hand, Friston (2002, 2003, 2005, 2010; Friston et al. 2006) proposes a free-energy minimization version of *predictive processing* according to which, in perception, the brain is in the business of predicting sensory input. In both cases, some form of non-perceptual knowledge needs to be in place for the (inferential) solution to work—some form of encoding/decoding look-up table in the case of the efficient coding hypothesis and some form of Bayesian prior distribution with knowledge about the relation between sensations and their causes in the case of predictive processing.

There are criticisms of both the effective coding hypothesis (see Brette 2019) and predictive processing (see, for instance, Anderson and Chemero 2019; Ramson et al. 2020; Litwin and Miłkowski 2020) on different grounds. But, generally speaking, they both seem to share the limitation classically attributed to all Helmholtz-like, inferential solutions to the central problem of perception: the inability to justify the non-perceptual resources needed for the solution to work (see, e.g., Dennett 1978; Chemero 2009; Turvey 2019). Put simply, if perception requires extra knowledge resources, what is the source of these resources? How does the brain have access to a look-up table to encode and decode sensory signals to gather perpetual information about the environment? Or how does the brain have access to the Bayesian prior with knowledge about the relation between sensations and their causes? If these resources are necessary for perception, then perception itself cannot be their source and the justification for the brain having them is not at all obvious. The inability to explain these extra resources needed for perception to work within this framework is, likely, one of the reasons why "nobody knows exactly how we see, even though there is an enormous body of knowledge about optics, the eye, and the brain." (Stone 2012, p. 1).

Along with the intractability of the relation between sensations and their causes, and the lack of justification for the knowledge resources contemporary models in cognitive neuroscience rely on, a different issue arises in the vicinity of the central problem of perception. The acknowledged gap between sensations—i.e., what we get at our sensory receptors—and the causes of sensations—i.e., the environmental events that cause sensations—is related to the under-determination of the notion of stimulation in cognitive neuroscience. Put simply, the notion of stimulation in cognitive neuroscience—and in neuroscience in general—is used indistinctly both for sensations and for their causes. A simple review of contemporary studies shows that what is called "stimulus" or "stimuli" in studies of perception ranges from the input of retinal ganglion cells (e.g., Sayood 2018; Stone 2012) or from the vibration of rats' whiskers (Ince et al. 2010) to the structural properties of pictures of faces (Hashemi et al. 2019) or the movie *Memento* (Kauttonen et al. 2018). Namely, "stimuli" in cognitive neuroscience ranges from different individual inputs of sensory receptors to full-fledged environmental events like a movie.

The ambiguity of the notion of stimulation in the cognitive sciences is not a recent phenomenon. James Gibson (1960) already pointed out that the physiological notion of stimulation was adopted in psychology and the cognitive sciences by changing its meaning. While stimulation in physiology refers to whatever kind of energy makes a sensory receptor activate, stimulation in psychology and cognitive science refers to whatever environmental event elicits a response in the cognitive system. These two distinct notions are merged in cognitive neuroscience and, depending on the needs of the experimental setup, stimulation is understood in the physiological sense (e.g., the input of retinal ganglion cells) or in the psychological/cognitive sense (e.g., the movie *Memento*). In principle, this is not a problem by itself. To adapt different aspects of the experimental activity to research goals may be seen as a legitimate scientific practice. However, the under-determination of the notion of stimulation becomes an important issue in light of the central problem of perception.

As the central problem of perception takes issue with the relation between sensations and their causes, different assumptions about what counts as stimulation—e.g., the energy that activates sensory receptors (sensations) or the environmental events that elicit responses (causes)—actually have important consequences. On the one hand, the assumptions regarding what counts as stimulation have a direct impact on what counts as naturalistic stimulation (Sonkusare et al. 2019; Wen et al. 2019) and, therefore, they have implications in decisions regarding experimental setups and also in issues like the replicability and generalizability of scientific results. For instance, several studies on perception have already shown different fMRI results when the stimulation presented to participants is based on real objects instead of on pictures of those same objects (Valyear et al. 2006, 2012). On the other hand, different assumptions about what counts as stimulation place neuroscientific research in other, diverse problematic situations. The physiological understanding of stimulation in terms of simple sensations leads to the cognitive seclusion that makes Helmholtz-like theories face the necessity of postulating extra knowledge resources to explain perception. In the case of the psychological understanding of stimulation in terms of environmental events, the main issue is that it bypasses the central problem of perception and, therefore, it is unable to offer a perceptual mechanism: as the relation between environmental events and caused sensations is intractable, when environmental events are considered stimulation there's no way to understand how the brain is able register them with the sensory inputs it gets. Finally, when the physiological and the psychological understandings of stimulation are indistinctly applied, as it is the case in cognitive neuroscience, the problem of their own relation and the relation of the studies that assume one definition or the other remains open.

