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ORIGINAL RESEARCH

Scientific practice as ecological-enactive co-construction

Guilherme Sanches de Oliveira[1] · Thomas van Es[2,3] · Inês Hipólito[4,5,6]

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Abstract

Philosophy of science has undergone a naturalistic turn, moving away from traditional idealized concerns with the logical structure of scientific theories and toward focusing on real-world scientific practice, especially in domains such as modeling and experimentation. As part of this shift, recent work has explored how the project of philosophically understanding science as a natural phenomenon can be enriched by drawing from different fields and disciplines, including niche construction theory in evolutionary biology, on the one hand, and ecological and enactive views in embodied cognitive science, on the other. But these insights have so far been explored in separation from each other, without clear indication of whether they can work together. Moreover, the focus on particular practices, however insightful, has tended to lack consideration of potential further implications for a naturalized understanding of science as a whole (i.e., above and beyond those particular practices). Motivated by these developments, here we sketch a broad-ranging view of science, scientific practice and scientific knowledge in terms of ecological-enactive co-construction. The view we propose situates science in the biological, evolutionary context of human embodied cognitive activity aimed at addressing the demands of life. This motivates reframing theory as practice, and reconceptualizing scientific knowledge in ecological terms, as relational and world-involving. Our view also brings to the forefront of attention the fundamental link between ideas about the nature of mind, of science and of nature

✉ Guilherme Sanches de Oliveira
gui.cogsci@gmail.com

1 Department of Psychology and Ergonomics, Technische Universität Berlin, Gebäude KWT-N, Eing. 1, Fasanenstr. 1, 10623 Berlin, Germany

2 IAS-Research Center for Life, Mind and Society, University of the Basque Country, Donostia, Spain

3 Department of Philosophy, Centre for Philosophical Psychology, University of Antwerp, Antwerp, Belgium

4 Berlin School of Mind and Brain, Humboldt Universität zu Berlin, Berlin, Germany

5 Department of Philosophy, Macquarie University, Sydney, Australia

6 Wellcome Centre for Human Neuroimaging, University College London, London, UK

itself, which we explore by outlining how our proposal differs from more conservative, and narrower, conceptions of "cognitive niche construction."

Keywords Scientific practice · Theory · Naturalism · Ecological psychology · Enactivism · Niche construction · Cognition

1 Naturalized philosophy of science, evolution, and embodied cognition

In stark contrast with traditional conceptions of philosophy of science as armchair speculation and "abstract epistemology" (Thagard, 1993), many today favor instead a view in which philosophy of science is best done through careful attention to, and close contact with, "real science" as practiced in the "real world". This shift can be seen as a "naturalistic turn" (Callebaut, 1993; see also, e.g., Shan, 2020; Soler et al., 2014) leading to the rise of a practice-oriented philosophy of science (Ankeny et al., 2011; Boumans & Leonelli, 2013; see also, e.g. Atanasova et al., 2021; Poliseli et al., 2022). In all its diversity, a key unifying aspect of this approach in philosophy of science is the shift away from exclusive focus on ideal theoretical knowledge and toward prioritization of practical dimensions of scientific work, such as experimentation and model building. In particular, while in the traditional philosophical conception these practical dimensions of science might have been treated as mere places for the "application" of theoretical knowledge, recent work is concerned with elucidating the much more complex relations that hold between scientific theory, experimentation and modeling, including the positive contribution that practice can make to theorizing (e.g., Morgan & Morrison, 1999; Peschard & van Fraassen, 2018).

Within this naturalized approach and greater emphasis on scientific practice, an interesting trend of productive cross-pollination is evident in recent work at the interface of philosophy of science with other fields and disciplines:

A. At the interface of philosophy of science with evolutionary biology, besides a wealth of work applying philosophical tools to examine the scientific standing of niche construction theory, its empirical adequacy and relation to other theories (e.g., Aaby & Ramsey, 2022; Godfrey-Smith, 2000; Okasha, 2005; Uller & Helanterä, 2019; Wallach, 2016; Wells, 2015), there has also been work drawing *from* niche construction theory to inform philosophical reflection on scientific knowledge and scientific practice, leading to understanding science as a biological phenomenon, one that arises from the activity of biological organisms and develops over time in an evolutionary context (e.g., Haufe, 2022; Renn, 2018; Rouse, 2014, 2015, 2016).
B. At the interface of philosophy of science with embodied cognitive science, besides a wealth of work applying philosophical tools to consider the scientific standing of enactivism and ecological psychology, their empirical adequacy and relation to other theories (e.g., Clark, 1999; Kaplan & Craver, 2011; Keijzer, 2002; Miłkowski & Nowakowski, 2021; Shapiro, 2007; Stepp et al., 2011; Zednik, 2011), there has also been work drawing *from* enactive and ecological views in cognitive science to

guide and advance philosophy of science, especially leading to novel accounts of the ontology and epistemology of model-based scientific research understood as an embodied cognitive practice (see, e.g., Knuuttila, 2011, 2021; Rolla & Novaes, 2022; Sanches de Oliveira, 2016, 2021, 2022a; Stegmann, 2020).

In addition to these productive uses in philosophy of science of ideas (A) from niche construction theory and (B) from embodied, ecological and enactive cognitive science, we find a further related but distinct link in the recent literature:

C. At the interface of embodied cognitive science with evolutionary biology, recent work has fruitfully drawn from niche construction theory to address pressing questions arising in the traditions of enactivism and ecological psychology relating to the notions of "affordances" and "sense making" as well as, more broadly, shedding light on the nature of organism-environment relations as these change over time, not only at the developmental but also the evolutionary scale (see, e.g., Chemero, 2009; Corris, 2020; Heras-Escribano, 2020; Heras-Escribano & De Jesus, 2018; Heras-Escribano & De Pinedo-García, 2018; Rolla & Figueiredo, 2021; Rothwell et al., 2021; Werner, 2020; Withagen & van Wermeskerken, 2010).

The present paper is motivated by the realization that these connections of ideas across fields and disciplines have, by and large, been pursued in isolation from each other, with negative consequences for each line of research:

- Work drawing from niche construction theory to guide philosophy of science toward understanding science as a biological phenomenon (i.e., A) has tended to lack substantive engagement with cognitive science and all that it can tell us about human intelligence, problem solving abilities, and epistemic agency more generally, especially neglecting *embodied* approaches to these cognitive phenomena. Given the goal of developing a naturalized understanding of *scientific practices*, this neglect amounts to a missed opportunity to anchor reflection in powerful and increasingly popular theories about the *practitioners* in question as embodied, situated cognitive agents.
- Research drawing from embodied cognitive science to inform philosophy of science (i.e., B) has, on the one hand, tended to be narrowly focused on specific scientific practices, especially modeling practices, and, on the other hand, it has typically operated within a limited spatiotemporal frame of reference, neglecting the biological evolutionary grounding of those specific practices. This is a missed opportunity to realize the full potential that embodied cognitive science has for guiding philosophical reflection on science as a whole (rather than only particular practices within science). It is also a missed opportunity to properly situate the embodied cognitive practices that make up science in their spatiotemporally-extended biological context at the evolutionary scale.
- And finally, the work drawing from niche construction theory to enrich theorizing in embodied cognitive science (i.e., C) has tended to neglect the implications that this move can have for how we understand the embodied, situated cognitive practices that people engage in when doing science. This amounts to a missed opportunity to address the widely-acknowledged challenge of "scaling up" non-representational explanations, expanding the scope of embodied cognitive science explanations beyond "online cognition" (i.e., real-time perception–action) so as to

make sense of "representation-hungry" phenomena at play in so-called "offline cognition," of which the abstract thinking, logical reasoning, creativity, imagination, and other processes scientists engage in are paradigmatic examples (see Clark & Toribio, 1994; Di Paolo et al., 2017; Gallagher, 2017; Rietveld & Kiverstein, 2014; Sanches de Oliveira, 2022b; Sanches de Oliveira et al., 2021; Zahnoun, 2021). It is also a missed opportunity for engaging in "reflexive" theorizing, extending what we say about cognition so as to account for what we do specifically as researchers, understanding ourselves in light of our theoretical commitments (see Bottineau, 2010; Sanches de Oliveira, 2022c; Stewart, 2010).

Our goal in this paper is to address these missed opportunities by sketching a novel, broad picture of science that we see as following naturally from the synthesis of an ecological-enactive view of cognition with the evolutionary biological perspective of niche construction theory. Figure 1 offers a visualization of the landscape of ideas just described, also indicating where our proposal fits.

