

The emergence of systematicity in minimally cognitive agents

Paco Calvo¹, Emma Martín¹ and John Symons²
¹Universidad de Murcia
²University of Kansas

PREPRINT. Final version to appear in:

P. Calvo & J. Symons (Eds.), *Systematicity and cognitive architecture: conceptual and empirical issues 25 years after Fodor & Pylyshyn's challenge to connectionism*. Cambridge, MA: MIT Press.

Introduction

The honeybee bounces against the pane of glass, the moth circles the light bulb, and the dog chases its tail. Honeybees, moths, and dogs are each capable of a complex and interesting set of behaviors. But sometimes we notice animals failing to accomplish their goals and being unable to adapt their behavior successfully in light of their failures. At moments like these it is natural to think less of the family dog, the honeybee, or the moth. This is not one of our dog's more impressive moments and while the dog is not a stupid creature, chasing its tail certainly appears to be a stupid behavior.

When a behavior is obviously automatic, repetitive, or arbitrary, we tend to downgrade the level of agency we ascribe to the animal or system in question. By contrast, when a system adapts to changing environmental conditions, contributes to the pursuit of some identifiable goal, can be combined in flexible ways with other behaviors, and has a variety of other systematic features, we are inclined to judge that the behavior is the result of some underlying intelligence or agency.

This chapter suggests that our intuitive judgments about the underlying intelligence or agency of non-linguistic cognitive agents are prompted by a set of systematic features that mark what we will call *intelligent behavior*. These systematic features of intelligent behaviors do not necessarily license the claim that there is any single coordinating or governing intelligence in the agent. However, we will argue that intelligent behavior is indicative of meaningful engagement with the environment. This meaningful engagement is phylogenetically and ontogenetically prior to the kinds of intellectual and cognitive capacities that we expect from adult humans.

In the pages that follow, we will explain what it means to locate systematicity in the behavior of infra-linguistic and minimally cognitive agents. Along the way, we will unpack the idea of meaningful engagement with the environment and will offer some ideas as to how such engagement might serve as the basis for the emergence of more sophisticated forms of cognition and agency.

Systematicity

Jerry Fodor, Zenon Pylyshyn, Brian McLaughlin and others argued that the productive and systematic features of thought should be explained in terms of a combinatorial system of mental representations with a syntactically and semantically classical character. They argue that since human language exhibits some essentially systematic features and since language is an expression of human thought, human thought must also have the systematic features we find in language. We can understand novel sentences when we hear them and can create new meaningful sentences by combining the parts of old meaningful sentences according to those systematic transformations we associate with competent use of a natural language. If one can genuinely understand the sentence "Carnap likes Quine" then one can understand the sentence "Quine likes Carnap". The fact that such transformations pose no challenge to the intelligence of adult humans is taken as evidence that thought itself has the same structure as language.

Competing approaches to the Fodorian model of mind included the view that thought works as a series of images, or that it has the same structure as action, or that thought is brain-like in the sense of being organized in a network. From the Fodorian perspective, all of the major alternatives failed to provide the explanatory power of the assumption that there exists a syntactically and semantically combinatorial system of mental representations.

As many cognitive scientists and philosophers argued in the 1990s, alternative cognitive architectures may also be able to produce behaviors that mimic the systematic features of human language.¹ However, for proponents of a Fodorian view of systematicity, merely being

¹ Notable early proposals are those of Smolensky (1987; 1990), who took issue with the challenge by exploiting microfeatural descriptions and tensor product variable binding for the purpose of modeling weaker and stronger forms of compositionality, respectively; Chalmers (1990), who modeled structure-

able to reproduce systematic properties is not the purpose of a science of cognition. The real goal is explanation rather than simulation and from the Fodorian perspective, a classical computational architecture provides the best path towards an *explanation* of mind insofar as the classical framework, like cognition and language, is systematic to the core.

Fodorians argue correctly that explaining the nature of human thought surely involves giving some account of its systematic features. However, the exclusive focus on linguistic systematicity has meant that other forms of systematicity have been neglected. So, for example, Robert Cummins pointed to the systematic features of visual perception as an example of a non-linguistic form of systematicity that also seems important to a full understanding of perception and associated aspects of human thought. (1996)

Our view is that we ought to extend Cummins' insight beyond perception, and we argue that systematicity can also be found in the behavioral repertoire of agents. The kind of systematic properties that we target are those that distinguish intelligent, adaptive behaviors from automatic, non-adaptive behaviors.

Very roughly, at this stage, we can intuitively recognize the difference between the way a wolf stalks its prey and the way that the wolf's stomach digests its prey: In a Dennettian spirit, one might say that understanding and explaining the hunting behavior of a wolf involves adopting something like an intentional stance towards the behavior whereas understanding processes in the digestive system does not. (Symons 2002) In the pages that follow, we focus on cases that fall somewhere in between fully automatic physiological processes and fully-fledged intentional action. The kinds of simple behaviors that we will discuss in this chapter are those exhibited by plants and other minimally cognitive agents.

Some biological processes, say the excretion of bile or the rhythm of a beating heart adapt to changing environments in a manner that reliably comports with the goals of an agent and yet, such processes do not warrant the honorific 'intelligent.' As mentioned above, automatic processes of this kind differ intuitively from the actions of intelligent agents insofar as they can be explained without reference to intentional content. So, how should we understand the transition from automatic processes to fully-fledged intelligent behaviors? The behavior of a plant shares some features in common with digestion while bearing some resemblance to the kind of intentional cognitive lives of animals like wolves and human beings. Examples of sophisticated plant behavior straddle the line between automatic physiological processes and systematic cognitive (albeit minimally cognitive) phenomena. These strike us as obvious opportunities to investigate the emergence of meaningful engagement with the environment.

The greatest strength of the Fodorian approach to systematicity was its careful attention to explanation. Rivals should also have an account of what is required for an account to qualify as genuinely explanatory in the cognitive or psychological domain. In this chapter, we propose taking a neo-Gibsonian approach to the explanation of behavioral systematicity. However, the target of explanation is different for us than it is for the Fodorian. Our goal is to provide an explanation of the *emergence* of systematic intelligence per se rather than providing a defense of a particular cognitive architecture. On our view, arguments concerning the virtues of cognitive architectures can be distinguished from arguments concerning explanation. Recognizing the distinction is likely to benefit progress on both topics.

On our view, explaining the emergence of intelligent behavior requires attention to marginal cases of behavioral systematicity in minimally cognitive agents like plants and insects rather than beginning with the linguistically-mediated cognition of adult human beings. To this end, we critically review some recent work coming from the field of 'plant neurobiology' for the purpose of determining whether the ecological perspective can account for the behavioral systematicity that interests us in plants and other minimally cognitive agents. The approach we present here offers a framework for a naturalistic account of the emergence of intelligent behavior over the course of natural history, and we hope that explaining the systematic features of the behavior of plants and insects can provide the basis for understanding systematicity in more familiar kinds of cognitive systems.

sensitive operations on Recursive Auto-Associative Memories (RAAM –Pollack, 1990); and van Gelder, who distinguished between functional and concatenative compositionality.

Minimal forms of cognitive agency

Common sense tells us that plants are unlikely to qualify as cognitive in any meaningful sense. One reason for this is the impression that plants do not really do much. Since plants generate their own food from light or other energy sources they move on a timescale than is normally imperceptible to animals.² Cognitive scientists and philosophers have assumed that there must be a strong connection between movement and cognition. Thus, Patricia Churchland represents the traditional view of plant intelligence as follows:

If you root yourself in the ground, you can afford to be stupid. But if you move, you must have mechanisms for moving, and mechanisms to ensure that the movement is not utterly arbitrary and independent of what is going on outside. (1986, p. 13)

elsewhere, she writes:

... first and foremost, animals are in the *moving* business; they feed, flee, fight, and reproduce by moving their body parts in accord with bodily needs. This *modus vivendi* is strikingly different from that of plants, which take life as it comes. (2002, p. 70)

Plants are usually slow moving, but are they stupid? Time-lapse photography has permitted plant researchers to notice non-programmed forms of movement triggered by differential changes in volume or in rates of growth. For example, consider the light-foraging behavior of the stilt palm (Allen, 1977); a plant that grows new roots in the direction of sunlight, letting the older ones die. In relation to light-foraging behavior of this sort, Anthony Trewavas (2003) writes:

the filiform stem explores, locates and recognizes a new trunk and reverses the growth pattern. As it climbs, the internode becomes progressively thicker and leaves progressively redevelop to full size... This behaviour is analogous to animals that climb trees to forage, intelligently descend when food is exhausted or competition severe, and then climb the next tree. (p. 15)

Apparently the stilt palm is not taking life as it comes. In addition, *pace* Michael Tye and others, we now know that the behavior of plants is often flexible.³ Strikingly, plants appear to learn from experience, not by modifying their ‘dendrites’, but rather by developing plasmodesmatal connections. (Trewavas, 2003) Goal-oriented over-compensatory growth, oscillations in gravitropic behavior and acclimatization under different forms of stress are well-studied illustrations of error-correction and learning in plants.

Our ignorance of the capabilities of plants has given way to the view that many plants do not simply sit passively photosynthesizing. Instead, plants can adapt in ways that may lead to an advantage in the future based on an assessment of current conditions. Plants can respond to soil structure, volume, and neighbor competition in ways that are advantageous to them. We now know of several examples of plant behavior that can be interpreted as territorial and that

² The obvious exception being the familiar behavior of the Venus Flytrap and the Mimosa.

