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A NeuroEcological architecture for situated cognizing systems

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Abstract

Situated approaches to cognizing—such as distributed, embodied, and extended—have exerted an immense influence on the cognitive and psychological sciences. Since such accounts typically do not prioritize neurobiology, their impact is felt far less in neuroscience. The influence of ecological psychology is largely responsible for this, which stresses the role of ecological information that dynamically unfolds at the scale of organism-environment systems as being critical for cognizing. A substantial criticism of this approach concerns the apparent absence of the brain's contributions to cognition. Insofar as they remain influenced by ecological psychology, such criticisms undermine other situated approaches as well. The primary aim of this work is to present a framework for integrating neuroscience with situated approaches, namely, the NeuroEcological Nexus Theory (NExT). To be successful, NExT must both maintain the core principles of ecological psychology and provide testable hypotheses concerning the neurobiological contributions to intelligent organism-environment events. The latter is provided by contemporary neuroscience work on the neural manifold hypothesis. In hypothesizing that situated cognition can be explained via interactions among environmental (ecological) information and classes of neuronal manifolds, NExT provides a step toward a more complete understanding of mind, one that spans the cognitive and psychological sciences, as well as the neurosciences. Such progress ought to be welcomed by ecological psychologists and proponents of situated approaches.

1. A little bit of history and a challenge

Situated approaches to cognition generally adhere to the view that intelligent systems are always embodied and embedded (e.g., Robbins & Aydede, 2009; Roth & Jornet, 2013; Walter, 2014). Though there is variety and controversy in how the term is used, as a starting point, "embodied" refers to the idea that cognition requires a body to occur (e.g., Varela, Thompson, & Rosch, 1991). In a more specific sense, this means that there tends to not be a sharp distinction between cognition and noncognition in the body and, related, that sensorimotor processes are important for cognition (Favela & Chemero, 2016). There is a spectrum in how weak or strong these positions are. At the weaker end of the spectrum, cognition is primarily a brain event, but the brain areas associated with the body's sensorimotor processes play important roles in causing and enabling even "higher" forms of cognition, such as abstract reasoning and language (e.g., Barsalou, 1999; Lakoff & Nunez, 2000). At the stronger end of the spectrum, cognition is not primarily a brain event, with the body's (i.e., nonneural) structures and processes causing and constituting even those previously-mentioned "higher" forms of cognition (e.g., Di Paolo, Buhrmann, & Barandiaran, 2017). In the current context, the term "embedded" is also fraught with variety and controversy, but as a starting point refers to the idea that cognition always occurs in a situation that is deeply tied to nonbodily features, such as the environment (e.g., light and temperature; e.g., Richardson, Shockley, Fajen, Riley, & Turvey, 2008) and social communities (e.g., classroom; e.g., Heft, 2013). So too does embeddedness fall along a spectrum. At the weaker end, cognition remains primarily a brain event, but nonbodily features, such as those in the environment, can play significant causal roles in cognition. At the stronger end, cognition both cannot occur without nonbodily features like a social situation and is constituted by those elements, such as thinking with nonneural tools (e.g., only being able to solve math problems with the aid of pen and paper).

The broad class of situated approaches to cognition have exerted an immense influence on the cognitive and psychological sciences. Since the earliest days of *scientific* psychology, people like John Dewey and William James promoted various forms of *functionalism*, or the idea that the aim of psychology is to study mind and behavior from the perspective of their roles in an organism's abilities to adapt to their environment (Hergenhahn & Henley, 2014).[1] This form of functionalism stressed the need for explanations of psychological phenomena to include what is happening in the body and environment (e.g., James, 1885).[2] Soon after, *behaviorism* became the dominant framework for scientific psychology. Commonly associated with the work of people like B. F. Skinner and John Watson, behaviorism had three main commitments: psychology is the science of behavior, the sources of behavior are not internal (i.e., mind) but are external (i.e., environment), and any use of mental concepts should be replaced by behavioral concepts (e.g., Graham, 2023). Granted that behaviorism had its share of problems, the point in mentioning it here is that, again, in the history of scientific psychology, the dominant approach emphasized the roles of the body and environment.

The emphasis on the body and environment would come to be relegated to the background in favor of the "autonomous" treatments of cognition (cf. Fodor, 1997), with developments in the mid-1900s that contributed to the *cognitive revolution* that dethroned behaviorism (Boden, 2006). Taken together, developments in computer science (McCarthy, Minsky, Rochester, & Shannon, 2006), information theory (Shannon & Weaver, 1949/1964), and linguistics (Chomsky, 1965/2015) motivated psychology—and the new *cognitive science*—to shift focus to the internal states that contribute to behavior and thought. The *cognitivist* framework that grew from those foundations treated scientific psychology's target of investigation as a kind of *information processing* (e.g., Thagard, 2023). In this context, "information processing" refers to the claim that cognition is fundamentally computational and representational in nature. The basic idea is that cognition is defined as procedural operations (i.e., computations) over meaningful structures (i.e., representations) to constitute or produce decision making, perception, problem solving, and the like (e.g., Neisser, 1967/2014). Notwithstanding the fact that most cognitive science and psychology textbooks trace a single historical trajectory along the lines just described—i.e., functionalism to behaviorism to cognitivism—it is a fact that other fruitful approaches continued to carry the torch of situatedness. One of the most influential situated approaches was ecological psychology.