Inspired by ecological and enactive perspectives in embodied cognitive science, on the one hand, and niche construction theory in biology, on the other, in this paper we propose a naturalized view of science in terms of embodied cognitive (ecological-enactive) co-construction. According to niche construction theory, evolutionary outcomes are co-constructed by natural selection and by organisms acting

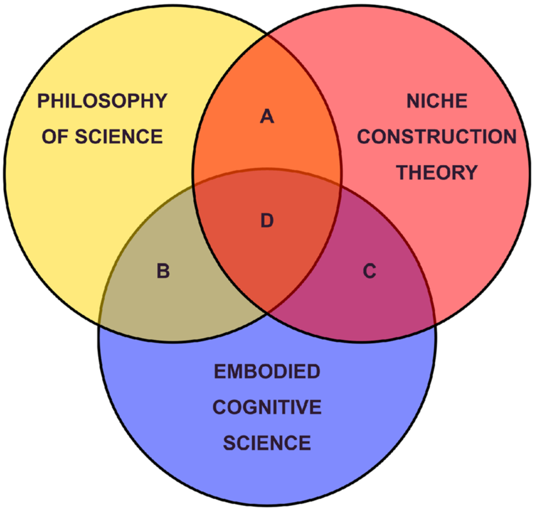

Fig. 1 Recent research in a "naturalized" orientation has drawn insight from different fields and disciplines to inform philosophy of science, including (A) work approaching science as a biological phenomenon that is only properly understood in its evolutionary context, and (B) work explaining specific scientific practices, especially modeling practices, in terms of the concepts and tools of enactive and ecological views in embodied cognitive science. The complementarity between biological views of niche construction and ecological-enactive views of cognition (i.e., C) has also been fruitfully explored in recent years. This paper sits at the intersection of all of these bodies of work (i.e., D), making a contribution to naturalized philosophy of science by leveraging the convergence in C to address the limitations of work in A and B

on their niche and thereby shaping selective pressure. In analogy to this view in biology, we describe scientific knowledge as developing through an interactive, iterative process in which the objects investigated (i.e., phenomena in "the real world") and the investigating subjects (i.e., scientists) constrain (i.e., restrict and enable) each other's activity and jointly contribute to the co-construction of scientific knowledge. But beyond mere analogy, the proposal is to understand this co-constructive process as literally continuous with biological niche construction: by developing ever novel ways of acting in, interacting with, and making sense of the world, scientific practice enriches human cognitive embodiment and drive human niche construction activity in new directions that both constrain and are constrained by the world.

Any way of understanding practices, including scientific practice, is unavoidably tied to more fundamental ideas about what the practitioners are like. In philosophy of science these fundamental ideas have tended to remain unacknowledged, operating in the background as implicit assumptions. In contrast, and to make our starting point explicit, we begin, in Sect. 2, with an overview of basic ideas in enactive and ecological views in embodied cognitive science. In Sect. 3 we offer an overview of niche construction theory, and briefly consider recent contributions that explore the relevance of niche construction for both embodied cognitive science and philosophy of science. Section 4 then moves on to sketching our view, combining, on the one hand, a philosophical perspective on science in terms of niche construction with, on the other hand, an embodied cognitive understanding of human activity (including epistemic activity) in terms of enaction rooted in ecological, organism-environment relations. In contrast with embodiment-inspired philosophical accounts which have tended to be limited to specific scientific practices (predominantly modeling), the broad picture we present motivates a more fundamental reconceptualization of science with wide-reaching philosophical implications, including implications for understanding the relation between scientific practice and theory—a central issue in naturalized, practice-oriented philosophy of science. On the view we put forward, theory doesn't just interact with practice, nor is it intimately connected to practice, or even bound up with it: rather, as we propose, theorizing *is* a practice, and alongside other practices, it contributes to human embodied, cognitive/biological niche construction activity. This perspective on "theoretical" scientific knowledge helps to situate science in relation to other aspects of human activity, and to see science as fundamentally grounded in our existence as living beings sensitive to the world and sensitive to our relation to it, acting not only *in* the world but also *with* it. Section 5 concludes the paper by circling back to the issues raised in this introduction, briefly emphasizing the context and upshots of our proposal.

2 Ecological-enactive cognitive science

Especially for readers who aren't already familiar with ecological and enactive views in embodied cognitive science, it can be helpful to begin with a contrast to traditional cognitive science. Broadly speaking, traditional theories of cognition can be characterized with four concepts: neurocentrism; synchronicity; computationalism; and representationalism. Though ecological and enactive approaches vary in a number of ways, advocates generally oppose these four, and replace them with: embodiment, environmental embedding and extension; diachronicity; and dynamic, reciprocal interactivity (see, e.g., Chemero, 2009; Di Paolo et al., 2017).

Neurocentrism in cognitive science refers to the focus on the brain or the nervous system more generally as the locus of significance for investigation. In this perspective, neuroscience theories, methods and concepts play center stage to research on cognition. If the rest of the body or the environment are to play a role at all, it is only in terms of the neural patterns that are correlated with them, or ‘represent’ them (see critical discussion in, e.g., Gallagher, 2017). *Synchronicity* refers to the assumption that cognition takes place at a snapshot, a single discrete moment, in which the mind/brain needs to make sense of, and produce a response to, the input from the external environment. The ‘poverty of the stimulus’ problem (Chomsky, 1980) stems from this assumption: at any one single moment, the environment does not provide the brain with sufficient information to distinguish the laptop in front of me from a cardboard cutout (or, if one has the prerequisite purchasing power, a hologram). C*omputationalism* then becomes enticing to explain the fluid and skillful way we generally get by: the brain, it is assumed, must make up for informational limitations (e.g., incomplete and potentially ambiguous sensory data) by engaging in complex computations over the bits that it *does* receive. Computationalist commitments vary. In weaker claims, neural (or behavioral) patterns are thought to *correspond* to logic gates, acting as successive logical or mathematical operations (such as in the active inference literature; see, e.g., Manicka & Levin, 2019). In stronger varieties, brains are thought *literally* to perform computations that humans have only developed relatively recently, such as Bayesian probabilistics (Rescorla, 2015, 2021). *Representationalism* is the final piece of the puzzle, which ensures that the computed data relate to the situation relevant to the organism. Typically, neural states and operations are assumed to be *representations* of features of the world, behavioral patterns, causal-probabilistic structures and so on. Just as computationalism, representationalism comes in many variations with weaker, deflationary notions of (exploited) structural similarity all the way to stronger notions involving propositional content (see, e.g., Coelho Mollo, 2021; Shea, 2018; Smortchkova et al., 2020).

“Ecological-enactive cognitive science” is not a unitary theory, but rather a family of loosely related views inspired by both ecological psychology and enactivism.[1] This ecological-enactive orientation in cognitive science can be summarized in diametric opposition to the above-mentioned four features of traditional cognitive science. Neurocentrism is rejected in favor of embodiment and embedding and extension into the environment. This is to say that rather than singling out an organ within an organism such as the brain as the seat of mind and cognition, ecological-enactive cognitive science advocates a more holistic approach in which the situated body in interaction takes

[1] The label “ecological-enactive” has precedent in the literature (see, e.g., Rietveld et al., 2018; Rolla & Novaes 2022; Segundo-Ortin, 2020; Van den Herik, 2021). We acknowledge that there is controversy surrounding the relation between ecological psychology and enactivism (see, e.g., Flament-Fultot et al., 2016; Heras-Escribano, 2019; Segundo Ortin et al., 2019). For this reason, while remaining neutral with regard to their full compatibility, in this paper we draw from both ecological psychology and enactivism, prioritizing concepts that we see as generally amenable to both, and as potentially opening the door, depending on the reader’s preference, for both more ecological and more enactive readings of our paper’s proposal.

center stage. The adjective 'ecological' emphasizes that the organism-environment system as a whole is key to understanding the complexity of our cognitive, or adaptive, behavior.[2] The general strategy is to "ask not what is inside your head, but what your head's inside of," as Mace (1977) phrased it. To be sure, this strategy doesn't entail ignoring the brain altogether; rather it calls for reconceptualizing the brain's role in the organism-environment system (see, e.g., Bruineberg & Rietveld, 2019; Dotov, 2014; Van Orden et al., 2012). Organism and environment are then considered to be reciprocally defined or mutually constitutive. As Levins and Lewontin put it in a different context: "just as there is no organism without an environment, there is also no environment without the organism" (Levins & Lewontin, 1985, p. 99).

The synchronicity assumption is replaced with an explicit diachronic approach in which cognition is only studied in movement, and is understood to be essentially durational (Port & Van Gelder, 1995; van Dijk & Withagen, 2016; van Geert & de Ruiter, 2022). This instantly solves the poverty of the stimulus problem. Viewed through a single snapshot, the laptop in front of me could surely be a cardboard cutout or a hologram. However, if I am allowed to explore over time—as I move my head and my body, studying it from different angles, the look of the laptop will differ, and its buzzing noise will change subtly—then it becomes much clearer why I interact with the laptop as the 3D object that it is. The 'stimulus' in movement is extremely rich, to the point that it seems mistaken to think of it in terms of 'stimulus' at all, i.e., as discrete and successive inputs to be processed. Rather, our activity over time (including our interactional history with 3D environments) provides us with plenty of 'information' to guide our skillful engagements with complex, dynamic environments. With this in place, the motivation for accepting computationalism and representationalism is undermined in one fell swoop. The general strategy is something akin to Occam's razor: if we can explain cognition using simpler means, we should. The idea that there's a need for elaborate computation is primarily motivated by the fact that, a priori, traditional cognitive science has bereft the organism-environment system of its engagement: the brain is cast as an independent, encapsulated agent left only with ambiguous clues and hints with no duration or history, thus no interactivity to aid it in understanding. In such a situation, the brain could only use elaborate computational schemes to hypothesize, infer, predict, model and so on the workings of the "external world." However, if the starting point is acknowledgement of a coupled organism-environment system, then there's a wealth of interactivity as well as historical regularities at our (epistemic) disposal to explain behavior and to reframe the brain's role in it.