³ Michael Tye dismisses any talk of plant intelligence by claiming that it is entirely genetically determined and inflexible: “The behavior of plants is inflexible. It is genetically determined and, therefore, not modifiable by learning. Plants do not learn from experience. They do not acquire beliefs and change them in light of things that happen to them. Nor do they have any desires.” (1997, p. 302)

plants can discriminate their own roots from alien roots.⁴ A number of examples of interplant communication have also been documented. Some plants communicate aerially with conspecifics and members of different species via a number of released volatile organic compounds that cause changes in the behavior of their conspecifics.⁵ Most famously, the physiological processes underlying the collective response of acacia trees to being eaten by giraffes, are well understood.⁶

Insights into the adaptive behavior of some plants have encouraged the development of a controversial field calling itself “plant neurobiology”. Plant neurobiologists induce considerable discomfort in many of their colleagues when they use terms like *communication*, *planning*, *navigating*, *discriminating*, *perceiving*, and *remembering* to describe plant behavior. According to plant neurobiologists, higher plants have physiological processes that are analogous to animal nervous systems. They argue that these systems allow plants to act in intelligent ways.⁷ But concerns immediately arise. Can the adaptive behavior of plants be considered cognitive in any meaningful sense? It is easy to find examples of plant neurobiologists providing inappropriately high-level cognitive explanations for the behavior of plants. Furthermore, many mainstream plant biologists have criticized plant neurobiology, describing it as “founded on superficial analogies and questionable extrapolations.” (Alpi et al., 2007).

On our view, the reasons that careful observers of plant behavior are tempted to use anthropomorphic language stems from the systematic features of plant behavior. In the behavior of plants, we see the first infra-linguistic glimmerings of the kind of intelligence that we see in higher animals. We now know that the behavior of plants, specifically their movement and the changes we detect in their morphology are often flexible, and non-automatic. For the most part, this behavior takes place very slowly, but with the benefit of time-lapse photography, we can clearly see how some plants respond to change in ways that solve problems in dynamic and competitive environments.

An objection to our approach would be to deny that there is anything *cognitive* associated with plant behavior. Admittedly, we set the bar low for the purposes of this chapter insofar as we consider *motility* and the possession of a dedicated *sensorimotor organization system* as sufficient conditions for minimal cognition. Minimal cognition initially consists of exploiting the spatiotemporally dispersed characteristics of metabolically relevant environmental features. This is achieved courtesy of free and reversible bodily movement and is enabled by organized sensorimotor activity.⁸ Plants may be taken to exemplify minimal cognition insofar as they manipulate their respective environments in meaningful ways.⁹

Our goal for the remainder of this chapter will be to show that these systematic features of behavior can be fruitfully understood in Gibsonian terms in a way that illuminates the meaningful interaction of the plant and its environment.

⁴ Chemical and electric signaling belowground (Schenk, Callaway, & Mahall, 1999) underlies root segregation, something that involves a form of self-recognition (roots must make decisions as to how to segregate), and amounts to a competitive form of territoriality.

⁵ This has been popularized as “talking trees”, or more aptly as “eavesdropping” (Baldwin et al., 2006).

⁶ For a review of plant biochemical warfare against the herbivore, see Mithöfer and Boland (2012).

⁷ Trewavas (2003) observes that a number of forms of plant memory “can be recognized by the ability to interact with, and modify, the transduction pathways to new signals... A more complex form of memory requires information storage of previous signalling, with the ability to retrieve the information at a much later time. Both forms occur in plants” (p. 7). As to plant learning, Trewavas (2003) notes that “Wild plants need trial-and-error learning because the environmental circumstances in which signals arrive can be so variable... Indications of trial-and-error learning can be deduced from the presence of damped or even robust oscillations in behaviour as the organism continually assesses and makes further corrections to behaviour” (p. 4).

⁸ Traditional anti-behaviorist considerations (Chomsky, 1959) do not pose a challenge to our account of minimal cognition insofar as dedicated sensorimotor organization and navigational capacities are globally organized.

⁹ Arguably, plants possess a far broader repertoire of cognitive capacities than those we discuss here. For elaboration of this proposal see Calvo & Keijzer (2011), and references therein.

The behavior of plants is intelligent insofar as it is engaged with the environment in ecologically meaningful ways. But unpacking precisely what it means to call something “ecologically meaningful” is a non-trivial challenge. Why would we even feel tempted to invoke notions like meaning in this context? Let’s consider an example: When we observe a vine in time-lapse photography exploring its environment we notice that its behavior has a systematic structure. Consider its ability to reach for a surface, test its suitability, withdraw if unsuitable, adjust its position slightly, and then to repeat the behavior as necessary. The intuitive sense that the plant is striving or has a plan, etc. is obviously anthropomorphic. However, this intuitive reading of the plant’s behavior is our response to the visual evidence that plants must cope with a dynamic landscape of threats and opportunities in their environment. While time-lapse photography allows us to notice plant behavior, and plant physiology can reveal the mechanisms at work in the plant, explaining the apparent meaningfulness and intelligence that is exhibited in plant behavior requires a different approach. We suggest that we can understand the intuitive meaningfulness of plant behavior by attending to ecological principles without thereby falling prey to anthropomorphism.

Fodorian objections to the ecological approach

Systematicity is a characteristic feature of intelligent behavior. The source of this systematicity is the manner in which the organism engages with its environment. When an organism acts, it will do so for metabolically relevant reasons. We assume that if a given organism has the ability to acquire a metabolically relevant piece of information from its environment, it will thereby acquire a variety of systematically related patterns. On our view, even at the lowest-levels, metabolically relevant patterns have systematic features. These systematic features of behavior are integral to the agent’s capacity to respond selectively to a changing environment. Systematically organized patterns in behavior and the environment are precisely what supports the agent’s capacity to freely and reversibly navigate its local environment. Getting clear on what we mean by “metabolically relevant” information and why a Gibsonian perspective is helpful here, is the central task of this section of the chapter.

In order to meet the charge of anthropomorphism, our account of systematicity in minimally cognitive systems must demonstrate that it does not rely on some prior cognitively-penetrated system of relations. On our view, the emergence of higher-level cognition depends on systematic features in behavior and the environment. (See Symons 2001) We contend that inquiry into the mechanisms that underlie the minimally cognitive capacities that are necessary for navigating environments containing metabolically relevant information will provide an account of how systematicity first appears over the course of natural history.

Following Fodor, philosophers have been very suspicious of claims like ours. During the 1980s, Fodor and Pylyshyn criticized Gibson’s account of perception before moving on to criticize connectionist cognitive architectures later in the decade. Their classic 1988 paper “Connectionism and cognitive architecture: a critical analysis” argued that the only way for connectionist theory to account for the systematicity of thought is by committing itself to a classical combinatorial structure. Their 1981 paper “How direct is visual perception: some reflections on Gibson’s ‘ecological approach’” argued that the only way for ecological theories of perception to account for vision is by allowing for cognitive penetrability in the form of inferential processing.

Their 1988 paper addresses the possibility of a representational realist alternative to a classical model of the mind. In their 1981 paper, they criticized the possibility of a non-representational alternative to a constructivist theory of perception. The ecological counterpart to representation and perceptual processing are information pickup and perceptual resonance, respectively. The connectionist counterparts to propositional, context-independent forms of representation and computation are context-dependent, vectorial representations and vector-to-vector transformations, respectively.

In what follows we read Fodor & Pylyshyn’s criticism of non-classical cognitive architectures and their criticism of ecological theories as related defenses of a classical

computational model of mind. Both lines of criticism challenge competitors to demonstrate how non-classical alternatives could provide explanations of genuinely cognitive phenomena. As we shall see, shifting from the systematicity of thought to the systematicity of overt behavior allows an alternative explanatory framework that circumvents some of their concerns.

It is helpful to briefly introduce Gibson's theory of perception by contrast with the classical view before arguing for the applicability of Gibsonian ideas to the systematicity of behavior. Theories of perception can be divided roughly into those that are congenial to some form of Helmholtzian constructivism (Rock, 1983) and those that adopt an ecological approach (Gibson, 1979). Proponents of the former regard perception primarily as the outcome of a logic-like process of inference, whereby perception is hypothesized to be mediated or indirect. Following the Gibsonian lead, ecological theories of perception assume that an agent's perception is organized around its actions. Opportunities for action are perceived directly by agents as they interact with their local environment.¹⁰

The two core principles of Gibsonian psychology that we stress are the *specificational* account of information and the idea that *affordances* are what is perceived by agents.¹¹ The notions of specification and affordance play a technical and idiosyncratic role in Gibson's thought so we shall introduce them first. When properties of the world match unambiguously the patterns of ambient energy arrays available to a perceptual system, the latter serve to *specify* the former. Matches of this kind result from constraints that operate at an ecological scale between the agent and its environment. This is the most obvious contrast with constructivists for whom there is an inherently ambiguous relation between the pattern in the energy array and the world. The assumption that this ambiguity must exist is precisely the reason that traditional constructivist theories call for an inferential treatment of perception.