Hopefully, the previous discussion has shown that the central problem of perception posits important limitations in our ability to understand the epistemological contact between organisms and their environments. The indeterminacy of the relation between sensations and environmental events along with the ambiguity of the notion of stimulation in cognitive neuroscience make the explanation of perception a real challenge. Additionally, proposed inferential solutions to this challenge in cognitive neuroscience face their own limitations. These solutions assume that the *only* way to make tractable the seemingly intractable relationship between sensations and their environmental events is to postulate some other resources that *already* have knowledge about that relation (e.g., a look-up table for decoding the sensory input or a Bayesian prior to predict the sensory input). However, explaining how those resources have such knowledge is precisely the aim of perceptual theories. Thus, these inferential solutions are unsatisfactory and appear, at least to some extent, to be begging the question (Friston 2002; Turvey 2019). But what if there is a different solution? What if there is a way to understand the relationship between what is there to be perceived and what the organism gets such that the gap between them can be reliably bridged or such that there is no gap at all? The forgotten tale of what is there to be perceived provides resources for finding an alternative solution.

As noted in the previous section, the *leitmotiv* of embodiment is the explanation of perception, action, and other cognitive events in terms of brain-body-environment interactions. Such *leitmotiv* readily provides a sense of delocalization in the explanatory trends of embodiment and, at the same time, offers new strategies and resources for facing problems in the cognitive sciences. In this context, cognitive neuroscience may discover resources in embodiment to help find alternative solutions to the central problem of perception. Concretely, the forgotten tale of what is there to be perceived offers a way to make tractable the relationship between sensations and their environmental causes without positing inferences and extra knowledge resources. This forgotten tale does so by re-describing that relationship in lawful terms (see Raja 2019b).

At the basis of the central problem of perception lies the irreversibility of sensations as a function of environmental events.[6] As already noted, there seems to be no way to map sensations and environmental causes without facing an explosion: *one* sensation may be caused by an infinite set of environmental causes and *one* environmental event may cause an infinite set of sensations. This explosion is unavoidable when only neural resources are taken to be available for the cognitive system. However, when resources of the brain-body-environment system as a whole are available, there are ways to avoid the explosion and to reliably relate the stimuli available in sensory receptors and environmental events. Theories of embodiment do so by allowing for action to be a constitutive part of perception and by promoting a new understanding of what is available to sensory receptors once perception is active. Two examples of this move are *sensorimotor contingencies* (O'Regan and Noë 2001) and *perceptual invariants* (Gibson 1966, 1979).

Both sensorimotor contingencies and perceptual invariants are founded in embodied re-descriptions of what is there to be perceived. If the theses of embodiment are correct, the activities of the body and its interactions with the environment of the organism must contribute to cognitive processes. Sensorimotor contingencies and perceptual invariants rely on these two factors to propose a solution for the central problem of perception. In the case of sensorimotor contingencies, the idea is that organisms do not get sensations in the void but always while engaged in some kind of activity; namely, organisms get sensations within specific motor contexts. For instance, when a person walks forward, she gets a specific kind of *optic flow*—i.e., a specific transformation of her visual field/ of the inputs of her sensory receptors—in the form of a centrifugal pattern from the center (focal) point of what is perceived. The same occurs when the person walks backwards: there is a specific kind of optic flow, in this case a converging pattern towards the focal point. These relationships between actions like walking and specific sensory patterns are what O'Regan and Noë (2001) labelled as sensorimotor contingences. Perceptual systems, so the story goes, must be understood in terms of being sensitive to these sensorimotor contingencies and not in terms of inferring the environmental causes from sensations. In this sense, sensorimotor contingencies open a new path for cognitive neuroscience: the study of the role of the brain in perception must be framed in terms of the way the brain is sensitive to sensorimotor contingencies and not in terms of Helmholtz-like, inferential processes. This path becomes even more salient in the case of perceptual invariants.