Since the organisms' activity precludes poverty in the 'stimulus' or the 'information', *embodiment* is, thus, crucial. After all, an organism's embodiment plays a determining role in what the organism is and is not sensitive to. Think of how the constitution and location of our eyes determine the wavelengths the receptors are sensitive to. A spider, simply in virtue of its embodiment, is sensitive to different aspects of the environment. Such sensitivities are understood *diachronically* with respect to

[2] It remains an open question to what extent enactivism is or should be seen as advocating for an indivisible organism-environment system or instead for a clearly separated organism interacting with an external world. Maturana and Varela (1980) is sometimes read as pushing a separable conception of living systems, but Varela (1976) already questions the validity and epistemology of this, indicating that the broader, ecological view is not necessarily a *deviation* from enactivism.

engagements, interactions and so on. We are sensitive to certain possibilities for action (i.e., affordances). Given an organism's relative height, steps on a stairway may or may not be (or seem) walkable, a chair may or may not be (or seem) sittable and a door may or may not be (or seem) openable and 'pass-through-able'. There are degrees to this: certain steps are more walkable than others, some chairs are more sittable than others, and certain doors and doorways are more accessible than others. To put it differently, some affordances are more 'inviting' than others (Withagen et al., 2012). Yet all of these possibilities do not depend merely on a single bodily feature like relative height, but instead are enacted given the totality of the organism, including its history of interactions. In our engagement with a given stairway, even without changing the relative height (e.g., by rebuilding the steps or by somehow becoming shorter or taller), the stairway becomes increasingly walkable as we walk it more often, get accustomed to the space between the steps, the slipperiness of the steps, and so on. This process of, over time, adapting oneself to the demands of the environment as they exist relative to one's embodiment can be understood in terms of attunement or resonance.

Attunement is a category term for the processes in which the organism engages with the environment in ways that are appropriate to the current situation, thus replacing the traditional computer metaphor for a material harmonics metaphor. The concept is grounded in the many instances of physical resonance found in attunement processes (see Lomas et al., 2022 for a review). A suggestive image here is that of a radio, which can produce very different sounds depending on whether it tunes to the frequency of one station or of a different one: much the same way, radically different behavioral outcomes can arise as organisms attune to different aspects of the structured environment (see, e.g., Raja, 2018, 2019, 2021).

Attunement can be successful or unsuccessful in varying degrees (Di Paolo, 2005): if someone is tired and tries to rest but does so in an environment that provides no opportunities for it (such as on a busy road or when running away from danger), then this person is not well attuned to that environment. That is, given this person's embodiment and history (which includes, for instance, the amount of exercise recently engaged in, or not, and the energy expended to get to their current situation), the person misaligned with an environment without resting opportunities. Attunement can then be seen as a process that occurs over various spatiotemporal scales. At smaller scales, attunement is increased by, say, taking a turn so as to not walk into a wall, opening a door or sitting on a chair. At larger scales, we develop skills and familiarize ourselves with various situations, increasingly becoming better prepared for novel ones (see ecological work on the "education of attention," e.g., Araújo & Davids, 2011; Gibson, 1966; Jacobs & Michaels, 2007).

Yet our world is not merely one of heights, surfaces and colors—it is filled with places of interest and other agents. We are born into, and become what we are in, populated environments (Reed, 1996); we are 'thrown in' a world that is always already structured (Heidegger, 1927). Whether a surface affords sitting is indeed not only a matter of its relative height and its smoothness, but also of the sociomaterial context. Chairs afford sitting more than tables do, for example. This typically has to do with the relative height of the chair *vs* the table, but also with the role of the respective surfaces in the historical, sociomaterial practices—that is, spatiotemporally distributed patterns of how people around us engage and have engaged with these surfaces. Sometimes these ‘invitations’ can clash: when you are tired, public monuments and statues may seem very sittable, even if you know it is frowned upon (or worse) to act on that invitation. This implies a ‘negotiative’ aspect to engagements (Di Paolo et al., 2018).

A particularly apt example of sociomaterial influence on the development of action possibilities in an organism-environment system concerns the perception of mailboxes as affording sending a letter (Gibson, 1979; Heft, 2017, 2020). As we grow up and learn to participate in the postal system, we learn how to address, stamp and post mail. It is only because of the education of our attention for and through participation in a community with a postal system that the bright-colored metal box with the wide slot affords sending letters. The bare physical design of the box aids this, but without participation in the postal system, the mailbox would not be associated with the practice of writing and sending letters any more than it would be associated with other practices that the box's material design also enables (e.g., depositing dog poop or fallen leaves from a nearby tree). The ‘social’ aspect of our environmental engagement is then not something that can be switched on or off, not something that is *added onto* a more ‘basic’, or more ‘fundamental’ psychological/cognitive functioning. It is fundamentally, ineliminably, part and parcel of our embodied cognitive activity. The world we engage in is thus always permeated with our complex, dynamic, sensorimotor, sociocultural interactional history.

3 Niche construction, science, and the ecological-enactive perspective

In the previous section we presented key features of the view of cognition and of cognitive agents coming from the broad ecological-enactive perspective in embodied cognitive science. For the purposes of this paper, we take for granted the ecological-enactive perspective reviewed above, and we argue that, beyond its original domain, the ecological-enactive perspective offers a fruitful starting point from which to philosophically make sense of science as a whole, above and beyond particular practices—and that it does so in a way that is not only *in line* with the recent move to naturalized, practice-oriented philosophy of science, but that even pushes it forward in important respects. In particular, we think that the ecological-enactive perspective can make a unique contribution to thinking about science *specifically when paired with insights from niche construction theory*—so this is the theory we turn to now.

A common simplistic view of evolution is as a “one-way street,” causally speaking: the environment exerts selective pressure and the members of a population or species that are fittest to survive in those environmental conditions end up having comparatively more success in passing on their traits to subsequent generations, thereby, in the long run, changing the population's or species' overall make up. Niche construction theory challenges this simplistic view of organisms as passive recipients of selective pressure and instead sees evolution as a “two-way street.” As scientists have observed, organisms of all kinds routinely engage in niche construction, acting in ways that change the environmental conditions that they (as well as conspecifics and members of other species) live in: in some cases this is by directly modifying their niche in ways that make it more amenable to their way of life, while in other cases it is by relocating to different niches that are more conducive to their survival. Based on this empirical biological fact, niche construction *theory* is a perspective in biological science concerned with the impact that niche construction activity can have on evolution. The more nuanced understanding is that organisms' activities of niche construction make a positive contribution to their (and others') evolutionary trajectory: these activities are "reciprocal causal processes that act alongside natural selection during the evolution of traits" (Laland & Brown, 2018, p. 130; see also, e.g., Laland et al., 2016, 2000; Odling-Smee, 1988; Odling-Smee et al., 2013). In other words, evolutionary outcomes aren't just imposed on the organism from the outside (literally, from the environment) in the form of natural, non-agential selective pressures; rather, evolutionary outcomes are co-constructed by the mutual influences of both organisms and environment, with each changing the other and being changed by it.

Since it was first articulated in the 1980s, niche construction theory has received growing attention from philosophers interested in the theory's scientific standing, empirical adequacy, relation to other theories, as well as potential limitations and challenges (see, e.g. Aaby & Ramsey, 2022; Godfrey-Smith, 2000; Okasha, 2005; Uller & Helanterä, 2019; Wallach, 2016; Wells, 2015). From this philosophical perspective, niche construction theory is treated as an object of philosophical analysis, something to be examined using the same philosophical tools we use to examine any scientific theory. But our goal and orientation in this paper is different. Our primary interest here is in approaching niche construction theory not as a topic for philosophical analysis but as a resource to be used in philosophical analysis of other topics. And there is some precedent to this approach. On the one hand, for instance, there has been important work drawing from niche construction theory to guide theoretical development in embodied cognitive science (this is the work in category C described in Sect. 1). An interesting idea here is that niche construction activity, and its evolutionary import, can help elucidate the "reciprocity" between organism and environment that ecological psychologists talk about, where, at different timescales, affordances act both as resources and as inheritances: at a single point in time, the affordances that exist for an organism constrain[3] the organism's niche construction activity; over time, however, niche construction activity changes the environment and ultimately (due to the activity's evolutionary impact) it changes organisms too, thereby also shaping which affordances exist (Heras-Escribano, 2020; see also, e.g., Chemero, 2009; Heras-Escribano & Pinedo-García, 2018). In short, work in this direction illustrates the applicability of niche construction theory in the domain of mind and behavior,

[3] In ordinary uses, "constrain," "constraining" and "constraint" have a negative connotation, suggesting the imposition of a limitation that is detrimental to whatever is being limited in that regard. Here and throughout this paper we use these terms with a neutral connotation, in line with the technical sense used in Dynamical Systems Theory and related domains, seeing constraints as *reductions in the degrees of freedom* of some system which are (or can be) not only *restricting* but also *enabling*: for instance, biomechanical constraints restrict the range of ways we can bend our knees but they thereby also enable the emergence of sitting as a position for resting, working, etc. This technical notion has been formalized in many different ways, but the differences are not relevant for our purposes in this paper, and where appropriate we merely emphasize the value-neutral nature of constraints by describing them as both restricting and enabling (for related discussions the reader is directed to, e.g., Abrahamson & Abdu, 2021; Anderson, 2015; Brymer & Davids, 2013; Chemero, 2009; Greeno, 1994; Raja & Anderson, 2020; Richardson et al., 2008; Wells, 2002; Yates, 2008).

showing how the theory can be a useful resource for clarifying key aspects of embodied cognition, and, in the particular case just described, shedding light on the nature of affordances. On the other hand, in parallel with this work connecting niche construction to (the philosophy of) embodied cognitive science, there has also been some work in philosophy of science drawing from niche construction theory to develop a naturalized understanding of scientific practice (i.e., in category A described in Sect. 1). This is what we will focus on in the remainder of this section.