How do Gibsonian theories explain visual perception without recourse to inferential processes? The optical variable tau (τ) (Lee, 1976) provides a canonical illustration of the way information of optic arrays specifies properties of the environment unambiguously. Consider the distance between a car and an intersection as the driver approaches a stop sign. How does the driver judge when to apply the brakes to stop the car? What type of information can the driver rely on? One answer is provided by tau theory. David Lee defines tau as the inverse of the relative rate of expansion on the retina of an incoming object (e.g., a traffic sign).¹² In this way, the ecological psychologist treats tau as an optical invariant insofar as it specifies time-to-contact, not just between driver and stop sign, but between any animal and the object in its vicinity in terms of rate of retinal expansion in the direction of motion. Presented formally,

$$\tau = \theta / (\Delta\theta / \Delta t)$$

where θ stands for the angular size of the incoming object, and $\Delta\theta / \Delta t$ for the image's rate of expansion, as projected into the eye. The ecological psychologist's working hypothesis is that the optic flow field that obtains in the changing ambient optic arrays during navigation permits the agent to grasp the rate at which action-gaps are closing. (Lee, 1998) In our example, a tau-theoretic approach does not demand articulation in terms of the agent's beliefs concerning the actual speed of the car or the size of the signal.¹³

The second major principle of ecological psychology is the idea that we perceive affordances. Gibson explains affordances as follows:

¹⁰ For an introduction to Helmholtz's theory of perception in the context of the early history of experimental psychology, and to some of the theoretical problems in the field of perception, see Kim (2009). A good entry point to the direct perception approach is Michaels & Carello (1981).

¹¹ For further discussion of specification and affordances in Gibson see Richardson et al 2008.

¹² For general criticism of tau theory that we ignore for present purposes, see Tresilian (1999).

¹³ Most traditional work in cognitive science has assumed that information processing tasks in visual perception must be articulated in terms of an inferential process. David Marr, for example, argued that the principal failure of the ecological theory of perception was its inability to grasp the actual complexity of visual perception. Tau theory provides reason to believe that some perceptual tasks might be simpler than Marr believed. For more on the issue of the complexity of information processing, see Symons (2007)

The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill. The verb to afford is found in the dictionary, but the noun affordance is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment. (1979, p. 127)

By contrast, from a Helmholtzian perspective, agent-independent variables, such as (absolute) distance, size or speed, serve as the basic building blocks of perception. On this view, we perceive the distance to an object or its size and subsequently infer the object's availability for some action. By contrast, affordances are ecological properties meaning that they are individuated by reference to the agent. Compare the ecological property of being reachable to the physical property of being 1 meter in length. Affordances are 'opportunities for behavior'; properties of the local environment that permit agents to interact in ways that are relevant to the agent itself. The availability of an object for grasping is a property that makes no sense apart from the relation to an agent.

Ecological theories of perception take their start from the notion that what a biological agent perceives depends initially at least on the aspects of the environment that are relevant for it. More specifically, on those aspects of the environment that are available for biologically relevant interactions. We perceive by directly resonating with informational invariants that specify opportunities for behavior in the form of affordances. Different biological agents will perceive different affordances; different opportunities for behavioral interaction within their respective environmental niches.¹⁴

Having outlined some of the central tenets of Gibson's view in very broad strokes, we are ready to turn to the objections. Ecological psychology is widely criticized as failing to do justice to the explanatory role played by systematic features of cognition. Consider speech perception, in particular the debate over 'rule learning' in infants. Marcus et al. (1999) performed a series of experiments with 7-month-old infants. After having exposed them for 2 minutes to strings of artificial syllables conforming to a simple grammar—e.g., "le le di", "ga ga li", etc., from an AAB grammar, or "wi je je", "ga li li", etc., from an ABB one—infants' speech perception skills were tested by analyzing their listening preferences for pairs of novel strings, one of which belonged to the same category they had been habituated to—e.g., "wo wo fe" (AAB) vs. "wo fe fe" (ABB). The results show that infants listen longer to those that did not conform to the pattern they had been exposed to during habituation.¹⁵

Marcus et al. interpret their results as showing that infants exploit abstract knowledge that allows them to induce the implicit grammar common to different sequences of syllables:

We propose that a system that could account for our results is one in which infants extract abstract-like rules that represent relationships between placeholders (variables) such as 'the first item X is the same as the third item Y' or more generally that 'item I is the same as item J'. (Marcus et al., 1999, p. 79)

Connectionist responses focused on the possibility that an associative learning mechanism might induce *sameness* out of the statistical dependencies between syllable tokens in the linguistic corpus. (Elman, 1999) Their working hypothesis was that infants might be exploiting discrepancies based on expectations in order to make successful predictions in accordance with

¹⁴ It is important to note then that with (unambiguous) direct perception requirements in terms of memory storage drop dramatically. Information does not need to be stored temporarily for the purpose of inferential information-processing. The direct pick-up of informational invariants in the ambient light serves to explain visual perception. According to ecological psychology, organisms pick up invariants and 'resonate' to (i.e., transduce) the ambient properties that they specify. The Gibsonian task then is to discover the type of information that is specificational for the non-inferential resolution of the perceptual problem in question.

¹⁵ See Marcus et al. (1999) for the details, and Gerken and Aslin (2005) for a review of the language development literature.

Marcus et al.'s data. If connectionist networks were to do so associatively, without recourse to universally open-ended rules, or to devices that store particular values of variables to perform variable binding, no classical implementation would be required.¹⁶ (Calvo & Colunga, 2003)

Likewise, the ecological psychologist may frame the challenge of explaining how infants perceive speech in terms of the *direct* perception of *sameness*-related properties. After all, the class of artificial syllables in Marcus et al.'s experiments corresponds to a set of objects in the infant's environment. We may thus try to make sameness available in the form of parameters that specify the property of 'item I belonging to the same set as item J'. Being an empirical matter, an infant's perceptual systems could in principle resonate to any such property. Certainly, the Gibsonian may conjecture, the resonator in question might be a complex one, but so be it.

A combined reading of the two papers by Fodor & Pylyshyn mentioned above (1981; 1988) provides the arguments against the possibility that sameness is transduced in this way. According to Fodor & Pylyshyn (1988):

Connectionist theories acknowledge *only causal connectedness* as a primitive relation among nodes; when you know how activation and inhibition flow among them, you know everything there is to know about how the nodes in a network are related. By contrast, Classical theories acknowledge not only causal relations among the semantically evaluable objects that they posit, but also a range of structural relations, of which constituency is paradigmatic. (p. 12)

On the other hand, as Fodor & Pylyshyn (1981) observe:

The reason that productive properties are *prima facie* not transduced is that, in many of the most interesting cases, membership in the associated set is inferred from a prior identification of the internal structure to the stimulus. (p. 177)

Swap "classical" and "connectionist" for "constructivist" and "ecological psychology", and "nodes" and "network" for "transducers" and "organism", respectively; bear in mind that a combinatorial syntax and semantics for mental representations and structure-sensitivity of processes operates as a constraint on candidate mechanisms,¹⁷ and the challenge takes the following form: Given that ecological psychology only acknowledges causal connectedness as the relation of transduction in the environment-organism coupling, these systems face the challenge of explaining how properties that are relevant to systematic features of behavior are transduced. Specifically, for example, how can sameness be directly perceived, without resorting to a prior internal structure of some sort that allows for the identification of membership itself?

The ecological theorist of perception acknowledges only causal relations among the meaningful opportunities for behavior that they posit in the form of affordances—in the form of the direct relation of interaction that obtains between organism and environment when observed at the appropriate ecological scale. From a Fodorian perspective, the ecological theorist of perception turns a blind eye to any *internal* structural relations and as such, the approach fails to deliver the kind of structural richness available to classical computational models. Were we to target ecological parameters that specify sameness non-inferentially, the Fodorian would complain that we have not provided an explanation as to how productive or systematic properties obtain.

¹⁶ Although for a skeptical appraisal of the alleged success of connectionism, see Marcus (2001).

¹⁷ To wit: "In particular, the symbol structures in a Classical model are assumed to correspond to real physical structures in the brain and the combinatorial structure of a representation is supposed to have a counterpart in structural relations among physical properties of the brain. For example, the relation 'part of', which holds between a relatively simple symbol and a more complex one, is assumed to correspond to some physical relation among brain states" (Fodor & Pylyshyn, 1988, p. 13).

There are a number of responses to this line of argument. One of us has explored the idea that arguments against ecological approaches that appeal to the complexity of some information processing task sometimes proceed with a different explanatory project in mind than Gibson's. (Symons 2001, 2007) Another general line of response is to see Fodorian criticisms as due to an unwarranted concern with the linguiform structuring of higher cognitive abilities. Linking cognitive phenomena to speech perception and similar cognitive tasks begs the question against non-classical alternatives insofar as non-classical approaches would regard language level systematicity as an achievement for an agent rather than a precondition for cognitive agency.

The critical issue here is clearly the question of the target of explanation. As is well known, the Fodorian perspective denies that there is an extralinguistic source of explanation for linguistic capacities. However, if we hope to explain the emergence of systematicity per se, then we will need to shift our focus from higher level cognition to non-human, infraverbal, minimal forms of cognition.¹⁸ In the sections that follow, we will explain the kinds of systematic features of behavior in minimally cognitive agents that we believe can serve as the scaffolding for the kind of linguistic systematicity that interested Fodor et.al in the 1980s and 90s. Once again, the target of explanation is the emergence of the kinds of systematic features that are exhibited by intelligent behavior.

A Neo-Gibsonian approach to minimally cognitive agents

We propose what we are calling a neo-Gibsonian response to Fodor & Pylyshyn's challenge.¹⁹ In this section we elaborate on the principles of 'general tau theory' (Lee, 2009) to give form to a neo-Gibsonian approach to the systematicity of behavior in minimally cognitive agents.

General tau theory (Lee, 2009) is a theory of the *skilled* control of goal-directed movement. The chief concern of tau theory is the control of movement as a system interacts with objects in its local environment. This requires the control of 'action-gaps' between a given current state and the desired goal state. The closure of action-gaps has been studied extensively, with general tau theory serving to account for such varied phenomena as the visual control of braking or steering by drivers (Lee, 1980), of diving by gannets (Lee & Reddish, 1981), or of docking on feeders by hummingbirds (Lee et al., 1991). These are examples of the 'time-to-collision' problem (Lee, 1976). What unites these apparently disparate phenomena is the coordinated control of action-gaps, and in these cases, tau is the informational variable that underlies goal-directed behavior.