The notion of a perceptual invariant originates in the ecological psychology literature (Chemero 2009; Gibson 1966, 1979; Segundo-Ortín et al. 2019; Turvey et al. 1981). In a few words, perceptual invariants are unchanging properties of the stimulation available to an organism when performing some action. In this sense, perceptual

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[6] Notice that the irreversibility described here is understood as the same notion is understood in mathematics. A function F is irreversible if granting F′ = G, there's no G' and, therefore, there's no way to go back to F from G. For instance, if G are the sensations as a function of environmental events F and the task of the brain is to find a way to bridge the gap from G to F, the fact that G' is impossible makes the brain face an intractable problem. I follow Frsiton (2002, 2003, 2005) in this characterization.

invariants are precedents of sensorimotor contingences but, at the same time, are further developed than the latter. A famous example of a perceptual invariant is *tau* (see Lee 2009).[7] In visual perception, *tau* is a property of the of the optic flow that lawfully specifies the time an approaching object will take to hit the visual system of an organism. Simply put, any object occupies some part of the visual field of a perceiver who is looking at it. From the point of view of the perceiver, the object occupies a specific visual angle. Then, as the object approaches the perceiver, the visual angle it occupies in her visual field dilatates. Tau is a specific property of this dilatation—concretely, tau is defined as the relative dilatation of the visual angle of a given object in a perceiver's visual field—and is lawfully related with the time remaining until the object closes the gap with the perceiver, or *time-to-contact*.[8] Thus, by detecting tau, organisms are able to know relevant aspects of their environment and their relation to it—e.g., how long it will take until a ball gets to a perceiver for her to kick it if she is a soccer player—without the need for any kind of inferential process. As we have already noted, inferential processes are postulated due to the irreversibility of the relation between sensations and the environmental events that cause them. However, once what is there to be perceived in time-to-contact situations is described in terms of tau, the irreversibility disappears as the relationship between what is there and what the organism gets is lawful. Therefore, no inferential process is needed.

Tau has been thoroughly and successfully described in the behavioral and perceptual sciences in a large variety of situations, like in the plummeting of gannets (Lee and Reddish 1981), in the punching of falling balls (Lee et al. 1983), in long jump (Lee et al. 1982), in the suckling activity of newborns during breastfeeding (Craig and Lee 1999), in reaching activities (Lee 2005), in several musical activities (Craig et al. 2005; Schögler et al. 2008), and in guiding one's swing while playing golf (Craig et al. 2000), among others (see Lee 2009 for a review). In this sense, tau is a reliable perceptual invariant that could inform perceptual studies in cognitive neuroscience. Instead of looking for the way the brain infers time-to-contact from simplistic, instantaneous sensations, cognitive neuroscientists could look for possible ways in which brains are able to detect the patterns of optic flow/sensory input correlated to tau. Doing that, cognitive neuroscientists could address a set of perceptual problems that involve time-to-contact (catching, braking, hitting, etc.) from a non-Helmholtzian strategy—i.e., a strategy that does not require any form of inference from sensory states to environmental events. The good news is that this is not just a speculative proposal but that there are a few studies that show the utility of incorporating tau in perception research. For instance, some neurons in the *nucleus rotundus* of pigeons are sensitive to tau (Sun and Frost 1998) and the theta band of the EEG dynamics of babies' visual cortex is tau-coupled in looming situations (van der Weel and van der Meer 2009; van der Weel et al. 2019). These studies show it is possible to find neural mechanisms able to detect

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[7] Examples of different perceptual invariants may be found in Jacobs and Michaels (2007) or Warren (2006), for instance.

[8] The lawfulness of the relation between tau and time-to-contact is founded in the physical properties of ambient light once it bounces off the surfaces of the local environment of the organism. These properties are described by what James Gibson named *ecological optics* (1960, 1966). A full account of ecological optics is out of the scope of this article, but the interested reader may check Chemero (2009), Michaels and Carello (1981), Segundo-Ortin et al. (2019), Turvey (2019), Warren (1998).

tau and, therefore, to gather knowledge in time-to-contact situations without the need for non-perceptual or inferential resources.