Ecological psychology is a research program and theoretical approach to perception and action originating with James J. Gibson in the mid-1900s (e.g., Gibson, 1966). While initially an investigative approach to perceptual psychology, Gibsonian ecological psychology has been a major influence on a wide range of fields, including, but not limited to, botany (Calvo, 2016), developmental psychology (Thelen, 2000), human-machine interaction (Favela, 2019), and virtual reality (Regia-Corte, Marchal, Cirio, & Lécuyer, 2013). Ecological psychology can be understood via the four primary principles at its core (Favela, 2024; cf. Chemero, 2013; Gibson, 1986/2015):

First, *perception is direct*. An organism's perceptual capacities can make unmediated contact with its environment in order to detect ecological information. Within the context of ecological psychology, "information" does not mean what it commonly does in other cognitive and psychological sciences, such as a measure of uncertainty (Shannon & Weaver, 1949/1964) or data (i.e., representations) processed in a formal way that can be communicated (Henderson, 2009). Most importantly, it does not involve any sense of "computation" or "representation" as being the defining nature of cognition or perception. In ecological psychology, "information" is the basis of meaningful interactions among an organism and its environment. Ecological information are "those patterns that uniquely specify properties of the world" (Richardson et al., 2008, p. 177; Gibson, 1986/2015, p. 67). It is not mere stimulus, but is the distribution of energy surrounding an organism. They are higher-order properties in that they are necessarily spatiotemporal in nature, such that an organism perceives them in their surrounding space over time (Gibson, 1966), for example, optic flow. The sense of "unmediated" at the heart of directness refers to the claim that perception does not require inferential processes to both perceive the environment and its meaningful elements for the organism (i.e., affordances).

Given that representational understandings of perception are the norm in the cognitive and psychological sciences (e.g., Edelman, 1999; Marr, 1982/2010), it is worth elaborating more upon the meaning of "direct perception" in ecological psychology. In the context of perception, "representations" are understood as mediating stimulation from the world that impinges upon sensory apparatuses like eyes. Such mediation is postulated as necessary because the stimulation is meaningless, that is to say, it is unstructured, which has the consequence of being unable to participate in guiding successful action. As a result, the perceiving system must transform the meaningless stimulation into meaningful representations. This line of thought is analogous to the poverty of stimulus (PoS) argument in linguistics (e.g., Berwick, Pietroski, Yankama, & Chomsky, 2011). In short, the PoS argues that there is not enough structure in the stimulation—e.g., sounds from parents speaking—to account for the speed and sophistication at which children learn and develop language capabilities. Thus, there must be inferences made on the stimulation within the system to make them meaningful. In the context of perception, the PoS argument claims that there is not enough structure in the stimulation—e.g., light reflecting from a surface impinging upon retinal cells in eyes—to account for the ability of organisms to successfully act in the world (e.g., grasp a branch, walk through an aperture, etc.). Thus, there must be inferences (i.e., transformations) made on the unstructured stimulation within the system to make them meaningful. Gibsonian ecological psychologists understand perception as *direct* in that they reject the notion that environmental energies—i.e., *information* as defined above—cannot guide meaningful action because they are unstructured. On the contrary, they claim that environmental (i.e., ecological) information is *rich* with structure; rich enough to guide action without needing to infer meaning in the form of representations.[3]

Second, *perception and action are continuous*. An organism's perceptual capabilities were selected (i.e., evolutionarily) to guide action and so were action capabilities selected to enable perception. For the Gibsonian approach, it does not make sense to attempt to understand either perception in isolation from actions or actions in isolation from perception.

Third, is *affordances*. As a consequence of perception being direct and the continuity of perception and action, it follows that detected ecological information can specify meaningful opportunities for action, namely, affordances. In short, affordances are perceivable opportunities for behavior (Chemero, 2013; Gibson, 1986/2015; Heras-Escribano, 2019). To properly utilize affordances as part of ecological psychology research, one must understand the significance of both the organism and the environment in acts of perceiving and acting. Affordances are not just features of the external world (i.e., consistent with behaviorism) nor are they just features of the internal organism (i.e., consistent with cognitivism). As Gibson put it, "an affordance is neither an objective property nor a subjective property; or it is both if you like. An affordance cuts across the dichotomy of subjective-objective. … It is equally a fact of the environment and a fact of behavior" (Gibson, 1986/2015, p. 121). While that statement may sound cryptic, it makes a clear point: Explanations of affordances cannot prioritize or neglect the contributions of the organism or the environment, which leads to the final primary principle.

Fourth, psychology is about the *organism-environment system*. The spatiotemporal scale of organism and environment interactions is the proper point of inquiry for investigating, explaining, and understanding the previous three principles. Treating the organism-environment system as the proper scale at which affordances must be explained has facilitated expansive knowledge in perceptual psychology and has facilitated the development of various sophisticated quantitative techniques. Consequently, ecological psychology provides a scientifically compelling research program for investigating and understanding perception-action events.