A good example of using ideas from niche construction theory in the philosophical analysis of science is the perspective put forward by Joseph Rouse (see, e.g., Rouse, 2014, 2015, 2016). The starting point for Rouse, as he describes it, is the tension between "our scientific understanding of ourselves as natural beings" and "our philosophical sense of ourselves as answerable to conceptual norms" (Rouse, 2014, p. 278). For Rouse this tension is a version of the conflict identified by Sellars (1956) between the "manifest image" and the "scientific image": accordingly, for Rouse it's important to understand how science, as grounded in the activities of the biological creatures that we are, relates to the "space of reasons," that is, the logical space of norms in which we humans situate ourselves as *rational agents* and treat one another as such, justifying our behavior and holding each other accountable.

Rouse contrasts his perspective on science with what he refers to as "representationalist conceptions." These, he claims, "identif[y] scientific understanding with some specific position or set of positions within the space of reasons, that is, as a body of knowledge that represents the world or aspects of it in particular ways" (Rouse, 2014, p. 280). But instead of taking science to be (only) internal to the space of reasons, Rouse argues that science plays a constitutive role, being capable of 'reconfiguring the entire space':

> The sciences change the terms and inferential relations through which we understand the world, which aspects of the world are salient and significant within that understanding, and how those aspects of the world matter to that overall understanding. Scientific research also brings aspects of the world into the space of reasons by articulating them conceptually, so as to allow them to be discussed, understood, recognized, and responded to in ways that are open to reasoned assessment. (Rouse, 2014, p. 280)

In all of these ways, science isn't just *part* of the space of reasons nor is it merely *subject* to normative-conceptual evaluation, but it can actually modify the landscape of rationality, by informing the way we understand the world and by shaping even the way we see ourselves as persons situated within that space. Science is an open-ended practice of conceptual articulation that, while grounded in our discursive involvement with the world, also helps construct the space of intelligible possibilities for understanding the world and ourselves.

The crucial question for Rouse thus becomes how to square, on the one hand, this view of science as shaping and (re)configuring the space of reasons with, on the other, a scientifically-informed view of humans as biological beings: to put it differently, the challenge is that of philosophically making sense of scientific knowledge in all its richness and complexity, but doing so while taking seriously the image that science itself provides of humans as part of nature and in (evolutionary) continuity with the rest of life—which requires understanding how, even in all its normative and conceptual sophistication, science can be something that animals (that is, humans) *do*. In contrast with the view of science as a representational effort to construct an optimally veridical picture of the world, Rouse proposes a view of science as an aspect of human niche construction, thus placing science in the same general category as our housing, our infrastructure and the tools we build with. Scientific practice, then, is first and foremost material engagement with the world, one that transforms our (and future generations') relation to the world. And making sense of how this works requires rethinking language: after all, even as it comprises material engagement, Rouse notes, science is characterized by discursive involvement with, and conceptual articulation of, the world.

In contrast with views that treat language as an internal, individual faculty, Rouse aligns himself with the view of language as most fundamentally a public phenomenon (see, e.g., Rouse, 2015, p. 77). And as Rouse explains, capacities for "intentionality and conceptual understanding" reflect "a long history of coevolution between human organisms and the discursive practices that have become increasingly central to a human way of life" (2015, p. 76). Importantly, this co-evolutionary history is material and biological through and through: "The ability to recognize and produce articulated linguistic performances is itself a biologically evolved capacity, which also materially changes the environment in which humans develop and to which we respond" (2015, p. 78). And it's precisely understood as a linguistic practice in this particular way that science can be seen as both constitutive of reason and as an aspect of human niche construction. Rouse explains that "the space of reasons," as he sees it, "is not an idealized or theoretical construction, however, but the practical configuration of the world we live in as *discursively articulated* environmental niche" (2015, p. 76, emphasis added); the space of reasons is "extensionally equivalent to our *discursive* biological niche" (2015, p. 158, emphasis added). Accordingly, scientific research changes the world we live in, and it does so directly, by modifying the environment and the tools we have for engaging with it, as well as indirectly, via linguistic articulation, by changing how we think about the world and relate to it. Science plays a role in reconfiguring the space of reasons because, as an inherently linguistic practice, it is also literally part of human niche construction activity through the reciprocal link between discursive articulation and material engagement: scientific conceptualization is "interdependent with practical skills, equipment, and the creation of new material arrangements in specially prepared work sites" (2015, p. 209); and conversely, "[e]xperimental practice is integral to conceptual understanding, and not merely instrumental" (p. 295).

Having briefly summarized only a few important aspects of Rouse's perspective, two points should be clear. The first concerns the general prospect of putting niche construction theory to work in philosophy of science: Rouse's perspective suggests that this link is interesting and promising, and that it has the potential to bring greater clarity in the pursuit of a naturalized philosophical understanding of science. The second point is that putting niche construction theory to work in philosophy of science, *specifically* in the way that Rouse does it, resonates with a lot of the central ideas at play in the ecological-enactive perspective in embodied cognitive science (seen in Sect. 2). Rouse himself seems to recognize the convergence, but he makes only passing reference to what he calls "extended and enactive cognition," in two footnotes (2015, pp. 19, 171), without substantive engagement. In our assessment, many elements of his proposal are indeed intuitively compatible with a broad ecological-enactive view as well as with uses of niche construction theory in embodied cognitive science such as the ones mentioned earlier in the current section. At the same time, it bears noting that the intellectualist (or at least intellectualist-sounding) conceptual framework that Rouse takes as his starting point, and the resulting emphasis on rationality and linguistic articulation (i.e., paradigmatic "representation-hungry" phenomena), seem problematic when considered from the perspective of ecological-enactive cognitive science. Recall that Rouse's project is motivated by a supposed tension between rational and biological pictures of humans (and, by extension, of scientific knowledge). While the solution he provides to this tension seems generally in line with the principles of an ecological-enactive perspective, it also seems clear to us that the ecological-enactive perspective *dissolves* the tension: if you start from the ecological-enactive perspective, the tension doesn't even arise in the first place because no gap is presupposed to exist between mind and body, reason and practice, language and material engagement—such that much of the same results can be accomplished without any concessions to intellectualist philosophical assumptions (see, e.g., Dreyfus, 2005, 2007; Gallagher, 2017; Zahnoun, 2021). This possibility is what we explore in the remainder of this paper.

4 Science and ecological-enactive co-construction

Throughout the history of philosophy, views about the nature of the human mind and views about the nature of knowledge and science have been very closely linked.[4] Yet, just as we may admire the façade of a building and explore the building's interior without ever thinking about the building's foundations, this link between ideas about mind and about scientific knowledge, however foundational, often remains out of sight and unacknowledged in philosophical discussions of either. This is how philosophers of science can make claims such as that "science is in the business of producing representations of the physical world" (Pincock, 2012, p. 3; see also, e.g., Godfrey-Smith, 2003) perhaps without realizing how this representationalist conception *of science* (Pickering, 1994, 1995; Sanches de Oliveira, 2021, 2022a, 2022b, 2022c) is closely tied to, and rooted in, representationalist conceptions *of mind*, for instance, as being in the business of creating internal representations of a supposedly separate "external" world so as to try to figure out "what is present in the world and where it is," as David Marr put (Marr 1982, p. 3). Conversely, this is how cognitive scientists come to describe the mind in terms of how science works, for instance, describing the mind (or brain) as literally implementing scientific tools such as Bayesian probabilistics (Rescorla, 2015, 2021) or scientific procedures of generating and testing hypothesis (e.g., Clark, 2015) and theory building (e.g., Gopnik & Meltzoff, 1997; Gopnik et al.,

[4] This link between views on mind and on science has traditionally also included views concerning morality and life in society: for instance, individualism and internalism in the domain of mind and knowledge have important consequences for how we construe the space of possibilities for organization at the social, political, economic and other dimensions. This is something we don't have space to explore in this paper, but see e.g. Lewontin et al. (1984) and Taylor (1989) for earlier discussion.

1999)—all perhaps without realizing the homuncular slippery slope of attributing to parts inside a person (e.g., the brain) the abilities and activities of entire persons (e.g., scientists), as well as without acknowledging the risk of reifying *conceptions* of science, taking them as matters of fact when they might just be myths (Bauer, 1992; Feyerabend, 1975; Kuhn, 1962).

This convergence of ideas about mind and about science in philosophical reflection about either is not surprising—arguably, it is a core feature of the Western philosophical tradition as a whole, and central to its modern phase in particular (see, e.g., Garber, 2001; Rorty, 1979; Taylor, 1989; Williams, 1978). What is surprising (and regrettable) is that this convergence has tended to be only *implicit*, precluding critical evaluation by philosophers of science of the assumptions about mind they rely on, as well as by cognitive scientists of the assumptions about science that they take for granted. Our goal here is to directly confront these deeper, typically unacknowledged relations and interconnections. We will draw from the ecological-enactive perspective in embodied cognitive science (reviewed in Sect. 2) and from niche construction theory (expanding upon uses reviewed in Sect. 3) to sketch our view of *science as ecological-enactive co-construction*. In so doing, we aim to explicitly articulate this foundational mind-science relation and, in particular, we aim to show how adopting a biologically-informed perspective that takes seriously the embodied cognitive nature of scientists opens up a fruitful direction for work in naturalized philosophy of science. We will proceed in three main steps.