The forgotten tale of tau, and more generally *the forgotten tales of sensorimotor contingencies and perceptual invariants*, are just illustrations of a general point regarding the possible contribution of embodiment to cognitive neuroscience. These tales show that what is seen as an intractable problem when research efforts are solely focused on brain activity becomes a tractable issue when the brain-body-environment interactions are included in the research strategy. Embodied theorists have been studying properties of the environment, properties of stimulation, and properties of the organism-environment interactions for decades now. In this sense, embodiment is full of reliable resources to target issues in perception, action, and cognition. And cognitive neuroscience does not need to go through a revolution to benefit from these resources. On the contrary, cognitive neuroscientists can open up new paths of research just by being skeptical of some of the contemporary practices in the field (e.g., the ambiguity on what counts as "stimuli") and by adopting some successful notions from embodiment.

3.2 The tale of how to get it

The second forgotten tale of embodiment may be seen as the other side of the perception-action coin. If the previous tale was about what is there to be perceived, the tale of how to get it is about the way organisms can control their actions and how these actions relate to perception. In terms of cognitive neuroscience, while the tale of what is there to be perceived provides resources for trying to solve the central problem of perception by re-describing the brain-body-environment interactions, the tale of how to get it provides resources for trying to solve a longstanding issue in motor control theories: the way organized behavior is related to brain activity. And it does so in the same way, that is, by an embodied re-description of the organization of behavior.

A common action such as being able to grab a mug with a hand is a more complex task than it prima facie seems to be. For someone to grab a mug with a hand, a very fine tuned process must be at place: without taking into account the joints and muscles of the hand, 3 joints with 7 degrees of freedom, about 26 muscles, and over 2000 motor-receptors must be coordinated and organized in order for the proper grabbing behavior to emerge. It is easy to see how such an amount of coordination and organization may be an overwhelming task and the *central problem of motor control* is to understand how the organism is able to succeed in such a task. For most cognitive neuroscientists working on this problem, the concrete issue is to understand how the brain is able to solve—or at least contribute to solving—the problem.

As in the case of the central problem of perception, the central problem of motor control is not a new one and it can be traced back, at least, to Nikolai Bernstein's (1967) formulation of the degrees of freedom problem. Bernstein's formulation may be seen as a concrete instance of the general problem in terms of how it is possible for the brain to control the impressive number of degrees of freedom involved in organized behavior. However, and as in the case of the central problem of perception, again the central problem of motor control is not a past issue but an alive concern in contemporary cognitive neuroscience. For instance, Krakauer et al. (2017) recently restated the problem by claiming:

> Neuroscience is replete with cases that illustrate the fundamental epistemological difficulty of deriving processes [e.g., behavior] from processors [e.g., brain]. For example, in the case of the roundworm (*Caenorhabditis elegans*), we know the genome, the cell types, and the connectome—every cell and its connections… Despite this wealth of knowledge, our understanding of how all this structure maps onto the worm's behavior remains frustratingly incomplete.[9] (p. 480)

On the one hand, such a difficulty to map the organization of the brain and its activity with the organization of behavior is reflected in the complexity of the models we use to try to solve it. These models usually involve forward and feedback inputs, predictions, internal models of the environmental layout, etc. On the other hand, and even more patently, the difficulty is reflected in our own artificial intelligence devices: we easily build up devices that are able to beat us at playing chess, but devices that are able to move like us when we walk or grab a mug with a hand are very scarce if not nonexistent (see, e.g., Brooks 1990, Der and Martius 2012).

The central problem of motor control gets exacerbated in cognitive neuroscience by the assumption that it *must* be solved by using only neural resources. In other words, by the assumption that the problem reduces to understanding how the brain is the only controller of behavior. Meijer (2001) refers to this narrower problem the 'King Charles V problem'. As the story goes, King Charles V had hundreds of pendulum clocks and was obsessed with making all of them tick at the same time. To do so, King Charles V went one by one trying to synchronize each tick with the previous one. He was never able to do it. The moral of the story is that King Charles V was acting as a central controller and that complex systems—i.e., systems with a great number of interacting components—cannot be centrally controlled. As organisms are complex systems themselves, their behavior cannot be centrally controlled only by neural resources. Meijer (2001) uses this story to illustrate the need for different explanatory strategies in the field of motor control. And these strategies are the forgotten tales of embodiment on how to get it.