According to general tau theory, for a movement to be *goal-directed* the agent must be able to control the action-gap between the current state of the system and a goal state. The ecological variable tau is the informational currency for the purpose of the controlling action-gaps. The tau of an action-gap can be sensed courtesy of a corresponding sensory-gap (Lee, 2009). As we saw earlier, direct sensing of the surrounding optic flow-field by a driver's perceptual system provides a canonical example. This is also how a gannet, as it dives into the ocean is capable of retracting its wings at the appropriate moment (Lee & Reddish, 1981).

In addition, general tau theory explains the coordinated control of two different action-gaps, X and Y, via the *coupling* of their respective taus. A canonical example of tau-coupling is provided by the way we can intercept with our hand (H) a given target (T) at a certain goal (G), via the maintenance of a constant proportion between the taus corresponding to the two action gaps: $\tau(HT) = k\tau(HG)$ (see Lee, 1998). Or consider, for the sake of illustration, two boats

¹⁸ The shift is strategic, as will become apparent below. Other than linguistic systematicity being a canonical illustration, there is no intrinsic connection between natural languages and the systematicity of thought to be found. McLaughlin (1993), for instance, explores systematicity in non-human animals. See also Aizawa (this volume).

¹⁹ "Neo-Gibsonian" insofar as Gibson himself would not have accepted an application of ecological theories of perception to minimally cognitive agents like plants. We briefly touch on Gibson's objections below.

moving in the sea at constant speeds along linear paths. Will the two boats collide with each other at a future time? This question may be approached ecologically by considering whether the two motion gaps, corresponding to their respective trajectories towards the hypothetical point of collision, close simultaneously or not. Were they to close simultaneously, courtesy of the maintenance of a constant ratio over a period of time, the two boats would enter into a collision trajectory. Note how drastically a tau-coupling based gloss differs from constructivist attempts to describe the closure of action gaps. In Fauconnier & Turner's (1998) 'network model of conceptual integration', for instance, cognitive integration ("blending") would underlie the inferential capacity to control action gaps, X and Y. Mark Turner vividly illustrates it with the metaphor of a 'shrinking triangle'.²⁰ We could imagine the two boats and the hypothetical point of collision forming an imaginary triangle. For the two boats to collide with each other would translate into the imaginary triangles that would form at time t and a subsequent time steps, being proportional. Thus, were we to superpose the resulting proportional triangles and animate the image, we would 'see' a shrinking triangle that collapses into the point of collision. According to Turner, decisions involved in collision-avoidance call for a cognitive blend, as the shrinking triangle illustrates. But we need not rely on inferential treatment of any sort. General tau theory allows us to talk in terms of the coupling of the taus of different action-gaps, and this is information that is specificational. Simultaneous closure delivers the goods *directly*.²¹

General tau theory serves to provide form and constraint to a neo-Gibsonian theory of minimal cognition. According to the ecological theory of perception introduced thus far there are invariant properties of objects in the environment that, when appropriately tuned to in terms of ambient energy arrays, result in direct perception. With a touch of analyticity, this is what Fodor & Pylyshyn have in mind when they read Gibson as meaning to say that:

for any object or event x , there is some property P such that the direct pickup of P is necessary and sufficient for the perception of x . (1981, p. 140)

Necessity and sufficiency aside, the issue boils down to the way to interpret 'ambient energy arrays' so as to bridge in between P and x , but there's the rub. Surely, the ecological psychologist has a clear picture in mind as to what 'ambient energy array' means. Nevertheless, and with apologies to the reader familiar with the specialized literature, we shall spell out our particular take in the form of a set of principles that will serve to ease out our neo-Gibsonian approach to minimal cognition. Starting with the less disputed principles, and moving in increasing order of controversy to the more contentious ones, the neo-Gibsonian theory of minimal cognition we propose is (i) not modality specific; (ii) includes intra-organismic properties; (iii) is substrate-neutral; and (iv) portrays perception as a function of the global ambient energy array. To these four principles we now turn.

- *A neo-Gibsonian theory of minimal cognition is not modality specific.*

For the purpose of introducing the ecological worldview we have focused thus far upon ambient *optic* arrays. However, there is ample evidence that information remains specificational regardless of the sensory modality involved. We may say that vision is only one facet of the question of action-gap closure. Considering a gap to be closed, such as the gap between a hummingbird and a feeder, its tau is the time needed to close it, to land on the feeder, at the current rate-of-closing. Likewise, the tau of a cell is the time needed to swim to a cathode by sensing electric fields at its current rate-of-closing (Delafield-Butt et al., 2013). Other tau-based studies include the steering bats perform courtesy of echolocation (Lee et al., 1995), and the gliding pitch between notes in expressive musical performance (Schogler et al., 2008). Illustrations abound. As Lee puts it:

²⁰ http://vrnewsscape.ucla.edu/mind/2012-05-03_Turner_Nutshell.html.

²¹ Tau-coupling also permits the intrinsic tau-guidance of action-gaps. Lee (2009) considers different guiding gaps, as the gap is closed with constant acceleration or with constant deceleration, as you speed up to hop onto the tram, or as birds dock on perches, respectively.

... to dispel a common misconception, tau is *not* the inverse of the rate of dilation of an optical image, any more than gravity is the apple falling on Newton's head. The apple falling is an example of the general principle of gravity. The image dilation is an example of the general principle of tau. (2004)

It is thus changes in the sensory gaps of any modality what informs as to which opportunities for behavioral output are present in the form of the closure of the action-gap in question.

- *A neo-Gibsonian theory of minimal cognition includes intra-organismic properties.*
The ecological psychologist distinguishes between ambience and environment. Ambience relates to the surrounded organism *and* the surrounding environment. In this way, the unity of interest is the reciprocity of the whole ecological scenario itself. Organism and environment are not detached, and in their interaction it is ambient (not environment) energy flows that count. However, once granted such reciprocal relation, a rather literal reading of Gibson's well-known aphorism—*It's not what is inside the head that is important, it's what the head is inside of*—preclude us from noting that direct ecological interaction between organism and environment, on the one hand, and intra-organismic, say, neural processing properties, on the other, are not antagonistic. With the emphasis on the relation between an organism and its surroundings it is easy to obviate that the ecological ambience does not need to be exclusively exogenous.

The neglect of endogenous ambience is clearly widespread among Gibsonians. A notably rare exception is Lee (2009). Affordances are neither external nor internal by necessity. Affordances are dispositional properties to close action gaps. We may then consider both endogenous and exogenous sources alike. The ecological ambience of a cell, or a population of cells, implies a reciprocity of the cell, say a neuron or a population of cortical neurons, and its surroundings, which may be the extracellular, cortical or subcortical, environment. Thanks to this, intrinsic guidance can take place. What counts is that information remains specificational, and not whether it is constrained by the scale of perception and action, or by the spatiotemporal scale of endogenous cellular processes.

- *A neo-Gibsonian theory of minimal cognition is substrate-neutral.*
Once the distinction between exogenous and endogenous ambiances is in place, it is important to note that intrinsic guidance need not be (exclusively) *neurally* based. This is often the case with the (neurocomputational) constructivist. Llinás and Churchland's (1996) concept of 'endogenesis', for instance, lays the stress in the fact that cognitive activity is the result of endogenous neural processes. But when the ecological psychologist decides to go inwards, the methodological constraint that operates is that the spatiotemporal scale of processes remains ecological, and not whether the substrate is neural or not. It may for instance be hormonal instead, granted that specificational information that can be detected for the purpose of appropriate resonance exists at the scale of hormonal processes. It is the fact that a property is appropriately defined at an ecological scale what counts. Bluntly, there is no reason why the neo-Gibsonian should be a neural chauvinist.
- *A neo-Gibsonian theory of minimal cognition portrays perception as a function of the global ambient energy array.*
According to our first principle, a neo-Gibsonian theory of minimal cognition is not modality specific in the sense that specification may take place in a number of energy arrays. Plausibly then, the specification of reality may not reside in a single ambient energy array. It is possible, however, that researchers have decided to focus upon the optic, instead of, say, the acoustic array simply on experimental or methodological grounds. In this way, a further twist comes with the idea that specification, unconstrained, may exist in the global energy array itself, in some higher-order format that cuts across sensory modalities (Stoffregen & Bardy, 2001). If there are intrinsic forms of tau-guiding action-gaps, we may be searching for transmodal integration via synchronous interactions between neurons; a process that under the hypothesis

that information is picked up from the global energy array itself could be couched non-inferentially. This would not be a radically innovative way of proceeding. Neuroscience is familiar with cross-modal integration (Kujala, 2001). What is at stake, rather, is the question whether there are transducers for global variables. This, despite Fodor & Pylyshyn's skeptical appraisal, is an open empirical question. Still, it is important to point out that, one way or the other, —whether specification is transmodal or unimodal—perception would remain unmediated.²²

As we saw at the outset of this section, Fodor & Pylyshyn (1981) stressed that the direct pickup of properties was both necessary and sufficient for the perception of objects and events, but questioned that ambient energy arrays may permit the specification of information in the form of affordances. In our view, the ecological link between properties and objects or events may be licensed or not as a function of the way we read 'ambient energy arrays'. According to our neo-Gibsonian reading, direct perception is a function of the global ambient energy array. This appraisal, combined with the lack of specificity with respect to modality, acknowledging intra-organismic properties, and an eschewal of neural chauvinism, sets the stage for assessing the plausibility of direct perception and behavioral systematicity in the remainder of the chapter. Direct perception is the emergent result of the organism-environment interplay. In the next section then we discuss the question of whether a neo-Gibsonian theory of minimal cognition may apply to plants.