Two points should be clear at this point: One is that from its origins in the mid-1900s to today—and like the earlier approaches to scientific psychology (e.g., Jamesian functionalism)—ecological psychology has maintained that the body and environment are necessary elements when investigating and understanding intelligence in its various forms. Taken together with its offering of a rich set of concepts and theories and sophisticated quantitative methods, it is clear why ecological psychology is a major influence on situated approaches in the cognitive and psychological sciences (e.g., see discussion in Varela et al., 1991). The other point is that there has been no mention of the brain's role in the phenomena investigated by ecological psychology. Notwithstanding the fact that brains are parts of many organism-environment systems, and while Gibson himself spent some time discussing the brain's role in perception (e.g., Gibson, 1966, 1986/2015), the vast majority of experimental and theoretical work by ecological psychologists has not focused on brains. For that reason, among others, it becomes clearer why situated approaches have not had as much impact on the neurosciences as they have on the cognitive and psychological sciences. Specifically, insofar as situated approaches are explicitly or implicitly adhering to the core principles of Gibsonian ecological psychology, their investigative reach is limited more to the body and environmental scales and less to the spatial and temporal scales relevant to neurobiological structure and function.

Proponents of situated approaches, especially those at the "stronger" end of the spectrum, have defended ecological psychology and other explicitly non-brain-centric approaches to cognition by arguing that brains and nervous systems have always been part of their theories of perception. For example, it is regularly pointed out that ecological psychologists have always treated perception as occurring in *perceptual systems*. As Gibson put it,

> The eye is considered to be an instrument of the mind, or an organ of the brain. But the truth is that each eye is positioned in a head that is in turn positioned on a trunk that is positioned on legs that maintain the posture of the trunk, head, and eyes relative to the surface of support. Vision is a whole perceptual system, not a channel of sense… One sees the environment not with the eyes but with the eyes-in-the-head-on-the-body-resting-on-the-ground. Vision does not have a *seat* in the body in the way that the mind has been thought to be seated in the brain. The perceptual capacities of the organism do not lie in discrete anatomical parts of the body but lie in systems with nested functions. (Gibson, 1986/2015, p. 195; italics in original)

Accordingly, perceptual systems like mammals have a brain and nervous system that partially constitute the organism part of organism-environment systems. Despite that point, critics have noted that Gibson's engagement with the neurosciences was unjustifiably minimal, being limited mostly to criticisms (e.g., "Neurophysiologists… are still under the influence of dualism, however much they deny philosophizing;" Gibson, 1986/2015, p. 215) and vague metaphors (e.g., "the brain resonates;" Gibson, 1966, p. 260). This has led to scathing criticisms of Gibsonian ecological psychology, which include caricaturing the Gibsonian view of organisms as being "stuffed with foam rubber" (Pribram, 1982, p. 370) and treating the brain with awe as if it were a "hunk of wonder tissue" (Dennett, 1984, pp. 149-150).[4]

Some critics may be right that situated approaches to cognition—especially of the strong variety like ecological psychology—have unjustifiably ignored the brain's contributions or made too little effort to engage with other research areas that do. While there has been some work by self-identified ecological psychologists to connect their research to the neural scale, those are few and far between.[5] Moreover, that work is typically not experimental in nature.[6] The majority of the experimental work in neuroscience that is about "affordances" does not adhere to the core principles of ecological psychology, such as perception being direct (i.e., nonrepresentational; e.g., Cisek, 2007). This situation raises an interesting challenge: to offer a framework that provides the neural scale part of the story for investigating and understanding phenomena that ecological psychologists study without compromising any of its core principles. The next section offers just such a framework: the NeuroEcological Nexus Theory (NExT; Favela, 2024). NExT provides an explicit account of the brain's contributions to an affordance event and does so while maintaining all four core principles of ecological psychology.[7] In doing so, NExT offers a cognitive architecture for even the strongest versions of situated approaches in the cognitive, psychological, and neural sciences. If compelling, NExT will provide a step toward a more complete understanding of mind, one that spans the cognitive and psychological sciences, as well as the neurosciences. Moreover, such progress should not be viewed as occurring within the neurosciences alone, and ought to be welcomed by ecological psychologists and proponents of situated approaches as well.

2. A NeuroEcological cognitive architecture

The *NeuroEcological Nexus Theory* (NExT; Favela, 2024) is a theory about cognitive systems and a theoretical program for the scientific investigation of such phenomena. NExT is appropriate for the investigation of cognizing organism-environment systems that have nervous systems. Since cognitive systems are always situated, NExT is committed to the position that such systems necessarily include organisms (i.e., embodied) that are tightly coupled with or constituted by their ecologies (i.e., embedded). The *nexus* part refers both to the framework as a point of convergence for ecological psychology and neuroscience, and as a "nexus" that constitutes the primary causal and/or constitutive links or junctions that connect the various elements of a cognizing organism-environment system. NExT is defined here via five hypotheses that provide a way to integrate ecological psychology (especially its four core principles) and neuroscience (i.e., neural spatiotemporal scales), while not treating one as being epistemically or metaphysically more fundamental than others during investigative work.[8]

Hypothesis 1 is that the organism-environment system is the privileged spatiotemporal scale of description to understand cognizing. NExT provides a scientific framework that aims to explain overlapping phenomena studied by ecological psychology and neuroscience, while not privileging the spatiotemporal scales of either. Consequently, a comprehensive investigation of cognition is not achieved by either neuroscience (e.g., neuronal activity) or ecological psychology (e.g., ambient arrays) alone. This does not mean rejecting what has been successful about each, such as computational modeling in neuroscience or relative measurements (e.g., body scaled) in ecological psychology. Additionally, treating the organism-environment system as a single spatial and/or temporal scale of investigation would be incorrect, as cognitive phenomena are *multiscale* in nature.[9]