The most obvious alternative solution to the central problem of motor control as it is understood in cognitive neuroscience is to try to look for resources that coordinate and organize behavior outside of the brain. This is the solution proposed by Bernstein (1967) when he claimed that in motor control coordination must precede control, that is, that the brain must control already coordinated structures named synergies (Kelso 1995) or coordinative structures (Tuller et al. 1982). The same spirit may be found in James Gibson's famous claim "behavior is regular without being regulated" (1979, p. 2015), that Warren (2006) interprets as suggesting that:

> [R]ather than being localized in an internal (or external) structure, control is distributed over the agent-environment system. I interpret this statement to imply that biology capitalizes on the regularities of the entire system as a means of ordering behavior. Specifically, the structure and physics of the environment, the biomechanics of the body, perceptual information about the state of the agent-

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[9] Notice the striking similarity between this claim and Stone's claim regarding our lack of knowledge regarding visual perception (above). To echo Watson & Crick's famous *motto*, it has not escaped my notice that this similarity immediately suggests a possible common root for both issues.

> environment system, and the demands of the task all serve to constrain the behavioral outcome. (p. 358).

This is already an embodied understanding of motor control. An understanding that considers the brain-body-environment interactions when explaining the emergence of organized behavior. In this sense, this is the core of the forgotten tale of how to get it that cognitive neuroscience could include when looking for alternative strategies needed to solve the central problem of motor control.

In more concrete terms, the forgotten tale of how to get it rests upon the approach to the study of behavior typical in ecological psychology and dynamical systems theory (see Warren 2006 for a review). From this point of view, behavior can be understood in terms of the dynamics of the organism-environment system. This system includes the brain, of course, but also the biomechanical properties of bodies (e.g., psychical limbs dynamics, fascial constraints, joint interactions, etc.) and the properties of the environment in which the behavior is performed (e.g., the layout and consistency of local surfaces, the gravity vector, and so on). This immediately suggests that there are sources distributed outside of the brain that participate in the control of coordinated behavior. For instance, in an organized behavior that involves the use of one arm such as grabbing a mug with a hand, the task of the brain might not be to control every component of the arm, but to control the arm as a synergy or coordinative structure that is already coordinated due to non-neural constraints such as the gravitational properties of the limbs (Schneider et al. 1989) or the interaction between its joints (Scholz et al. 2000).[10]

As in the case of the embodied proposals regarding perception, the embodied explanatory strategies for motor control have found a good amount of success in cognitive science. Since the original dynamical accounts of behavior appeared within the field of ecological psychology, the explanation of behavior in terms of organism-environment dynamics has described phenomena like rhythmical movements (Haken et al. 1985), learning (Newell et al. 2008) and skill learning (Baggs et al. 2020), locomotion (Fajen and Warren 2003), interpersonal coordination (Schmidt and Richardson 2008), speech production (Port 2003), behavioral variability (Nalepka et al. 2017), and human–computer interactions (Nalepka et al. 2019; Lobo et al. 2019), among others. In all these examples, the organization of the behavior of interest is understood at the scale of the organism-environment interactions and takes into consideration all the factors that may contribute to the emergence of said behavior. By adopting this kind of embodied strategy, cognitive neuroscientists would have a deeper understanding of the organization of behavior, and this understanding would serve as a good framework to characterize the role of the brain in motor control. Such a deeper understanding of organized behavior can fulfill, for instance, the request for a better conceptual framework in the cognitive neuroscience of action, as expressed by Krakauer et al. (2017):

> Neural data obtained from new methods cannot substitute for developing new conceptual frameworks that provide the mapping between such neural data and behavior in an algorithmic sense (and not just a correlative or even causal way).

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[10] It is worth noting that work on modern robotics and minimal cognitive agents have used similar kind of insights to solve various computational puzzles that were deemed as unsolvable. An example of this is Rodney Brook's work (1990). I am thankful to an anonymous reviewer for this suggestion.

> Accomplishing this task requires hypotheses and theories based on careful dissection of behavior. (p. 481; see also Gomez-Marin and Ghazanfar 2019).

The forgotten tale of how to get it, as far as it tells the story of the embodied understanding of organized behavior, is perfectly suited to be the conceptual framework cognitive neuroscience can use to find new paths towards a solution for the central problem of motor control. And, as in the case of the forgotten tale of what is there to be perceived, this is not just a speculative proposal. There are some works in cognitive neuroscience that already follow an embodied path when trying to solve particular issues in the field—e.g., the work on human-computer interaction (Dumas et al. 2020) and the work on the dynamics of the Fitts' task (Pillai and Jirsa 2017).