Plants as perceiving and behaving organisms

Gibson did not believe that plants were capable of perception and he might have worried that our claim that plant behavior can be understood according to the principles of ecological theory of perception as equivalent to a reductio argument against his view.²³ However, contrary to Gibson's own view of the capacities of plants, if perception is understood in terms of resonance to specificational information then there is ample ground to argue that plants perceive. Plants are animate, move about, and have an internal system for organizing behavior that, in some important respects, is similar to the animal nervous system.²⁴ Circumnutation in climbing vines, a helical and rotational form of oscillatory movement already studied by Darwin (1875), provides one of the best well-known illustrations of the endogenously governed exploratory

²² The principle that information is specificational can be given a strong and a weak reading. The strong reading says that when a given pattern in the energy array bears a one-to-one correspondence to properties of the world, information is uniquely specified. On the weaker reading, the relation between ambient energy arrays and properties of the world may be many-to-one. That is, patterns of the ambient energy array may allow for the transduction of environmental properties in a manner that, although non-unique, is unambiguous with respect to properties of the world. Note that this weaker reading is all we need for perception, being a function of the global ambient energy array, to remain unmediated.

²³ Gibson did not regard plants as perceiving:

In this book, *environment* will refer to the surroundings of those organisms that perceive and behave, that is to say, animals. The environment of plants, organisms that lack sense organs and muscles, is not relevant in the study of perception and behavior. We shall treat the vegetation of the world as animals do, as if it were lumped together with the inorganic minerals of the world, with the physical, chemical, and geological environment. Plants in general are not animate; they do not move about, they do not behave, they lack a nervous system, and they do not have sensations. In these respects they are like the objects of physics, chemistry, and geology. (p. 7)

²⁴ This should appear obvious to many since the pioneering research on plants by Charles Darwin and his son. Despite, nevertheless, their groundbreaking work (*The Movements and Habits of Climbing Plants*, and *The Power of Movement in Plants*) it is difficult to make sense of the fact that conventional cognitive science has continued to ignore the perceptual and behavioral capacities of plants over a century later.

strategies of the surrounding environment performed by plants. Furthermore, the behavior of plants is often systematic in the sense of being reversible, non-automatic, and repeatable in a manner that responds to metabolically salient features of the environment.

Not all ecological theorists shared Gibson's dim view of the perceptual capacities of plants. In a reply to Fodor & Pylyshyn (1981), Turvey et al. (1981) consider from an ecological point of view *Monstera gigantea*, a climbing vine, whose seeds are able to perceive an affordance (climb-ability) skototropically, as they grow towards darkness. As we saw earlier, it was essential to distinguish between ambience and environment, the former being inherently relational with respect to perception-in-action. Consider how climbing plants (Isnard & Silk, 2009) can be understood as perceivers. Vines may well perceive Gibsonian affordances, possibilities for action, such as when a support is directly perceived as affording climbing. To understand climb-ability it is necessary to bear in mind that a vine and its support are functionally coupled subsystems. The vine should not be seen as a kind of organism that acts, by climbing, onto a separate kind of thing that is the support. As Gibson observes,

... the words *animal* and *environment* make an inseparable pair. Each term implies the other. No animal could exist without an environment surrounding it. Equally, although not so obvious, an environment implies an animal (or at least an organism) to be surrounded. (1979, p. 8)

Replacing “animal” for “plant”, we see that the rest of Gibson's claim holds in a relatively straightforward manner. Thus, a vine could not live without an environment that furnishes it with rocks, tree trunks, and all sorts of supports that are directly perceived as affording climbing. The complementarity of the plant and its vicinity means that the plant-in-its-environment serves as the proper unit of analysis.

On the other hand, we saw that action-gap closure is not only a matter of distance, but can also cover angle, pitch, frequency, etc., In addition to the well-studied case of vision, action-gap closure also figures in other modalities including haptics and echolocation, among others. It is thus ambient energy arrays of any form that can serve this purpose. Plants tune to a wealth of information beyond the vectors of light and gravity. In the case of plants, we cannot ignore forms of sensory input such as electrical, magnetic, chemical, or acoustical and vibrational. Consider plant bioacoustics, a field of research that informs us that plants may have benefited at an evolutionary scale from the perception of sound and vibrations (Gagliano et al., 2012). And yet, more intriguingly, there is evidence that plants even exploit bioacoustics to communicate with insects (Barlow, 2010). Overall, to the best of our knowledge, plants can sense, and integrate, up to 22 different biotic and abiotic vectors. (Trewavas, 2008) At first sight, then, if plants perceive, it seems there is no reason to exclude the possibility that direct perception takes place as a function of the plant's global ambient energy array.

We may furthermore dig deeper and address intrinsic guidance by plant structures, once we recognize the role of the plant's endogenous ambience. In fact, neuroid conduction (Mackie, 1970) applies to protists, plants and animals alike insofar as they all have non-neural cells with electric signaling properties. Thus, the fact that plants lack neurons is not a handicap from the ecological perspective.²⁵

Plant neurobiology (Brenner et al., 2006) has consolidated in the last few years as a discipline that studies plant behavior from the analysis of the integrated signaling and electrophysiological properties of plant networks of cells, with special attention to the involvement of action potentials, long-distance electrical signaling, and vesicle-mediated transport of auxin, among other phytohormones. As Baluška et al. (2006) point out:

Each root apex is proposed to harbor brain-like units of the nervous system of plants. The number of root apices in the plant body is high, and all “brain units” are interconnected via vascular strands (plant neurons) with their polarly-transported

²⁵ For a recent reinterpretation of the early evolution of nervous systems, and what they can do, that is congenial with our treatment of plants, see Keijzer et al. (2013).

auxin (plant neurotransmitter), to form a serial (parallel) neuronal system of plants. (p. 28).²⁶

If plant behavior is partly the result of endogenous non-neural processes, vascular strands and auxin correlates, we surmise, may serve to guide endogenously goal-directed climbing behavior towards tree trunks or other supports under the principles of tau-coupling and the intrinsic tau-guidance of action-gaps. Following the analogy with animal models, it may be the case that taus of auxin action-gaps underlie the type of hormonal information that directs tropistic responses in plants. Tau information may guide climbing, and plant neurobiology may well show that the type of activity that underlies sensorimotor coordination across the plant may also be tau-based.²⁷

A condition for minimal cognition was that the navigational capacities and sensorimotor organization were organized globally. The ‘root-brain’, a concept inspired in the discovery of the ‘transition zone’ (TZ) within the root-apex, may play an important role here. Plant neurobiologists consider TZ—the only area in plant roots where electrical activity/fields are maximal, and where electrical synchronization obtains (Masi et al., 2009)—to be a ‘brain-like’ command center (Baluška et al., 2004; 2009), with a polar auxin transport circuit underpinning patterns of root growth. TZ integrates not only hormonal endogenous input, but also sensory stimulation. Plant roots determine root growth that results in alignment or repulsion movements as a function of the global structure of its vicinity. We may then consider the role of the root-brain in the integration of sensorimotor pathways for the purpose of adapting flexibly as a number of global tropistic responses take place in the form of differential growth. We may thus take into account the role of the root-brain in the specification of plant-environment reciprocity, and plant perception as a function of the global ambient energy array. To think of perception as a function of the global ambient energy array may mean searching for TZ cells at the root-brain that respond selectively to the embracing activity, with invariants spanning across the vectors of gravity, light, and the like, on the one hand, and across endogenous hormonal stimuli, on the other.

Our hypothesis is that root-brains resonate to high-order invariants. This hypothesis is congenial not only with perception being a function of the global ambient energy array, but also with the other neo-Gibsonian principles described above. Note that, for convenience, we simplified matters by considering tropistic behavior as if triggered by energy arrays on a case by case basis. However, Gibson provided many different examples of lower- as well as higher-order invariants, among them, gravity (1966, p. 319) and the penumbra of a shadow (1979, p. 286). A more realistic portrayal should be amenable to multiple sources of perturbation. A possibility then is that TZ could be sensitive to structure in the global array directly, in the same way we have hypothesized animals are (Stoffregen & Bardy, 2001). In this way, we do not need to interpret synchronized firing at TZ cells as inferential processing. Rather, TZ cells, under the ecological lens, resonate to information from the global array. As we saw, there are intrinsic forms of tau-guiding action-gaps. Considering that interactions in the plant brain between TZ cells offers a way of integrating endogenous and exogenous information, affordances may be systematically perceived in terms of higher-level combinations of invariants.

Bearing this background in mind, we conclude this section with a consideration of honeybee behavioral systematicity by way of contrast. We then consider in the next section how to scale up from plant and insect direct perception and behavioral systematicity to human-level performance.

Having assumed that the globally organized exploitation of the environment by means of motility enabled by various sensorimotor organizations marks the borderline between purely reactive and minimally cognitive behavior, we may now assess the capabilities of insects as

²⁶ Alpi et al. (2007) complain that “there is no evidence for structures such as neurons, synapses or a brain in plants” (p. 136). For clarification, see Brenner et al. (2007) and Trewavas (2007).