Hypothesis 2 is that neural population dynamics generate the relevant states for cognizing organism-environment systems. While the single neuron continues to be a significant aspect of understanding neural systems, much work in the neurosciences has come to investigate "populations" as the primary unit for explaining various activity. It has been argued that the neuron doctrine ought to be replaced by the "neural population doctrine" (Ebitz & Hayden, 2021; Saxena & Cunningham, 2019). Here, neural populations are defined in terms of "well-specified function" (Kohn, Coen-Cagli, Kanitscheider, & Pouget, 2016, p. 237), which is further illuminated via Gerald Edelman's theory of neuronal group selection, or Neural Darwinism (Edelman, 1987). Neural Darwinism explains brain structure and function in terms of population thinking, or selectionism, which says that variance within biological populations is necessary for the process of evolution, such that those individuals who can best cope with their environment will reproduce more successfully (Edelman, 1988). Neural Darwinism offers a rich justification for the hypothesis that neural populations generate the most relevant dynamics for organism-environment system activity and does so in a way that is linked to well-specified function (cf. Kohn et al., 2016). Accordingly, a *neural population* is a neuronal group that has been selected for over species development timescales, individual organism lifetime, and moment-to-moment experience timescales, which have been selected for due to their contributions to synchronized and integrated brain-body-environment structures that have facilitated evolutionary advantages.

Hypothesis 3 is that cognizing is based on low-dimensional neural dynamics. The relevant dynamics occur at the neural population scale and are low-dimensional in terms of manifold theory, especially topological manifolds. Topology is the mathematical study of the properties of objects that are maintained despite changing their shape (e.g., twisting), without compromising their integrity (e.g., ripping; Weisstein, 2022). The "objects" of topology are called *topological spaces*. When two or more topological spaces have the same properties (e.g., shape), then they are called *homeomorphic*. These concepts underlie the idea of manifolds. In topology, a *manifold* is a mathematical object that looks locally like Euclidean space, but globally may have a more complicated structure. This means that if a small part of a manifold looks flat and Euclidean when zoomed in upon, zooming out and seeing the entire space of the manifold may reveal more complicated features (e.g., holes). The classic example of a homeomorphic topological space is the coffee mug and donut, or torus. *Manifold theory* is the study of such mathematical objects, with a focus on features like curvature and differentiability (Edgar, 2008; Ma & Fu, 2012).

The concepts and tools from manifold theory, and topology more broadly, have come to be increasingly utilized in data science. In particular, this is evident in widening applications of the *manifold hypothesis*, which is the claim that very high dimensional datasets have much lower dimensional manifolds that capture their principal structure (Fefferman, Mitter, & Narayanan, 2016). Here, "very high dimensional datasets" can be understood as referring to any large amount of recorded data from sources like neural activity (Cunningham & Yu, 2014). The *neural manifold hypothesis* is the claim that very high dimensional datasets—specifically, neural population dynamics—have much lower dimensional manifolds that capture their principal structure (i.e., "neural modes") that generate specific behaviors (Gallego, Perich, Miller, & Solla, 2017). The neural manifold hypothesis claims that the spatiotemporal scope of neural activity causally related to and/or constitutive of a range of phenomena (e.g., motor control) may seem incredibly large but is in fact confined to a much smaller scale. In line with Hypothesis 2, NExT hypothesizes that those neural modes are found at the mesoscale of population activity. This commitment claims that relevant neural activity is not found in individual neurons or in brain regions. Thus, statistical methods that average across activity of individual neurons or across larger brain regions will not suffice. As Gallego and colleagues put it:

> Here we argue that the underlying network connectivity constrains these possible patterns of population activity… and that the possible patterns are confined to a low-dimensional manifold… spanned by a few independent patterns that we call "neural modes." These neural modes capture a significant fraction of population covariance. It is the activation of these neural modes, rather than the activity of single neurons, that provides the basic building blocks of neural dynamics and function. (Gallego et al., 2017, p. 978)

Identifying these modes requires extracting ω variables from a recorded set of α variables. Because ω is not directly observed, they are called *latent variables*. In neuroscience, the α variables typically take the form of neuronal timeseries. Thus, the neural manifold hypothesis expects that because α neurons are part of an interconnected network, only ω will be needed to explain their activity. These neural population dynamics are processed with various dimensionality reduction techniques to produce a *neural manifold*, which is a set of activity plotted in an *n*-dimensional states space (e.g., Chaudhuri et al., 2019). After, the latent dynamics across the plotted states are weighted to assess if there are patterns in the activity, or persistent homologies. If the neural manifold hypothesis is supported by the data, then this analysis should reveal a topological manifold in the noisy cloud of data points.