A final remark on the relationship between the two forgotten tales is noteworthy. Both forgotten tales favor an understanding of perception and action in terms of brain-body-environment interactions, and it is precisely this fact that makes them part of the same story. According to the tale of what is there to be perceived, perceptual events must be understood as emerging from the different interactions of the brain, body, and environment. In this sense, a relevant factor to include when explaining a perceptual event is the act of looking. Looking is a bodily activity that occurs within an environment. It usually requires several movements of the body, the head, the eyes, etc., to be successful. These movements are a form of organized behavior! Thus, in this case, the forgotten tale of how to get it would be the forgotten tale of how to look. This tale would explain the organized behavior of looking as emerging from the interactions of the brain, body, and environment. And perceptual events are themselves among those interactions. Thus, perceptual events and their correlates (e.g., perceptual information) are part of the embodied explanation of looking. And, as we have seen, looking is part of the embodied explanation of perceptual events. In other words, perceiving requires organizing one's behavior within an environment, and organizing one's behavior requires perceiving the environment. The two forgotten tales are part of the same overarching story: that perception and action are inextricably tied together within the brain-body-environment system. It is a story cognitive neuroscience could benefit from adopting when trying to solve the central problems of perception and motor control.

4 Concluding remarks: a farewell to arms

One of the common threads running through this article is that embodiment takes cognitive events to be a matter of brain-body-environment interactions. In some sense, this claim is a truism. Except a few philosophers of mind and some sci-fi movies (e.g., *The Matrix* or *Inside Out*), most researchers in the cognitive sciences accept that cognitive events are predicated on organisms acting in their environments. However, in a different sense, the preceding embodied claim is a threat for cognitive neuroscience because, as already noted, it seems to diminish the role of the brain in cognition. For this reason, many cognitive neuroscientists are generally skeptical about the adequacy and usefulness of embodiment for their research. And it is difficult to blame them.

Many researchers working on the most radical theses of embodiment have been almost dismissive when talking about the role of the brain in cognition. An example of this is William Mace's popular claim within ecological psychology: "Ask not what's inside your head, but what your head's inside of" (Mace 1977/2017, p. 44; see also Bruineberg and Rietveld 2019). This is most likely an overstatement with regard to the original theses of ecological psychology, but it illustrates one of the reasons for the chiasm between cognitive neuroscience and embodiment (ecological psychology in this concrete case).[11] In most cases, however, the relationship between the radical forms of embodiment and cognitive neuroscience take the form of cold and reciprocal skepticism: they look at each other as alien creatures that will eventually attack. In this situation, the dominant position of cognitive neuroscientists leads them to ignore most embodied theses and the precarious position of researchers of embodiment—including the current author—often leads them to call to arms against cognitive neuroscience.

In this paper, however, I have tried to defend three theses against this state of affairs. The first thesis is that there are some *forgotten tales of embodiment* in the field of cognitive neuroscience: *the tale of what is there* and *the tale of how to get it*. The second thesis is that there are two central problems in the cognitive neuroscience of perception and action: how organisms are able to be in epistemological contact with their environment given what they get from it, and how organisms are able to control their behavior. And the third thesis is that the two forgotten tales of embodiment offer new resources to help cognitive neuroscience solve these problems. To be clear, I have not claimed that, by incorporating the forgotten tales of embodiment, cognitive neuroscience will certainly solve these problems. My claim is humbler: that, by incorporating the forgotten tales of embodiment, cognitive neuroscience will find new perspectives on the central problems of perception and motor control, and new tools for tackling these problems. However, in order to do so, the cold skepticism between embodiment and cognitive neuroscience needs to end, making room for collaboration. This seems to be the only feasible way to find richer theoretical frameworks to study and understand the complex events of perception, action, and cognition. In this sense, I hope what I have shown here is not viewed as a call, but as a farewell to arms.

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[11] A simple reading of Gibson's works on perceptual systems, specially *The Senses Considered as Perceptual Systems* (1966), shows that he was concerned with the activity of the brain—referred to on many occasions as *neural resonance*—and that he was disappointed in the lack of knowledge about said neural activity . Gibson claims, for instance: "We do not know much yet about the neural action of resonance at higher centers, but it too may prove to be the reaching of some optimal state of equilibrium. If the neurophysiologists stopped looking for the storehouse of memory perhaps they would find it." (Gibson 1966, p. 271). In this sense, the somewhat dismissive attitude regarding neuroscience/neurophysiology that is patent in some Gibsonians is not present in Gibson (although maybe it was present in his attitude towards the neurophysiologists of his time).

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