²⁷ Here we have in mind directional responses, but the same ecological principles may hold in the guidance of non-directional (nastic) responses, such as the thigmonastic response of the Venus flytrap (*Dionaea muscipula*) and other carnivorous plants when they close their traps in response to touch.

they navigate their metabolically relevant environment, an intelligent form of behavior usually couched in constructivist terms. Consider the swarming behavior of honeybees (Visscher, 2003), where an individual contributes to the creation of a “spatiotemporal order characterized by the alignment of directions and maintenance of equal speeds and distances” (Ciszak et al., 2012). Honeybees can estimate and communicate distance and direction of hive-to-nectar and nectar-to-hive through the “waggle dance” (von Frisch, 1993). Abilities of this sort are not exclusive to bees. More generally, we may say that insects that are able to acquire a piece of information that is metabolically relevant, have the resources to acquire related pieces of information that are metabolically relevant too.

Can we account for the behavior of honeybees ecologically? At first sight, it may seem that we cannot. Peter Carruthers, for instance, claims that:

bees have a suite of information-generating systems that construct representations of the relative directions and distances between a variety of substances and properties and the hive, as well as a number of goal-generating systems taking as inputs body states and a variety of kinds of contextual information, and generating a current goal as output. (2004, p. 215)

This should remind us of Marcus’s take on infant speech perception. Bees, like infants, appear to exploit abstract knowledge that allows them to induce underlying regularities. This process appears to call for the implementation of operations defined over abstract variables algebraically. Constructivism appears again to be the default stance. To find both the nectar and their way back to the hive honeybees exploit directional data computationally by generating a spatiotemporal representation of the sun’s course (Dyer and Dickinson, 1994).

The basis for an ecological explanation is on offer. By running experiments in which bees are forced to fly in narrow tunnels, Esch et al. (2001) have been able to experimentally manipulate optic flow fields. Interestingly, their results are inconsistent with absolute distance or any other bee-independent variable being computed in the waggle dance, as would need to be the case under an algebraic interpretation. Rather, the estimation of distance is consistent with reliance upon self-induced optic flow in the open. Srinivasan et al. (2001) provide converging evidence in terms of bee-dependent properties, and other insects, such as desert ants (Ronacher & Wehner, 1995), appear to follow a strategy with similar ecological credentials. Collett and Collett (2002) also interpret honeybee navigation in Gibsonian terms. This research is compatible with ecological forms of navigation that make no cognitive usage of representational-cum-computational maps/operations of any sort.

As we saw earlier, minimal cognition initially consisted of exploiting the environment, courtesy of free and reversible bodily movements enabled by various sensorimotor systems of organization. Of course, the analogy with plants cannot be cast straightforwardly in finding-their-way-back-home terms.²⁸ Circumnutation, or other forms of plant movement, are specific to plants’ needs and constraints. Still, the analogy is functional, and operates when drawn in relation to the exploration of roots for nutrients, for instance. Roots literally navigate systematically through their local environment.

In effect, the navigational repertoire of plants is considerable, and a number of highly sophisticated and intriguing navigational capabilities may be considered beyond tendril-climbing, such as search and escape movements performed by roots in response to competition (see Baluška, Mancuso et al., 2010, and references therein), or the photophobic behavior of crawling maize roots; a behavioral response that cannot be interpreted as a simple form of unidirectional negative phototropism (Burbach et al., 2012). Root swarming behaviors exhibit similar levels of behavioral complexity. Roots not only must navigate the soil structure, but must also coordinate their root system so as to optimize nutrient intake in addition to other adaptive considerations such as territoriality. In these cases, information must be shared across

²⁸ Interestingly, Frantisek Baluska (personal communication) observes that growing roots perform circumnutation movements that in a sense resemble the waggle dance of bees, although of course not in the information-processing sense that Carruthers, for instance, would endorse.

the plant root system. In fact, communication takes place not only between root apices of the same plant, but also with respect to the root systems of neighboring ones. In this way, the concept of adaptive swarming behavior applies to plants, as they solve by social interaction problems that outstrip the individual when viewed in isolation (Baluška et al., 2010).

Two forms of interaction between roots that have been studied meet our criteria for minimal cognition. As Ciszak et al. (2012) report, roots may align/repulse and grow in the same/different direction in the absence of physical contact (distance-based alignment/repulsion). On the other hand, root crossing may take place when roots first attract each other, to repulse afterwards. Overall, complex patterns of collective behavior have been observed, with groups of roots being able to choose the same or opposing growth direction (see Ciszak et al., 2012, for details). We may thus consider how the position and orientation of individual roots relates in an emergent manner to the tendencies of other roots to respect alignment in growth.

These studies are consistent with the idea that roots that are able to acquire metabolically relevant information have the resources to acquire related information that is metabolically relevant too. Roots can estimate and communicate distance, direction of nutrient vectors in soil patches, and potential competition through angle adjustment in navigation, and the adjustment of angle can be signaled by electric fields that roots generate, and sensed in turn by other individual roots or root systems.²⁹ In this way, swarming behavior results in systematic patterns of navigation that we understand are in principle subject to a methodological treatment akin to the one pursued by Collett and Collett (2002), Esch et al. (2001), Srinivasan et al. (2001), and other authors, in the case of insect ecological navigation.

Summing up, minimally cognitive systems exploit the spatiotemporally dispersed characteristics of metabolically relevant environmental features by performing free and reversible bodily movements. As a result, both insects and plants generate a flow (plausibly by root circumnutation, in the case of plants) that is informationally rich insofar as navigational paths are ecologically specified. Invariant information is generated through navigation, a capacity that is itself guided by the structure of that very information. It is this reciprocity between perception and action that tells against a cognitivist rendering of minimal cognition, and against an inferential treatment of systematicity as conceived for such minimal agents.³⁰

The ecological approach to (minimal) cognition

Finally, is it possible to scale up from a neo-Gibsonian approach to minimal cognition to higher-level forms of systematicity? One option is to maintain that higher cognition inherits its combinatorial power from the structuring role of public language itself (Dennett, 1995; Clark, 1997; Symons 2001). The systematicity of thought might then be seen as the felicitous outcome of an agreed-upon systematicity of language. Sympathizers with this route may come, for instance, from the connectionist corner (Bechtel & Abrahamsen, 2002) or from a dynamic and interaction-dominant perspective (Gomila et al., 2012).³¹

Rather than denying systematicity at the behavioral level one could imagine a split into an ecological lower-level system, and a constructivist higher-level one. We will not consider the former option, as we have granted the systematicity of behavior under our ‘minimal cognition’ approach.³² The two visual systems model (Goodale and Milner, 1992) provides the canonical

²⁹ For other possible forms of communication between root tips, see Baluška, Lev-Yadun et al. (2010).

³⁰ Heft’s work on ecological navigation is illustrative: “A commonly held view is that knowledge of environmental configuration must be based on cognitive operations that construct a mental representation, or a “cognitive map”, from discontinuous perceptual encounters. Such a constructivist account seems to be required because the overall layout cannot be perceived from any single location in the environment... In contrast to this position, the most radical aspect of Gibson’s treatment of navigation is his claim that by following paths through the environment, eventually one does come to perceive the overall layout of the environment.” (1996, p. 124).

³¹ On interaction-dominance, see Chemero (this volume).

³² Gomila et al. (2012) defend this view, although see Martínez-Manrique (this volume) for an alternative.

illustration of the second option (Norman, 2002), where the ventral (“what”) and dorsal (“where”) pathways serve different purposes. Whereas the ventral pathway, being inferential and memory-based, connects vision with cognition proper and fits therefore nicely with constructivist concepts, the dorsal pathway, being in charge of the control of motor behavior, is more in line with ecological principles.

Clark’s (2012) ‘hierarchical generative model’ provides yet another type of conciliatory strategy that although, to the best of our knowledge, not thought of for the purpose of responding to the systematicity challenge, will serve by way of contrast to pin down our methodological proposal. Clark (2013) invites us to consider a ‘unified theory of mind and action’ by combining Bayesian (top-down) and connectionist (bottom-up) methodologies into a single architecture. According to ‘probabilistic models’ of thought (Griffiths et al., 2010), configurations of sequences of symbols obtain as a result of probabilistically tinkering with a number of parameters that determine syntactically correct structures. Together with particular mechanisms in the hippocampus and neocortex (McClelland et al., 2010) that account for the possibility of combining rapid parsing and associative learning, a conciliatory solution might be forthcoming.³³

By contrast with these methodological choices, we believe that ecological psychology has the resources to avoid the potential pitfalls of these strategies: neglectfulness of systematicity itself or, possibly, becoming implementational. Our claim is not that ecological psychology might be able to account for those cognitive phenomena that resist a description in terms of systematicity. Rather, we believe that a great deal of behavior (behavior that we identify with minimally cognitive flexible responses) is thoroughly systematic, and that the neo-Gibsonian may be able to explain it. This includes the perception of speech. Gibson notes:

Now consider perception at second hand, or vicarious perception: perception mediated by communications and dependent on the “medium” of communication, like speech sound, painting, writing or sculpture. The perception is indirect since the information has been presented by the speaker, painter, writer or sculptor, and has been *selected* by him from the unlimited realm of available information. This kind of apprehension is complicated by the fact that direct perception of sounds or surfaces occurs along with the indirect perception. The sign is often noticed along with what is signified. Nevertheless, however complicated, the outcome is that one man can metaphorically see through the eyes of another. (1976, p. 412; see Fowler, 1986)

Gibson’s comments may appear at first sight to drive us straightforwardly into constructivism. But, in Gibson’s usage, being “indirect” is not tantamount to cognitive penetration. Despite his distrust for mental abstractions, in *The Senses Considered as Perceptual Systems* Gibson already hints at the way to bridge language and ecological psychology with an eye to articulating the direct perception of meaning. For example, he considered ‘the pick up of symbolic speech’ (pp. 90-ff.) and ‘the effect of language on perception’ (pp. 280-82). Unfortunately, Gibson did not elaborate much beyond some preliminary remarks.³⁴ We close our chapter by inviting the reader to consider the supra-communicative role of language as an ecological *tool*.