Consider the example of a mouse's head movement (Figure 2.1). The aim is to identify the neural populations that play causal and constitutive roles in head movement. The idea is that particular neurons will be active depending on where the mouse is orientated (Figure 2.1A). The neural manifold hypothesis claims that if the population dynamics embody a variable of particular dimension and topology, then those dynamics would be focused on a subspace of corresponding manifold dimension and topology (Figure 2.1B). If head direction is a single variable (i.e., topologically 1-dimension), then the expectation is that among the high dimensional data there will be a low dimensional spline that is also a single variable (i.e., topologically 1-dimension). In the current context, a "spline" is mathematical function applied to interpolate or smooth data, and can be helpful in identifying trajectories and regions of data that is of particular interest when explaining a phenomenon. This is exactly what is seen in this research. The mouse's head direction (indicated by diamond shape-tipped arrow; Figure 2.1A-C) occurs across a 1-dimensional topology within Euclidean space (Figure 2.1A). So too, do the latent variables track along 1-dimensional topology (Figure 2.1B), which, if straightened out conforms to a torus (Figure 2.1C). This point cannot be stressed enough: The topology of the actual mouse's head direction and its causal and constitutive neural population activity are homeomorphic, not just in shape (i.e., torus) but in direction (i.e., the neural population activity along the spline tracks identically with the direction of the mouse's head). In short, the mouse's head direction in real space, neural population activity in the brain, neural population activity in the state space along the spline, and the location along an abstract torus are equivalent. Examples like this motivate the reasonable assumption that such successes will generalize the neural manifold hypothesis to other neural-involving cognizing events as well.[10]

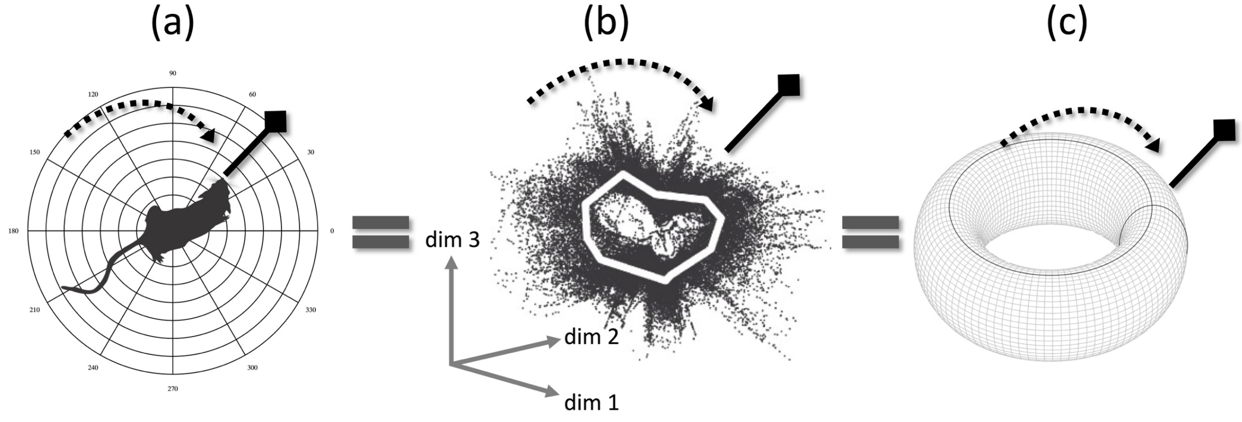

Figure 2.1. Neural manifold hypothesis methodology. (a) During the task of rotating the mouse's head direction in Euclidean space (indicated by diamond shape-tipped arrow), activity from the relevant neural population is recorded. (b) Dimensionality reduction techniques are applied to isolate the neural activity, and then further analyzed to identify the latent variables via a

generated spline. (c) Movement in Euclidean space and along the spline are equivalent to the location on the abstracted torus. ((a) Public domain; (b) Modified and reprinted with permission from Xia et al. (2021), CC BY 4.0; (c) Public domain.)

Hypothesis 4 is that the body organizes into low-dimensional synergies to generate relevant states. In the context of bodily action, *synergies* are functional assemblies of parts (e.g., neurons, muscles, etc.) that are temporally constrained to act as a single unit (Kelso, 2009). The body can be understood as a synergy when its various parts are organized into a functional unit, where "functional" is understood in terms of tasks conducted by the unit (Kugler, Kelso, & Turvey, 1980). For instance, when somebody with a visual impairment is wielding their cane, the particular assemblage of their skeleton and muscles, along with the tool, are a synergy in that they are a functional unit aimed at accurately navigating the world (cf. Favela, Amon, Lobo, & Chemero, 2021).

The uncontrolled manifold (UCM; Scholz & Schöner, 1999) is a methodology for assessing the variability of movements with regard to tasks, or the aim of functional units. Here, a distinct configuration space is defined that is populated by variables hypothesized to capture a particular movement. UCM treats motor control as being fundamentally about the stabilization of performance variable values. Those values are quantified in terms of their being compensatory and uncompensatory with regard to the task. The methodology generates a state space where a manifold depicts the variables contributing to the task and quantifies the amount of constancy among those variables. The result is a "synergy index" (Latash et al., 2010), where variance along the manifold are compensatory variables when they maintain task performance (i.e., "good variability") and variance perpendicular to the manifold are uncompensatory variables when they result in loss of performance (i.e., "bad variability;" Latash, 2012).