4.1 Anti-dualisms in continuity

The first step to sketch our view involves highlighting the *anti-dualism* that comes with the ecological-enactive perspective we adopt. Embodied views of cognition challenge the dichotomization of mind and body. This is in contrast with traditional dualist views according to which mind exists as an immaterial substance separate from the extended, material body, and it's also in contrast with views that, in line with more contemporary thinking, frame mind functionally and computationally, in terms of data structures and algorithms that interact causally with the body but remain constitutively distinct from it. A broadly embodied perspective, then, rejects this tendency to separate mind from body, instead seeing cognition as always necessarily embodied, and not only requiring some body or other to exist, but even being fundamentally constituted by the body. But besides encompassing this rejection of the dichotomy of mind and body, the ecological-enactive perspective further rejects the assumption of a rigid separation between perception and action. This dichotomy is related to the first: here a common assumption is that perception and action constitute separate bodily processes, the former involving using the body to take in information from the world in the form of sensory inputs and the latter involving the bodily implementation of motor commands as the output of internal cognitive processing. In the ecological-enactive view, in contrast, it makes more sense to see perception and action as, at most, two sides of the same coin, namely the coin of embodiment: we can't help perceiving while acting, and perception itself is active, it is an act of exploration inextricable from bodily adjustments (even if minute ones) with which we enact our sensitivity and adaptive responsivity by attuning to the environment and our relation to it.[5] In this sense, then, the ecological-enactive perspective also entails a rejection of strong distinctions between subject and object, organism and environment. Tools that in some contexts can be the object of attention and contemplation, can also, in other situations (in the context of use), functionally become bodily appendages *with which* we attend to other objects to solve problems and so on: this shift has been conceptualized by phenomenologists as one between an object being "present at hand" and "ready to hand" (Heidegger, 1927; see also Dotov et al., 2010; Favela et al., 2021), and it makes salient how the subject-world boundary is flexible and dynamic, and moreover how artificial the subject-object distinction is as an analytical construct. As indicated earlier, organism and environment mutually define each other. "Space," as an abstract physical notion,[6] is independent of whatever may or may not occupy it; but this is not the world we live in: the environment we inhabit is our biological niche, not Euclidean space—although some animals have found geometric abstractions and other mathematical tools to be useful for organizing thought and dealing with the demands of life.

The previous sentence already hints at the view we're aiming for here, namely one in which we understand science as something that embodied cognitive agents *do*, an accomplishment of situated living things. To elaborate on this, we want to emphasize further anti-dualisms that give shape to this view. Having roots in the classical North-American pragmatist tradition (Crippen & Schulkin, 2020), the ecological-enactive perspective echoes the pragmatist rejection of strong distinctions between humans and Nature. Just as the 'ghost in the machine' is an inadequate image of our existence *as* inherently embodied cognitive beings, so the idea of humans as surrounded by the natural world but distinct from it (as if somehow escaping the domain of nature) is also a problematic starting point for understanding our knowledge of reality—most crucially because this way of thinking neglects the fact that our knowledge of the natural world is itself a natural phenomenon. Traditional contrasts between culture and nature, or society and nature, paint humans as gazing into the "wild" while standing outside of it, without participating in the natural order. But as Dewey (1929) suggested, this amounts to an artificial distinction between the (supposedly non-mental) experienced nature and the (supposedly non-natural) experiencing mind (p. 24), which is really just the separation "of *what* is experienced from *how* it is experienced" (ibid, p. 32, italics original): while potentially useful for some limited analytic purposes, this separation is never realized in actual experience in the real world. Along similar lines, in putting forward his pragmatist view of truth, James (1907) famously claimed that "the trail of the human serpent is thus over everything." In its original context, James's claim can be seen as affirming the continuity between culture (or society) and nature, and thus denying the plausibility of "truth" in the abstract, detached from human interests and

[5] Gibson is explicit in emphasizing the inherently perceptual nature of action and inherently active nature of perception in his ecological approach to visual perception (Gibson 1979; see also Richardson et al., 2008). This is also foundational for enactivists, as is clear in the description of "perception" as "perceptually guided action" (Varela et al., 2017, p. 203): that is, perception is not a separate thing that (sometimes or even always) accompanies action; rather, as an aspect of action, "perception" is just a name for the sensitivity inherent to the activity of living beings.

[6] For instance, in the modern "intuitive" or "folk" physics that follows from a Newtonian paradigm. The move toward relational conceptions of space in physics can be seen as a point of convergence with enactive-ecological and phenomenological views on how the world we live in is structured.

practical uses and needs. But besides this traditional reading, James's quote has also been used more recently by environmental philosophers to comment on the impossibility of defining "nature" as that which is free from human influence and in contrast with the "artificial" and human-made: after all, in the Anthropocene there's nothing left that doesn't bear the human mark (see, e.g., Vogel, 2003, 2015).[7]

Both readings of James's claim complement each other in emphasizing our fundamental situatedness as biological, embodied beings acting in the world, within and with nature—which has important consequences for how we think about science and scientific knowledge as natural phenomena. This brings us to the distinction, so entrenched in philosophy of science, between theory and practice, which, in the domain of mind, is often thought of in terms of a distinction between knowledge and activity, and even branching further into a distinction between theoretical and practical knowledge. But as Dewey warns us, separations "between knowing and doing, theory and practice, between mind as the end and spirit of action and the body as its organ and means" are rooted in contingent and historical socio-political arrangements that the distinctions are also used to reinforce, namely "the division of society into a class laboring with their muscles for material sustenance and a class which, relieved from economic pressure, devotes itself to the arts of expression and social direction" (Dewey, 1915/2004, p. 361). We might, as philosophers, wonder about the extent to which theoretical and practical work in science capture natural kinds. Still, the distinction between the two—theory and practice—is itself not something we would find by carving nature at its joints. In this respect at least, we think Rorty encapsulates important ideas from the pragmatist tradition that are also in line with our ecological-enactive perspective:

> All areas of culture are parts of the same endeavour to make life better. There is no deep split between theory and practice, because on a pragmatist view all so-called 'theory' which is not wordplay is always already practice. To treat beliefs not as representations but as habits of action, and words not as representations but as tools, is to make it pointless to ask, 'Am I discovering or inventing, making or finding?' There is no point in dividing up the organisms' interaction with the environment in this way. (Rorty, 1999, p. xxv)

To understand science as ecological-enactive co-construction, as we are proposing here, thus begins with seeing how the inadequacy of the dualist worldview—and of the dichotomies of mind and body, perception and action, subject and object, organism and environment, the human and the natural—also casts doubt on the traditional distinction in philosophy of science between theory and practice. This latter distinction can be seen as one between competing understandings of what philosophy of science is a philosophy *of*: in the more traditional conception, philosophical work about science is work on the nature of theoretical knowledge and on the logical structure of scientific theories, for instance; in contrast, more recent work has tended to prioritize practice and accordingly focus on scientific experimentation and modeling "in the real world" as

[7] A reviewer reminds us that "anthropocene" is a disputed category, at least in part because many if not most humans today still live in poor conditions and have a relatively small ecological footprint while the majority of the destructive force is exerted by a minority of humans in particular contexts and with particular ways of life (see, e.g., Hughes et al., 2023), a situation that has motivated some to prefer the term "capitalocene" (see, e.g., Moore, 2016, 2017). We thank the reviewer for this suggestion.

what is philosophically interesting to understand. But given the preceding discussion, the division itself is problematic, because theory and practice do not stand in contrast with one another as separate subcomponents of science: rather, theory is a dimension of scientific practice, and scientific practice in turn just is what "science" means, which is not distinct in kind, or separate from, humans acting in the world to satisfy varied and variedly complex demands of life. This is the anti-dualist foundation upon which we build our view of science as ecological-enactive co-construction. To continue fleshing out this view we now move to the second step, which concerns elucidating what we mean by *co-construction*.

4.2 Co-construction

An old idea that grew in popularity in the modern era, but which dates farther back into antiquity, is that the goal of science is to write out the "Book of Nature," and accordingly to gather all of the facts, to compile descriptions that accurately describe what there is and how it works—in short, to ascertain, through observation, the "constitution" of the natural world, or the laws that govern it. This way of thinking is traditionally tied to realist conceptions of the success of scientific knowledge: the reason science works is that it captures, at least approximately, what actually exists in the world (even, e.g., unobservable entities), leading to the conclusion, for instance, that "mature and genuinely successful scientific theories should be accepted as nearly true" (Psillos, 1999, p. xv). The traditional alternative to this kind of view is the class of anti-realist perspectives according to which scientific knowledge is most fundamentally a *product* of human making. This includes views in which reality is socially constructed, claims that scientific observation is 'theory-laden', and the idea that scientific facts are created, e.g., that "the daily activities of working scientists lead to the *construction* of facts" (Latour & Woolgar, 1979, p. 40, emphasis added). In these views, as critics have put it, there can be "no easy inference from widespread agreement [among scientists] to realistic correctness" (Pincock, 2012, p. 3), and moreover, "when we explain why one side succeeded and another failed in a scientific controversy, we should never give the explanation in terms of nature itself" but rather in terms of human agency, social negotiation, and similar factors (Godfrey-Smith, 2003, p. 133).

Our view of ecological-enactive co-construction is set against both types of positions. We like to think of the first, realist, Book-of-Nature type of view as one in which scientific knowledge is "constructed" by the world and our job is just to gather facts in order to reconstruct the world's structure, in contrast with the second view, of scientific knowledge as socially constructed: while in the former view knowledge is out there waiting to be gotten, in the latter we are the builders or creators, and knowledge is begotten by us. Our view of knowledge co-construction expressly rejects both alternatives. To be clear, however, this is not a straw person argument targeting extreme positions that nobody holds: although extreme, the broad views in question have in fact been defended by real people, as well as criticized by many more moderate, and equally real, interlocutors falling somewhere along the spectrum from realism/objectivism to anti-realism/constructivism. The reason we identify these extreme positions is to emphasize how our ecological-enactive perspective is *not* a middle-ground position, but amounts to a rejection of the spectrum as a whole.