³³ We do not have the space to elaborate further on this (see Calvo et al., 2013), although we suspect that by allowing top-down processing to inform the output of the emergentist bottom-up part of the model, the price to pay will be subsumption under Fodor & Pylyshyn’s charge of implementation.

³⁴ Since then, a number of authors have made further efforts to conciliate the principles of ecological psychology with language. Verbrugge (1985) approaches language in terms of the direct perception of speech as a type of event subject to ecological laws (acoustical laws, in the case of verbal speech). Reed (1987) tries a quasi-grammatical approach to language that is congenial with Chomskian principles (Noble, 1993). We shall not review this literature here (see Hodges & Fowler, 2010; Fowler & Hodges, 2011, for further insights).

An ecological approach cannot be in the business of developing a generative grammar for verbal behavior; its aim is rather to foster an understanding of language use that is integral to the emergent and self-organized (linguistic and non-linguistic) behavior of humans; to the sort of activities they engage in. In this way, the development of an ecological approach to language ought to start with the realization that language is not that *special*; (at least, not special in the sense implied by cognitivism).³⁵ Clark (1998), in this same spirit, proposes a supra-communicative role of language, although his approach is alien to ecological psychology concerns. Clark starts by clearing up potential misunderstandings in the very title of his article “Magic words”:

...Of course, words aren't magic. Neither are sextants, compasses, maps, ... In the case of these other tools and props, however, it is transparently clear that they function so as to either carry out or to facilitate computational operations important to various human projects. The slide rule transforms complex mathematical problems (ones that would baffle or tax the unaided subject) into simple tasks of perceptual recognition... These various tools and props thus act to generate information, or to store it, or to transform it, or some combination of the three... Public language, I shall argue, is just such a tool. (p. 162)

Clark (1998) is proposing a supra-communicative role for language. He criticizes non-computational models of cognition for emphasizing communicative aspects of language to the detriment of its exploitation as an external artifact. His is nonetheless an approach that calls for the augmentation, courtesy of “magic words” of our computational powers.³⁶ Being non-computational, our interest resides in identifying the role of language in serving not to augment computations but to allow for an ecological manipulation of the environment for the purpose of perceiving a brand new set of affordances that non-linguistic animals are unaware of.

Tools are part and parcel of the Gibsonian worldview. The environment contains artifacts, and these alter the layout; which results in a global change of the affordances the environment furnishes the human animal with. Tools offer a different set of opportunities for interaction. Language, as an ecological tool, is not intrinsically different from artifacts such as telescopes or microscopes, which permit us to go beyond the native capacities of our visual systems. Language further alters the layout, providing novel ways to interact in the sociolinguistic environment. The ecological approach to language as a tool has to do with behaving adaptively in the face of linguistic information. In general, we perceive the affordances of artifacts; likewise, we contend, we perceive the affordances of words, as a more sophisticated type of artifact. We perceive inter-individual emergent properties, such as public conversation, in pretty much the same way that we perceive rocks and their contextual affordances, or social affordances (Costall, 1995), for that matter.³⁷ In this way, external linguistic scaffolding provides yet another set of ecological properties to be taken on a par.³⁸

Conclusion

Our approach appears to be open to a very basic challenge. This is posed clearly by Ken Aizawa, (this volume) who argues that post-connectionist cognitive science has drifted away

³⁵ Noble (1993), who elaborates on the evolutionary emergence of language from a neoGibsonian stance, dubs this the ‘language is special’ doctrine.

³⁶ Of course, such a supra-communicative role is already present in Vygotskian (1978) approaches.

³⁷ See also Travieso & Jacobs (2009).

³⁸ Symons (2001) presents an early version of this position. That paper argued that systematic patterns of intelligent behavior do not necessarily license the view that internal representations play a role in the cognitive system analogous to that played by syntactic structures in a computer program. Linguistic structures are instead regarded as external targets for the development of individual brains.

from a focus on cognition and has lapsed into a kind of uncritical behaviorism. He contends that an increasing emphasis on behavior has led to confusion concerning the importance of systematicity as a distinctive mark of the cognitive. We agree with Aizawa that denying the difference between the behavior we find in plants and the systematic features of higher cognition more generally would be foolish. However, we do not accept the view that we must mark the distinction between the cognitive and non-cognitive by the presence or absence of structured systematicity.

Aizawa and others have long regarded cognition as essentially representational. While this view comports with our understanding of normal, adult human intelligence and provides a useful explanatory framework for psychological research with such subjects, it fails to shed any significant light on the emergence of cognition over the course of natural history. We contend that one cannot explain the emergence of the kind of sophisticated representational capacities that are assumed to play a role in adult humans if our account of systematicity presupposes preexisting representations.

The neo-Gibsonian strategy involves recognizing alternative paths to the emergence of cognition over the course of natural history. Rather than assuming that we arrive at cognition via representation an explanation of the emergence of cognition supposes that we can provide explanations in terms of increasingly sophisticated causal patterns of relations (García & Calvo, 2010). If minimally cognitive systems need not involve representations (our neo-Gibsonian take) then objections like Aizawa's can be addressed. What we have assumed is that cognition is a form of adaptive behavior and that becoming a cognitive system involves an organism managing to succeed as an adaptive system. Of course, not all forms of adaptive behavior must be regarded as cognitive. On our view minimal cognition involves adaptive behavior that is systematic.

Traditionally, the objection to projects like ours is that we risk conflating cognition with behavior, or ignoring cognition entirely. However, this is not the case. Instead, we have attempted to demonstrate how systematicity at the cognitive level can emerge from the kind of meaningful engagement with the environment that is phylogenetically and ontogenetically prior to the kinds of intellectual and cognitive capacities that we expect from adult humans. We assume that there are ways of meaningfully engaging with one's environment that are non-representational. We also assume that the concept of meaningful engagement can come apart from the concept of representation.

Clearly, our work departs from traditional debates over the systematicity of thought insofar as it is directed towards a different explanandum. If we see the goal of cognitive science as accounting for the emergence of intelligence and cognition then it will be natural to attend to minimally cognitive agents and the emergence of simple forms of systematicity in behavior.

Acknowledgments

This material draws from preliminary work presented at the following workshops: *Varieties of representation: Kazimierz naturalist workshop* (Kazimierz Dolny, Poland); *Smart solutions from the plant kingdom: beyond the animal models* (Florence, Italy); and *12th European workshop on ecological psychology* (Miraflores de la Sierra, Spain). This research was also presented in seminars held at the Universitat Autònoma de Barcelona (Spain) and the *Laboratoire de Psychologie Cognitive* (CNRS and Aix Marseille Université, France). We would like to thank all these audiences, and Frantisek Baluška, Stefano Mancuso, and Dave Lee, for their inspiring work in plant neurobiology and ecological psychology, respectively. We are grateful to Anastasia Seals for comments. Very special thanks go to Ken Aizawa for his detailed criticisms and helpful suggestions on an earlier draft of this manuscript. This research was supported by DGICYT Project FFI2009-13416-C02-01 (Spanish Ministry of Economy and Competitiveness) to PC and EM, and by Fundación Séneca-Agencia de Ciencia y Tecnología de la Región de Murcia, through project 11944PHCS09 to PC and JS.

References

- Allen, Paul H. *The Rain Forests of Golfo Dulce*. Stanford: Stanford University Press, 1977.
- Alpi, Amadeo, Nikolaus Amrhein, Adam Bertl et al. “Plant Neurobiology: No brain, no Gain?” *Trends in Plant Science* 12, no. 4 (2007): 135–136.
- Baldwin, Ian T., Rayko Halitschke, Anja Paschold, Caroline C. von Dahl and Catherine A. Preston. “Volatile Signaling in Plant-plant Interactions: ‘Talking trees’ in the Genomics era.” *Science* 311, no. 5762 (2006): 812–815.
- Baluška, František, Stefano Mancuso, Dieter Volkmann and Peter W. Barlow. “Root Apices as Plant Command Centres: The Unique ‘brain-like’ Status of the Root Apex Transition Zone.” *Biologia* 59 (2004): 9–17.
- Baluška, František, Stefano Mancuso and Dieter Volkmann, eds. *Communication in Plants: Neuronal Aspects of Plant Life*. Berlin: Springer-Verlag, 2006.
- Baluška, František, Stefano Mancuso, Dieter Volkmann and Peter W. Barlow. “The ‘root-brain’ Hypothesis of Charles and Francis Darwin: Revival after more than 125 years.” *Plant Signaling and Behavior* 4, no. 12 (2009): 1121–1127.
- Baluška, František, Simcha Lev-Yadun and Stefano Mancuso. “Swarm Intelligence in Plant Roots.” *Trends in Ecology & Evolution* 25, no. 12 (2010): 682–683.
- Baluška, František, Stefano Mancuso, Dieter Volkmann and Peter W. Barlow. “Root Apex Transition Zone: A Signalling–response Nexus in the Root”. *Trends in Plant Science* 15 (2010): 402–408.
- Barlow, Peter W. “Plastic, Inquisitive Roots & Intelligent Plants in the light of some new vistas in Plant Biology.” *Plant Biosystems* 144 (2010): 396–407.
- Bechtel, William, and Adele Abrahamsen. *Connectionism and the Mind: Parallel, Processing, Dynamics, and Evolution in Networks* (Second edition). Oxford: Blackwell, 2002.
- Brenner, Eric D., Rainer Stahlberg, Stefano Mancuso, Jorge M. Vivanco, František Baluška and Elizabeth van Volkenburgh. “Plant Neurobiology: an Integrated View of Plant Signaling.” *Trends in Plant Science* 11, no. 8 (2006): 413–419.
- Brenner, Eric D., Rainer Stahlberg, Stefano Mancuso, František Baluška and Elizabeth van Volkenburgh. “Response to Alpi et al.: Plant Neurobiology: the Gain is More than the Name.” *Trends in Plant Science* 12, no. 7 (2007): 285–286.
- Burbach, Christian, Katharina Markus, Zhang Yin, Markus Schlicht and František Baluška. “Photophobic Behavior of Maize Roots.” *Plant Signaling and Behavior* 7, no. 7 (2012): 1–5.
- Calvo, Paco, and Eliana Colunga. “The Statistical Brain: Reply to Marcus’ The Algebraic Mind.” In *Proceedings of the Twenty-Fifth Annual Conference of the Cognitive Science Society*, edited by Richard Alterman and David Kirsh, 210–215. Mahwah, NJ: Lawrence Erlbaum Associates, 2003.
- Calvo, Paco, and Fred Keijzer. “Plants: Adaptive Behavior, Root Brains and Minimal Cognition.” *Adaptive Behavior* 19 (2011): 155–171.