NExT claims that a body can self-organize into synergies. As a synergy, the body is partially caused and constituted by neural population dynamics across a flexible range of variance that is constrained only by their ability to facilitate successful task completion. This is consistent with selectionist view of evolution (see above discussion of Neural Darwinism). So too does the environment contribute to the body's performance in flexible ways (e.g., adapting to new forms of ecological information to guide action). UCM methodology allows investigators to empirically assess the presence of and degree to which a system is a synergy. This allows for defining synergies without adhering to a priori definitions about where the boundaries of an intelligent system must be drawn. Variables that contribute to synergies can be located in the brain, arm, or environment, as long as they facilitate successful task completion. Accordingly, bodies are properly understood as being part of cognizing organism-environment systems.

Hypothesis 5 is that cognizing fundamentally emerges at low-dimensional states of organism(neural, body)-environment activity. NExT claims that cognizing is a multiscale phenomenon that emerges from systematic relationships among brain, body, and world. Each spatiotemporal scale is high dimensional, but the principal structure of each is low dimensional (Figure 2.2B). This is motivated by the neural manifold hypothesis regarding neural populations and uncontrolled manifold regarding body synergies. From those methods, targets of investigative interest at each spatiotemporal scale can be modeled and depicted via phase space plots that present the state space of empirically-verified activity. As neural populations and body synergies are dynamical systems, these data can take the form of dynamical landscapes (Figure 2.2C). A *dynamical landscape* is a qualitative description of system's states based on quantitative data from characteristics like directionality and strength. As brain and body spatiotemporal scale activity has low-dimensional structure within high-dimensional data sets, so too does the environment (Figure 2.2C, bottom). Here, the "high dimensionality" of the environment refers to the flood of potential stimulation constituting the world—e.g., light, odors, trees, etc.—and "low dimensional" refers to ecological information that specifies affordances.

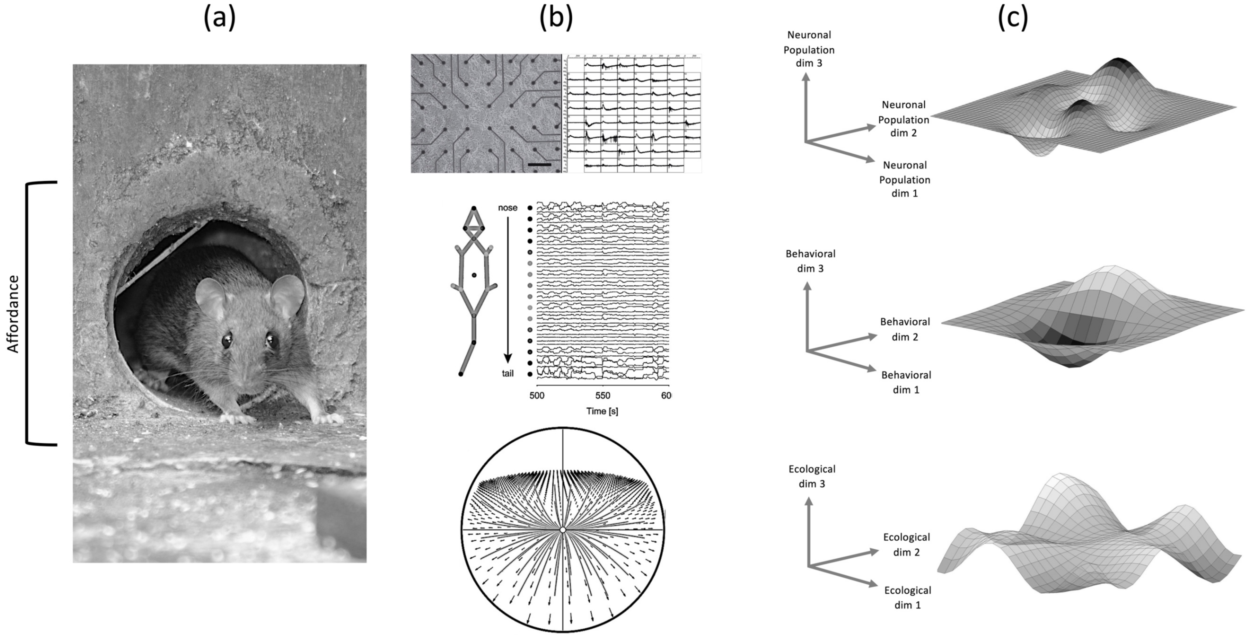

Figure 2.2. The NeuroEcological Nexus Theory (NExT) applied to the affordance of pass-through-able. (a) The affordance pass-through-able is exhibited when a mouse walks through a hole, and involves features of the environment (e.g., hole in wall), organism (e.g., shoulder width), and brain (e.g., sensorimotor neural populations). (b) Each row depicts a potential data source that contributes to a NExT-based explanation. Top: Time series from multielectrode recording of relevant neural populations. Middle: Motion tracking markers on mouse body and trace data. Bottom: Optic flow as example of relevant ecological information. (c) Each row depicts a dynamical landscape generated from low-dimensional principal structure identified from high-dimensional data recorded from sources such as those depicted in column (b). ((a) The author generated this image in part with DALL-E, a multimodal implementation of GPT-3, which is OpenAI's large-scale language-generation model. Upon generating the image, the author reviewed, edited, and revised the image to their own liking and takes ultimate responsibility for the content of this publication. https://openai.com/product/dall-e; (b) Modified and reprinted with permission from Niedringhaus et al. (2015), CC BY 4.0; Huang et al. (2021), CC BY 4.0; Matthis et al. (2022), CC BY 4.0.)