It is in the context of developing his nuanced account toward the realist end of the spectrum that Pincock (2012) approvingly articulates the common (if usually implicit) idea cited earlier, that "science is in the business of producing representations of the physical world" (p. 3). Views throughout the spectrum (including extreme positions) can be seen as relying on this same assumption, only disagreeing with regard to how they understand the basis for evaluating scientific knowledge—whether by reference to human-independent states of affairs or by reference to inherently agential, social factors as what most fundamentally shapes, informs, or provides the content and validity of scientific representations of the world. This way of thinking is depicted in Fig. 2, which emphasizes how both extremes (as well as other positions in between) can fall prey to the inadequate dichotomization of humans and nature as well as of knowledge and practice. It might seem intuitive and straightforward to think that practice lies at the interface between humans and the world as the point of contact at which we can gain insight into the world, either by unveiling (at least partially accurately) mind-independent truths or (because of the theory-ladenness of scientific observation, for instance) by constructing the relevant facts through social negotiation.

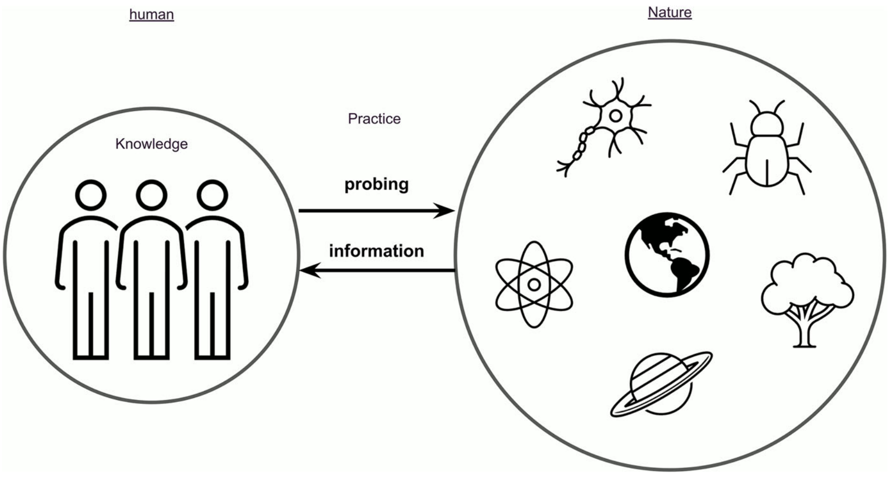

Fig. 2 Basic picture of scientific knowledge arising through our practical contact with, and extraction of information from, the world. This basic picture can be interpreted in many different ways, from positions in which scientific knowledge is seen as socially constructed (because, e.g., observation cannot transcend our socially-specific theoretical ladenness) all the way to positions in which scientific knowledge is, in contrast, perhaps better described as 'constructed' by the world and we merely compile the facts, or create representations that (are valuable to the extent that they) approximately capture the way the world actually is. Whatever the interpretation (i.e., whether affirming or denying the possibility of epistemic contact with mind-independent reality), the basic picture is the same, namely one in which humans stand apart from nature, and the domain of knowledge (including theoretical and practical knowledge) and the domain of activity or practice are distinct and separate from each other. [Notice that this picture of *science* has the same general schema at play in traditional views of *mind* (e.g., as an input/output system characterized by internal information processing) in that both presuppose the existence of a gap that separates us from the world and that we hope to overcome somehow.]

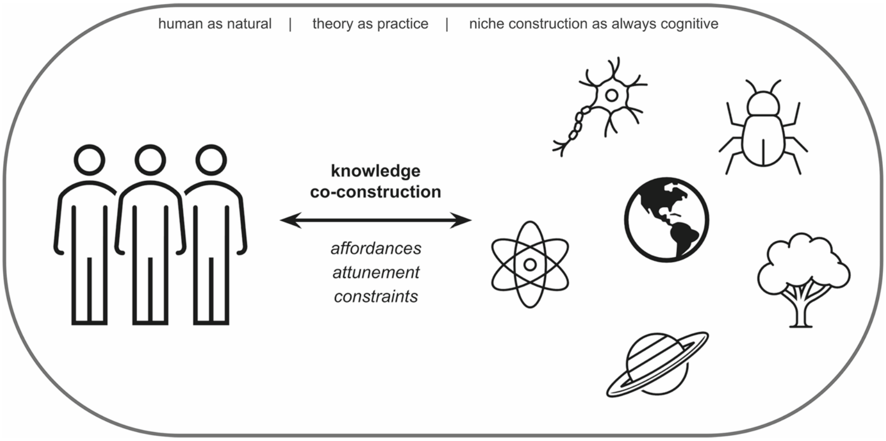

Fig. 3 In our view, rather than scientific knowledge being limited to the human domain (e.g., as human representations that 'reconstruct' reality more or less objectively, depending on the interpretation), scientific knowledge is relational and dialectically co-constructed by humans and world, through human embodied (ecological-enactive) cognitive agency in and with the world. The bi-directional arrow emphasizes the relational, dialectical nature of knowledge as co-constructed, and as emergent from the (equally relational and dialectical) affordances, attunement and mutual constraining at play. This picture is fundamentally anti-dualist, rejecting the dichotomization of humans and nature as well as of theory and practice, among others; moreover, in this view all niche construction activity is also cognitive in the relevant embodied sense. See text for further details. [As was the case with Fig. 2, this picture of *science* embodies the same schema at play in the view of *mind* as ecological or relational and world-involving.]

The ecological-enactive starting point motivates rejecting this way of thinking, along with all its dichotomies, and favoring instead one in which scientific knowledge is "co-constructed" in the sense of arising dialectically through (embodied cognitive) niche construction activity (see Fig. 3).

As we saw, niche construction theory frames evolutionary outcomes as being co-determined by environmental selective pressure as well as by organismic activity, and in particular by organismic activity that transforms the niche and that thereby changes what selective pressures are in place for organisms and species. Analogously, science develops through a process in which the objects of investigation (i.e., phenomena in "the real world") and the investigating subjects (i.e., scientists) constrain each other's activity and jointly generate scientific knowledge. This mutual constraining (i.e., mutual restricting and enabling) is evident in how what becomes a recognizable phenomenon depends on the scientists' needs and interests, or what scientists are looking for, yet, at the same time, you can't find what isn't there, and you can sometimes find what you weren't looking for. The possibilities for intervention, experimentation and observation are *affordances* and, as such, they are relational and dialectically constituted: that is, they exist not only for, and because of, the scientist as the subject attuning to those possibilities, but also for, and because of, what the object of investigation is like, including how it (re)acts and thereby shapes the scientist's subsequent range of affordances, needs and interests. In analogy to how evolutionary outcomes arise through niche construction, then, epistemic outcomes in science arise through this complex interplay of human agency and nature pushing back—agency in and with nature.

But beyond mere analogy, we think it's important to understand this notion of "co-construction" as literally in continuity with biological niche construction. What scientists do isn't *only* metaphorically similar to what different organisms do in changing their niche and thereby changing themselves and their species' evolutionary outcomes. Like other animals and living beings, humans also engage in niche construction activity, perhaps even more dramatically so than other species. Science is the name we give to a fuzzy set of shared practices that humans engage in in this process of niche construction. Niche construction activity includes changing the environment and changing environments (i.e., moving to new ones), improving access to shelter, sustenance, and other necessities, with consequences for ourselves, our communities and future generations. The way we humans do this involves building, testing and using new tools to facilitate these activities (and building, testing and using tools to facilitate building tools), which involves developing methods for organizing our activity as well as methods for obtaining the materials needed for activity—methods that, when articulated (e.g., verbally, pictorially), can be shared with others and improved upon in a distributed way. Science directly and indirectly contributes to our developing ever novel ways of acting in, interacting with, and making sense of the world. Through this, science enriches human cognitive embodiment and drives human biological niche construction activity in new directions that both constrain and are constrained by the world, all the while enabling us to learn and become something new in the process.

Importantly, in our view of science as literally part of human niche construction, saying that scientific knowledge is co-constructed means that it's not quite right to say, as we did above, that scientific knowledge is constructed by humans *and* by nature *in interaction with each other*. Interaction suggests the coming into contact of two things that are independent from each other and that (typically) remain independent after the contact. But we aren't independent from nature: we *are* nature. So, it's artificial to separate the human inquiring subject (the scientist) from the object inquired upon (some part of the world), as much as subject-object distinctions are problematic in the domain of cognition and mind. Through the ecological-enactive lens, then, by saying that scientific knowledge is co-constructed, what we mean is that it is a feature of the organism-environment system as a whole. Talk of organism-environment systems can sometimes sound too individualistic (as if concerning the single, individual organism and its surroundings) and thereby as inadequate for talking about a socially, materially and temporally extended phenomenon such as science. But, as should be clear from the discussion at the end of Sect. 2, we see "the social" as pervading the (dynamic, historical) organism-environment system: on the one hand this is because the environment is not a-social, but is shaped by others before us, and shared with others now and into the future; and, on the other hand, the individual itself is social through and through, having its activity fundamentally constrained (enabled and restricted) by that of others, including others with whom we, through experience and over time, sculpt our sensitivities.

This inherently social and dynamic nature of organism-environment systems is crucial for the co-construction of scientific knowledge as resulting from the mutual sensitivity and adaptivity of different (human and non-human) parts of the system.

At the individual level, consider how any simple action you can accomplish requires sensitive adjustments of different parts of your body to whatever the other parts are doing or not doing well. In getting up from a chair and walking while holding a mug full of hot coffee, for instance, the action is never performed in exactly the same way, and although it might seem like only your legs or arms are involved, when all goes well that's in fact because different parts of the body were sensitive to, and compensated for changes in, the rest of the body: if you misstep with your right foot, not only does the left leg typically adjust, but even the shoulder or elbow of the mug-holding hand/arm will smoothly shift to compensate for the abrupt displacement and keep the coffee from spilling. This kind of mutual sensitivity and adaptivity is commonplace in our embodied experience, applying not only to the relation between different limbs and parts of the body (i.e., *intra*personal coordination), but also to groups of people working together (i.e., *inter*personal coordination), being sometimes taken as revelatory of the workings of a system at any level or scale (see, e.g., Anderson et al., 2012; Dale, 2015; Richardson et al., 2014; Riley et al., 2011). The case of interpersonal coordination can already be seen as an instance of sensitivity and adaptivity at the level of the organism-environment system, that is, the extra-organismic system considered from the perspective of the individual. The point is that, as ecological-enactive co-construction, scientific knowledge arises through relations of sensitive adaptivity that hold between not only individuals and groups of people using instruments, but also cells, insects, forests, and whatever else scientists in different disciplines study.

The rats, monkeys and other model organisms used in laboratory science, for instance, undoubtedly engage in activities aimed at bettering their own lives—they just happen to do so in artificially (and sometimes abhorrently) impoverished environments imposed on them by some of us, and, to the extent that these organisms can still be healthy and thrive in a species-relevant sense, they do so by enduring various courses of treatment and interventions (e.g., by solving silly puzzles we give them) so as to get some reward (e.g., pellets, peanuts, grapes or juice). Alongside constraining (i.e., enabling and restricting, see footnote 3) the scope of the animal's activity in various ways, it is essential for scientists that there be room for the animal to do "its thing" and push back, thereby revealing answers to the driving research question or in some cases perhaps motivating reframing the question. Detailed, regimented human intervention in these cases prevents any kind of drastic and cumulative niche construction activity on the part of the animals; but the scientists' activity itself (even in this environment-managing role) only makes sense as part of a larger, complex set of niche construction activities humans engage in, activities through which we seek direct improvement of human life (e.g., by finding better medicines to target human diseases), or less directly by contributing in other ways to what we (or some of us) see as conducive to, in some sense, greater quality of life for ourselves (e.g., research on different diets or cosmetics). In saying this we're not condoning any research practices, but only sketching a way to naturalize them, that is, to see them as natural phenomena, in continuity with the biological, and niche constructive, activity of different organisms and species. And this is not limited to scientific research on living animals, as in the case of model organisms just described, which many people would be ready to admit as having some degree of agency. Rather, the (at least partial) independence of systems and phenomena in the real world is what makes it possible for us to learn something through interventions: that is, if a common path for learning is by observing what happens when we intervene in different ways, there has to be something acting in some way or other that is differentially responsive to our intervention. In this sense, we are sensitive to the world and we adapt to it, but so is "the world" sensitive to us and to what we do, and it also adapts in its own way. It seems overly simplistic to think that scientists are the only ones *attuning* to the inquiry situation and imposing *constraints* on the object of investigation so as to realize current *affordances* and create new ones: on the contrary, our interventions are only epistemically valuable because they also set up a situation that the object of investigation can, as a subject, attune to in its own characteristic manner and respond in ways that realize affordances (e.g., eating grapes, for some laboratory animals, or avoiding punishment), with consequences that further constrain (i.e., enable and restrict) the range of future possibilities for all parties involved. We humans try to impose our will, but nature always pushes back to some extent; in the human-nonhuman nexus, neither is a passive recipient of something coming solely (and fully formed) from the other, and neither is the sole agentive force.

Co-construction is thus characterized by this inextricable link between us and the things we study, as well as by our study of them in the context of our niche construction activity to address the demands of life. Besides reframing the organism-environment system in this way, the perspective we are sketching also has consequences for how we conceptualize different aspects of the scientific contribution to human niche construction. What scientists do and what scientists say, think or write are in continuity with one another, as perhaps analytically distinguishable but in practice inextricable from each other: designing experimental manipulations, operating measuring instruments, cutting tissue here and generating a visualization there, writing down equations by hand and computationally simulating solutions to them, linguistically expressing certain patterns and regularities observed so as to frame them in ways compatible with previous observations of other phenomena, sharing these accounts with fellow practitioners or reacting to their accounts, and so on—all of these are aspects of the same general sorts of practices that human animals engage in, acting in and with the world, which also means with (and because of) others. At no point can one leave theory and knowledge behind to engage in purely practical activity, or vice-versa. The practices of the embodied cognitive beings that we are are infused with knowing and with talking about what we know: every theoretical change or change in knowledge, to be a change at all, must necessarily also be a change in doing (including, at least, a change in saying and thinking); in turn, changes in practice are, for us, meaningful to the extent that practical effects fit the rest of the things we do, including the way we talk and think about the world and their effect on how we act.

4.3 Cognition and niche construction

This brings us to our third and final point. So far we considered the *anti-dualism* of the ecological-enactive perspective and we considered what this means for understanding science and scientific knowledge literally in terms of niche construction as ecological-enactive *co-construction*, including implications for traditional dichotomies such as between theory and practice, or knowledge and activity. The last point for clarifying the view we're proposing involves more precisely identifying the "cognitive" character of our proposal and how it relates to the notion of *cognitive niche construction*.

In the philosophical literature inspired by niche construction theory, an interesting notion that has gained popularity in recent years is that of "cognitive niche construction" (see, e.g., Bertolotti & Magnani, 2017; Clark, 2005, 2006; Stotz, 2010; Fabry, 2018; Werner, 2020; Wheeler & Clark, 2008). In the usual sense, as clearly expressed by Andy Clark, cognitive niche construction is "the process by which animals build physical structures that transform problem spaces in ways that aid (or sometimes impede) thinking and reasoning about some target domain or domains" (Clark, 2005, p. 256). Defined in this way cognitive niche construction is a special kind, or subset, of all of an organism's niche construction activity—that is, it designates those niche construction activities that are in some sense "cognitive" in contrast with those activities that contribute to niche construction but which aren't "cognitive" in the relevant sense. Now, given that we are drawing from the ecological-enactive perspective in embodied cognitive science, it might be tempting to assume that our proposal is just a particular description of "cognitive niche construction," in particular one that construes the "cognitive" in terms amenable to radical (e.g., non-representational, non-computational) embodied views. But this would be a mistake. The reason we have been talking about "co-construction" more generally and without adding the adjective "cognitive" is that we think that, properly understood in light of the ecological-enactive perspective, *all niche construction activity is cognitive*.[8]

Historically, the term "cognitive" was used to mean "epistemic" or "that which has to do with knowledge," and it was only in the twentieth century that it came to be commonly seen as synonymous first with "psychological" or "mental," and afterward—with the cognitive revolution of the 1950s and 60s—as "that which involves the storage and processing of information" (see, e.g., Boden, 2008; Costall, 2007; Green, 1996; Heft, 2001; Reed, 1991a, 1991b; Skinner, 1989). In the traditional epistemic sense, a "cognitive science" would be a science of knowledge, a science of how and what we know, that is, a scientific counterpart to philosophical epistemology. While including many psychological phenomena, this science of knowledge would also leave out many other ones: for instance, *if* you construe hallucinations as purely subjective psychological experiences that are entirely disconnected from reality and can't provide knowledge of the world, *then* in the strict traditional sense, by definition, hallucinations do not count as "cognitive" processes; by the same token, in the traditional sense it is reasonable to ask about other mental/psychological states and processes (e.g., imagination or emotion) whether they are cognitive, that is, whether they are the sort of mental/psychological states and processes that are relevantly related to the production of knowledge or whether they are epistemically sterile. With the cognitive revolution, this epistemic sense of "cognitive" comes to be operationalized in terms of declarative statements of fact (i.e., statements you might make when you know something, to communicate what you know) or equivalent symbolic structures that encode the

[8] Here, and in the discussion that follows, we adopt a non-anthropocentric stance on "cognition" in line with that advocated by many in the enactive, ecological literature (see, e.g., Barrett, 2011, 2016; Calvo & Lawrence, 2022; Carello et al., 2012; De Jesus, 2016, 2018; Froese & Di Paolo, 2009, 2011; Noë, 2021; Segundo-Ortin & Calvo, 2019, 2022; Stewart, 1992, 1995; Turvey & Carello, 2012).

same content. The computationalist turn can thus be seen as an attempt to explain "cognition" (namely, the epistemic relation, a relation of knowledge or familiarity) in terms of structures and processes internal to the organism (i.e., structures and processes that supposedly realize the cognitive relation, such as mental representations as "knowledge structures" or "bits of information," and algorithms for manipulating those structures); but "cognition" is (or was) the more fundamental epistemic fact (i.e., a subject-world or organism-environment relation), something that traditional accounts based on information storage and processing simply leave unexplained (Costall, 2007; Reed, 1991a).