With the hypotheses explained, all of the pieces can be put together and demonstrate how NExT is applied to an affordance event. Consider the case of a mouse deciding if a hole affords pass-through-ability (Figure 2.2A). The mouse detects ecological information about the hole (e.g., optic flow; Figure 2.2B, bottom), which informs its actions (i.e., head movement; Figure 2.2B, middle), which in turn alters the structure of the ecological information it is detecting, and so on (ecological psychology core principles 1 and 2). Contributions by neural spatiotemporal scales is accounted for by the neural manifold hypothesis (Figure 2.1). Given the research aim to identify the neural populations most relevant to the affordance pass-through-able, the neural population that causes and constitutes head movement will be one of the focuses because it plays a significant role in the mouse's engagement with ecological information that guides the most applicable action (Figure 2.1 and Figure 2.2B, top). The activity of these particular neurons will be dependent on the mouse's orientation in Euclidean space (Figure 2.1A-B). The neural manifold hypothesis claims that the principle structure of these population dynamics will be expressed by particular topological dimensions, such that head direction is one variable (i.e., 1-dimension topology) that fits on a low dimensional spline within the high dimensional cloud of data (Figure 2.1B). Prior research (e.g., Chaudhuri et al., 2019; Gallego et al., 2017) has demonstrated location equivalence in Euclidean space of the mouse's body (Figure 2.1A), location of activity along the low-dimensional spline (Figure 2.1B), and the abstracted torus (Figure 2.1C).

Although the current discussion thus far seems to emphasize neural population activity, the affordance event is multiscale across the organism-environment system (principle 4) and the mutuality of perception-action (principle 2) are maintained. A crucial reason for this is that the activity of neural population dynamics do not hold a unidirectional causal relationship with the body or environment. The state of the body (i.e., head location; Figure 2.1A) and the environment (i.e., aperture edge; Figure 2.2A) inform and constrain the state of the neural activity. If the head cannot move any further to the left because it hits up against the hole's edge, then the neural population will also not continue activity in that direction, as exhibited by its location on the low dimensional manifold (Figure 2.1B and Figure 2.2C, top). So too does the state of the neural activity inform and constrain the state of the body and environment, such that where the direction of the head points will provide the perspective from which the body (e.g., eyes) will detect ecological information (e.g., light reflecting from the surface edges of the hole). In that way, direct perception (principle 1) is also maintained due to the fact that neural activity is informed and constrained by the direct engagement with ecological information. In this way, NExT offers an approach to investigating and explaining an affordance event (i.e., pass-through-able), while maintaining the four core principles of ecological psychology and offering an account of the contributions at the neural spatiotemporal scale via the neural manifold hypothesis.

3. Conclusion

Situated approaches to cognizing are highly influential in the cognitive and psychological sciences. I argued that the influence of ecological psychology on such approaches has undermined their influence in the neurosciences. One reason is that ecological psychology motivates a strong version of situatedness, where cognizing is not primarily a brain event and cannot occur without nonneural elements such as those in the body and environment. A major criticism of this approach is that even in organism-environment systems constituted by organisms with brains, those neural elements play crucial roles in cognizing events, such as those involving affordances. Thus, the challenge taken up by the current work was to offer a framework for investigating and understanding cognizing systems, one that does not compromise any of the four core principles of ecological psychology and suggests a plausible account of contributions from the neural spatiotemporal scale.[11] The NeuroEcological Nexus Theory (NExT) is such a framework. By way of the example of the affordance of pass-through-able, NExT provides a plausible account that honors both ecological psychology and neuroscience. Accordingly, NExT bolsters even the stronger versions of situated approaches to cognizing in offering the neural part of the story of strongly embodied and embedded systems.

In closing, to say that cognizing fundamentally emerges at the low-dimensional scales of organism(neural, body)-environment systems is to adhere to a set of metaphysical and epistemological claims. Metaphysically, it is to maintain that cognizing is caused and constituted by an organism's body—including its nervous system—and spatiotemporal structures of the environment. Epistemologically, it is to maintain that more complete explanations of cognizing systems necessitates concepts, methods, and theories that do not privilege "lower" (e.g., neuronal activity) or "higher" scales (e.g., ambient arrays), but integrate understanding across multiple scales. Taken together, the metaphysical and epistemological aspects of NExT contribute to its ability to offer an architecture for situated cognizing systems, one that provides a more complete understanding of minds and, thus, benefits both the cognitive and psychological sciences (including ecological psychology) and the neurosciences.

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[1] For the sake of brevity, I am focusing on the strand of scientific psychology predominantly associated with the United States. Of course, other regions of the world developed scientific psychologies, and sometimes concurrently with those mentioned in the current work, such as the structuralism of Edward Titchener and Wilhelm Wundt in Europe (Hergenhahn & Henley, 2014).

[2] It is important to not confuse the functionalism of Dewey and James with the "functionalism" of twentieth century philosophy of mind, namely, a theory about the nature of mental states, defined by what they do (e.g., pain is defined along the following lines: If bodily damage is detected and unwanted, then remove that body part from the source of damage) rather than by what they are made of (e.g., neurons; Putnam, 1975).