The notion of ecological-enactive co-construction we are putting forward is "cognitive" precisely in this more traditional epistemic sense. The organism-environment relation, as it plays out over time, is characterized by sensitivity and selective reciprocal adaptation; in other words, it is characterized by growing acquaintance, familiarity or knowledge between organism and world, each in its own ways accommodating the other and accommodating to the other. But knowledge doesn't live inside the organism any more than it lives in the environment outside the organism instead; rather, as a relation, knowledge lives in the interaction, that is, in the organism-environment system as a whole. All embodied practice (i.e., anything we do) is cognitive in this epistemic sense, because it involves coming to know the world, attuning to some aspect of it and potentially expanding the scope of what we are familiar with and what we are able (i.e., know how) to do, the range of affordances available to us. Similarly, or by extension, scientific practice (which includes practices of theorizing, as seen above) is cognitive because it is in continuity with these embodied practices, even as it is a particular case/domain of our embodied, shared sense-making. To view science as ecological-enactive co-construction is thus to view science as making a cognitive (as well as material, etc.) contribution to human niche construction, which is itself always already cognitive (and material, etc.). Yet this is different from saying that science contributes to our "cognitive niche construction," because this would mean taking "cognitive" to designate a distinct domain or type of activity separate from other niche construction activities. Instead, we see *any and all niche construction (human or otherwise) as cognitive* in the sense that any and all niche construction is characterized by sensitivity to the environment and selective responsivity to it—that is, by familiarity, or knowing. Accordingly, drawing from the ecological-enactive approach to cognition provides a fresh perspective on science not just as contributing to "cognitive niche construction," but rather as an aspect of general human niche construction, and in continuity with other (cultural, political, technological, discursive, etc.) practices that enable and constrain our present and future activities, changing the world, our relation to it, and even ourselves in the process.

5 Conclusion

We began this paper by noting two trends in philosophy of science. The first was the trend toward a naturalized orientation in philosophy of science. This trend has involved a shift away from the prior traditional conception, popular among many positivists and post-positivists, according to which what was philosophically significant about science was its theoretical dimension, and the proper philosophical attitude toward scientific theory was normative (see, e.g., Popper, 1959/2005 and discussions in Ladyman, 2002, Curd & Psillos, 2014). In this traditional conception, given that science is in the business of generating knowledge about the world, the goal of philosophical reflection is to understand the logical structure of scientific theories against an ideal standard of rationality: while historians, psychologists and sociologists can shed light on various interesting aspects of how science works, philosophers are uniquely positioned to understand how science *should* work, regardless of whether many scientists (or conceivably all of them) fall short of that ideal. The naturalistic trend can thus be seen as a reaction to the feeling that, in this traditional idealistic conception, philosophy of science risked becoming philosophy *of fictional science*, or *what we wish science was*, rather than of what science actually is. The naturalistic reorientation has accordingly led to the proliferation of practice-oriented philosophical approaches, including work sometimes labeled "philosophy of science-in-practice" and other times "philosophy-of-science in practice" depending on the specific focus and character of engagement with scientific tools and methods, whether observing them or using them (Ankeny et al., 2011, Boumans & Leonelli, 2013; see also, e.g. Atanasova et al., 2021; Poliseli et al., 2022).

The second trend, within this first one, is that of drawing from (A) niche construction theory and (B) embodied cognitive science to inform work in naturalized philosophy of science. Work in A, we have seen, applies concepts and ideas from niche construction theory to provide a broad view of science as a biological phenomenon situated in, and shaped by, the human evolutionary context: here, research has helped elucidate how the conceptual, linguistic basis of scientific explanation and theorizing not only provides us tools for understanding natural phenomena but can be understood as a natural phenomenon in its own right (Rouse, 2015). Work in B, we noted, has typically applied concepts and ideas from embodied cognitive science (especially ecological and enactive perspectives) to try to elucidate particular aspects of specific scientific practices, with special focus usually given to modeling practices: here, the recent literature has helped shed light on how building and using models in scientific research can, for instance, be understood as involving enactive material engagement or the cognitive extension of the scientific imagination (Knuuttila, 2017; Rolla & Novaes, 2022). Yet these projects have remained separate from each other—no big-picture conception of science *both* in terms of biological, evolutionary niche construction *and* of embodied and situated, ecological-enactive cognition has been offered so far. Having sketched our wide-ranging proposal leveraging both, we now conclude by noting some of the beneficial implications for naturalized philosophy of science.

First, our view shows how a big-picture evolutionary, ecological-enactive perspective can connect directly to debate surrounding the question, central in recent philosophy of science, concerning the relation between theory and practice. As we have noted, the currently popular *practice-oriented* conception of philosophy of science arises historically as a reaction to what had been a normative, idealized *theory-centered* conception of philosophy of science. But it's interesting to consider how this shift could be (or be perceived as) merely a "change of subject." That is, in emphasizing the importance of practices of model-building, experimentation etc. and de-emphasizing theory, the shift might appear to be centered around *which* aspects of science are deemed most philosophically pressing or interesting rather than amounting to a more fundamental transformation in how we conceptualize those aspects: along these lines, it might seem that, having given up on traditional philosophical concerns with the domain of the theoretical and ideal, we now simply choose to focus on practice instead—a move that would still leave unchallenged the traditional assumption that theory and practice are in fact separate, independent and distinct domains.

The view sketched here shows how, more than simply a shift in focus or a change of subject, the turn to practice in philosophy of science more radically provides (or can provide) a reconceptualization of science as a whole, including how we understand "theory" and "practice." In a biologically-informed, embodied cognition-inspired view, it's not possible to choose between theory and practice as alternative objects of philosophical analysis, because theory and practice are no longer seen as separate domains within science, and understanding one requires understanding both as part of human embodied (cognitive) niche construction activity. In the picture of science we have sketched, following the ecological-enactive perspective in embodied cognitive science, theory is not only closely linked to practice, but it is better understood *as* practical, as continuous with other ways we use our bodies to attune to our situation and to perceive and realize affordances, acting in the world and with the world (e.g., using instruments, inscriptions, specimens, and so on). Theorizing is thus an embodied cognitive practice—but, then again, any practice is also necessarily embodied, and any embodied activity is necessarily a manifestation of, and a means to developing, our epistemic relation with the world. Scientific knowledge (as a relation and activity) and scientific theory (as a practice) are thus neither socially constructed nor human re-constructions of mind-independent reality, but they arise dialectically, interactively and iteratively, through human niche construction activity, as joint co-constructions of organism-environment systems.

The second point is related to the first and has to do with our proposal's unifying power on different dimensions. We cannot pretend that the idea we've just emphasized, of theory as practice, is new. Different versions of the same general idea have been explored in great works of philosophy of science, from old classics like Kuhn's (1962) *The Structure of Scientific Revolutions* and Feyerabend's (1975) *Against Method* to more recent classics such as Longino's (1990) *Science as Social Knowledge*, Lloyd's (2006) *The Case of the Female Orgasm*, and many others, which in different ways reveal the circular relation between human activity, social organization, and knowledge claims, with one shaping and being shaped by the other. We like to think of our proposal as corroborating these time-tested perspectives in philosophy of science, embedding them in contemporary work in other disciplines outside philosophy of science (i.e., in embodied cognitive science and evolutionary biology) while also connecting them even farther back in the history of philosophy (i.e., older perspectives in the classical pragmatist tradition). We lean toward pluralism and don't think that cross-disciplinary integration/unification is mandatory or to be expected everywhere. Still, the productive convergence of distinct perspectives from different fields, alongside the cross-historical philosophical ties we've identified, are definite boons, enhancing understanding by revealing hidden commonalities and suggesting further directions for inquiry. This is not to say that the work by philosophers like the ones just mentioned was worse off for not combining, as we have proposed here, an ecological-enactive cognitive perspective with a niche construction view of biological evolution: rather, although their work may have been perfectly adequate for their purposes given their context, the fact that we have these theories at our disposal now in our own different context enables us to move forward with an enriched understanding—and not only enriched understanding of the phenomenon under investigation (i.e., science and the co-dependence of embodied activity, social organization, and knowledge claims) but also enriched understanding of the categories, concepts, methods and tools at our disposal for this investigation, which we can now better position in their intellectual situation (e.g., in the history of philosophy of science) as well as in a larger cognitive and biological context.

The third and final point to emphasize is the hope to encourage greater attention by philosophers of science to the implicit assumptions they might be taking for granted about mind and cognition in theorizing the practices of scientists. Epistemology, philosophy of mind and philosophy of science have traditionally relied on representationalist foundations, leading to a number of different interpretations of our possibility to transcend various limitations so as to gain access to a mind-independent reality. But these representationalist assumptions are just that, assumptions, and their popularity and typically implicit status does not make them more legitimate than the alternatives. Besides articulating the link between these related questions and views that arise independently in different philosophical domains, our proposal offers an alternative foundation for philosophical inquiry as well as an alternative conclusion. On the view we've proposed, rather than fundamentally representational and only secondarily practical, our engagement with the world (including in science) is first and foremost practical, and even our use of inscriptions and descriptions to crystalize what we say and think, and to share it with others, is a form of practical, material engagement. Moreover, these practices are only properly understood in continuity with the rest of our niche construction activity, the things we do and create to (try to) make life better, with long-lasting consequences for ourselves and the world. This makes the idea of knowledge of "mind-independent reality" seem irremediably naive. And this is not because we think that reaching such knowledge is difficult to obtain or even impossible, but rather because the notion of "mind-independence" in question belies a problematic dichotomization of humans and nature. On the view sketched here, we can't have knowledge of a reality independent of ourselves because, given our niche construction activity, the world is always already human, and we become who we are in transaction with the world, such that any and all knowledge is jointly produced by humans and the world, sensitively adapting and responding to one another.

Our proposed big-picture view of science as a whole as relational and world-involving is explicitly inspired by and built upon particular psychological and biological conceptual frameworks. Being explicit about this inspiration also suggests the prospect of explicitly articulating the implications that these psychological and biological commitments have for philosophical reflection on specific aspects of science, including modeling, experimentation, hypothesis testing, explanation, as well as questions concerning social values and the science-society nexus. The same is true when it comes to competing psychological and biological assumptions: naturalized philosophy of science will be better off if, in our attempt to understand scientific practice, our assumptions about the practitioners in question are not relegated to the background, but are brought out into the open and available for scrutiny.

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