[3] Claire Michaels and Claudia Carello go to great pains to explain what "direct perception" means to ecological psychologists, and attempt to dispel with a naïve interpretation. As they state:

"We certainly do not mean 'direct' as in the 'unmediated' phone-to-phone example cited; that is, we do not go along with Plato's notion that objects can be directly apprehended without reference to the senses. Rather we mean that the structure of environmental objects and events as they relate to a behaving animal is preserved in the energy patterns stimulating perceptual systems. The converse of this view, which we have attributed to more traditional theories, is that the structure of environmental objects and events is lost (in the light or at the receptor surface or in the stimulation) and must be restored by the brain" (Michaels & Carello, 1981, p. 184).

[4] The full quotes are worth reading in full:

"Gibson tends to leave the organism, if not empty, apparently stuffed with foam rubber" (Pribram, 1982, p. 370).

"J. J. Gibson's theory of perception, for instance, seems to treat the whole visual system as a hunk of wonder tissue, for instance, resonating with marvelous sensitivity to a host of sophisticated 'affordances.'" (Dennett, 1984, pp. 149-150).

[5] For recent exceptions to this, see de Wit and Withagen (2019), Favela (2024), and Raja (2018).

[6] For a rare recent exception, see van der Weel, Sokolovskis, Raja, & van der Meer (2022).

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[7] A reasonable concern can already be made about the current project: Why preserve the principles of Gibsonian ecological psychology, especially the more controversial principle that perception is direct (i.e., antirepresentational)? The current work aims to maintain these principles for five reasons. First, the NeuroEcological Nexus Theory (NExT) is intended to be part of ecological psychology. As such, it attempts to preserve that which makes an investigative approach "Gibsonian," namely, to abide by the four principles. Second, and conversely, if NExT did not attempt to maintain the four principles, then it would not be "ecological" in the sense highlighted in the current work, namely, Gibsonian *ecological* psychology. Third, if it is true, as claimed above, that ecological psychology was a major influence on the broader category of situated approaches, then maintaining the principles of ecological psychology via NExT ought to preserve what was appealing about the Gibsonian approach and may thus make NExT appealing to other situated approaches as well. Fourth, if it turns out that NExT is not compelling, then it could be due to any or all of the four principles. Conversely, if NExT is compelling, then that would be further support for said principles. Finally, and regarding the specific principle that perception is direct and its related commitment to antirepresentationalism, there are reasons to view the concept of representation as unnecessary to both experimental work and theorizing—especially concerning perception-action—even in the neurosciences. One reason comes from experimental work suggesting that the concept of representation plays unclear and confused roles in the neurosciences (cf. Favela & Machery, 2024; also see Favela & Machery 2025a, 2025b, and related commentaries by Rosa Cao, Frances Egan, and John Krakauer). Another reason is that the concept of representation may not be necessary to explain at least some brain activity (e.g., motor control; e.g., Shenoy, Sahani, & Churchland, 2013). Consequently, approaching perception-action as direct (i.e., nonrepresentational) may not be viewed as quite so controversial after all.

[8] A fuller explanation of NExT is provided in Favela (2024). There, NExT is defined by six hypotheses. The sixth hypothesis is not crucial for the current work.

[9] Admittedly, the claim that "the organism-environment system is the privileged spatiotemporal scale of description to understand cognizing" lends itself to misinterpretation. Moreover, it seems, at first glance, contradictory to the last sentence in the same paragraph: "cognitive phenomena are *multiscale* in nature." How can a phenomenon have a privileged scale of description *and be* multiscale? The two claims are not contradictory if one is viewed as primarily an epistemic claim and the other metaphysical. The first statement is intended to be epistemic, that is, from the perspective of NExT, cognizing (i.e., intelligence, mind, etc.) is fruitfully approached from the perspective that organisms act in environments for ends such as fighting and reproduction. As such, while understanding such phenomena can involve investigations at "smaller" (e.g., immune system) or "larger" (e.g., city) spatiotemporal scales, such work must be in the service of illuminating how those scales contribute to the cognizing event (e.g., affordances). The second statement is intended to be metaphysical, that is, from the perspective of NExT, cognizing organism-environment systems are caused and constituted by features at multiple scales (e.g., ambient temperature, cells, etc.).

[10] It could be argued that that the neural manifold approach looks a lot like typical work by computational cognitive neuroscientists (CCN). In the sense that CCN utilizes computational methods like modeling, then it is true that CCN and NExT overlap. However, a more substantial

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difference is clear when the theoretical commitments of the CCN are highlighted, especially if they understand the brain as *being* a computer. Within NExT, brains are not computers, at least not in any substantial sense (e.g., Turing machine). If the CCN researcher merely means that brain processes with regularities, then NExT accepts that the brain is a "computer." One way to think about how CCN and NExT differ is that they have radically distinct *motifs*, or guiding ideas that characterize their work (Raja, 2024).

[11] It is worth drawing attention to the fact that others have attempted to integrate considerations of situatedness in neuroscience without adhering to the principles of ecological psychology—especially the first, that perception is direct—and do so without eliminating concepts like computation and representation (for an illustrative example, see Piccinini, 2018, 2022, 2024).