- Carruthers, Peter. "On Being Simple Minded." *American Philosophical Quarterly* 41 (2004): 205–220.
- Chalmers, David J. "Syntactic transformations on distributed representations." *Connection Science* 2 (1990): 53–62.
- Chomsky, Noam. "A Review of B. F. Skinner's Verbal Behavior." *Language* 35, no. 1 (1959): 26–58.
- Churchland, Patricia S. *Neurophilosophy: Toward a Unified Science of the Mind Brain*. Cambridge, Mass.: MIT Press, 1986.
- Churchland, Patricia S. *Brain-wise: Studies in Neurophilosophy*. Cambridge, Mass.: MIT Press, 2002.
- Ciszak, Marzena, Diego Comparini, Barbara Mazzolai, František Baluška, F. Tito Arecchi et al. "Swarming Behavior in Plant Roots." *PLoS ONE* 7, no. 1 (2012): e29759. doi:10.1371/journal.pone.0029759
- Clark, Andy. *Being There*. Cambridge, Mass.: MIT Press, 1997.
- Clark, Andy. "Magic words: How language augments human computation." In *Language and Thought: Interdisciplinary Themes*, edited by Peter Carruthers & Jill Boucher. Cambridge, Mass: MIT Press, 1998.
- Clark, Andy. "Whatever Next? Predictive Brains, Situated Agents, and the Future of Cognitive Science." *Behavioral and Brain Sciences* (2013).
- Collett, Thomas S., and Mathew Collett. "Memory use in insect visual navigation." *Nature Reviews Neuroscience* 3 (2002): 542–552.
- Costall, Alan. "Socializing Affordances." *Theory and Psychology* 5 (1995): 467–482.
- Cummins, Robert. "Systematicity." *The Journal of Philosophy* 12, Vol. 93 (1996): 591–614.
- Darwin, Charles. *Insectivorous plants*. New York : Appleton, 1875.
- Delafield-Butt, Jonathan T., Gert-Jan Pepping, Colin D. McCaig and David N. Lee. "Prescriptive Guidance in a Free-swimming Cell." *Biological Cybernetics* (2013).
- Dennett, Daniel C. *Darwin's Dangerous Idea: Evolution and the Meanings of Life*. New York: Simon & Schuster, 1995.
- Dyer, Fred C., and Jeffrey A. Dickinson. "Development of Sun Compensation by Honeybees: How Partially Experienced Bees Estimate the Sun's Course." *Proceedings of the National Academy of Sciences* 91 (1994): 4471–4474.
- Elman, Jeffrey L. *Generalization, Rules, and Neural Networks: A Simulation of Marcus et al.* University of California, San Diego, 1999. <http://www.crl.ucsd.edu/~elman/Papers/MVRVsim.html> (accessed by June 10, 2012)
- Esch, Harald E., Shaowu Zhang, Mandyan V. Srinivasan and Juergen Tautz. "Honeybee Dances Communicate Distances Measured by Optic Flow." *Nature* 411 (2001): 581–583.

- Fauconnier, Gilles, and Mark Turner. "Conceptual Integration Networks." *Cognitive Science*, 22, 2 (1998): 133–187.
- Fodor, Jerry A. and Zenon W. Pylyshyn. "How Direct is Visual Perception? Some Reflections on Gibson's 'Ecological Approach'." *Cognition* 9 (1981): 139-96.
- Fodor, Jerry A. and Zenon W. Pylyshyn. "Connectionism and Cognitive Architecture: a Critical Analysis." *Cognition* 28 (1988): 3–71.
- Fowler, Carol, and Bert Hodges. "Dynamics and languaging: Toward an ecology of language." *Ecological Psychology* 23 (2011): 147–156.
- Gagliano, Monica, Stefano Mancuso and Daniel Robert. "Towards Understanding Plant Bioacoustics", *Trends in Plant Science* 17, no. 6 (2012): 323–325.
- García Rodríguez, A. and Paco Calvo. "Is cognition a matter of representations?: Emulation, teleology, and time-keeping in biological systems." *Adaptive Behavior* 18 (2010):400-415.
- Gerken, Lou A., and Richard N. Aslin. "Thirty Years of Research on Infant Speech Perception: The legacy of Peter W. Jusczyk." *Language Learning and Development* 1, no. 1 (2005): 5–21.
- Gibson, James J. *The Senses Considered as Perceptual Systems*. Boston: Houghton Mifflin, 1966.
- Gibson, James J. *The Ecological Approach to Visual Perception*. Boston: Houghton Mifflin, 1979.
- Gomila, Antoni, David Travieso and Lorena Lobo. "Wherein is Human Cognition Systematic?" *Minds and Machines* 22, no. 2 (2012): 101–115.
- Goodale, Melvyn A., and David Milner. "Separate Visual Pathways for Perception and Action." *Trends in Neurosciences* 15 (1992): 20–25.
- Griffiths, Thomas L., Nick Chater, Charles Kemp, Amy Perfors and Joshua B. Tenenbaum. "Probabilistic Models of Cognition: Exploring the Laws of Thought." *Trends in Cognitive Sciences* 14 (2010): 357–364.
- Heft, Harry. "The ecological approach to navigation: A Gibsonian perspective." In *The construction of cognitive maps*, edited by Juval Portugali, 105–132. Dordrecht: Kluwer Academic Publishers, 1996.
- Hodges, Bert, and Carol Fowler. "New affordances for language: Distributed, dynamical, and dialogical resources." *Ecological Psychology* 22 (2010): 239–253.
- Isnard, Sandrine, and Wendy K. Silk. "Moving with Climbing Plants from Charles Darwin's Time into the 21st Century." *American Journal of Botany* 96, no. 7 (2009): 1205–1221.
- Kim, Alan. "Early Experimental Psychology." In *Routledge Companion to Philosophy of Psychology*, edited by John Symons and Paco Calvo, 41–59. London: Routledge, 2009.
- Kujala, Teija. "Brain Science: A more Direct Way of Understanding our Senses." *Behavioral and Brain Sciences* 24, no. 2 (2001): 224–224.
- Lee, David N. "A Theory of Visual Control of Braking based on Information about Time-to-Collision." *Perception* 5 (1976): 437–459.

- Lee, David N. "The Optic Flow Field: the Foundation of Vision." *Philosophical Transactions of the Royal Society London B* 290 (1980): 169–179.
- Lee, David N. "Guiding Movement by Coupling Taus." *Ecological Psychology* 10 (1998): 221–250.
- Lee, David N. "Tau in Action in Development." In *Action, Perception & Cognition in Learning and Development*, edited by John J. Rieser, Jeffrey J. Lockman and Charles A. Nelson, 3–49. Hillsdale, N.J.: Erlbaum, 2004.
- Lee, David N. "General Tau Theory: Evolution to Date." *Perception* 38, no. 6 (2009): 837–858.
- Lee, David N., and Paul E. Reddish. "Plummeting Gannets: a Paradigm of Ecological Optics." *Nature* 293 (1981): 293–294.
- Lee, David N., Paul E. Reddish and D. T. Rand. "Aerial Docking by Hummingbirds." *Naturwissenschaften* 78 (1991): 526–527.
- Lee, David N., James A. Simmons, Prestor A. Saillant and Frederick H. Bouffard. "Steering by Echolocation: A Paradigm of Ecological Acoustics." *Journal of Comparative Physiology A* 176 (1995): 347–354.
- Llinás, Rodolfo, and Patricia S. Churchland, eds. *The Mind-Brain Continuum*. Cambridge, Mass.: MIT Press, 1996.
- Mackie, George O. "Neuroid Conduction & the Evolution of Conducting Tissues." *Quarterly Review of Biology* 45 (1970): 319–332.
- Marcus, Gary F., Sugumaran Vijayan, Shoba Bandi Rao and Peter M. Vishton. "Rule Learning by seven-month-old Infants." *Science* 283 (1999): 77–80.
- Marcus, Gary F. *The Algebraic Mind*. Cambridge, Mass.: MIT Press, 2001.
- Marr, David. *Vision*. San Francisco: Freeman, 1982.
- Masi, Elisa, Marzena Ciszak, G. Stefano, Luciana Renna, Elisa Azzarello, Camila Pandolfi et al. "Spatio-temporal Dynamics of the Electrical Network Activity in the Root Apex." *Proceedings of the National Academy of Sciences USA* 106 (2009): 4048–4053.
- McClelland James L., Mathew M. Botvinick, David C. Noelle, David C. Plaut, Timothy T. Rogers, Mark S. Seidenberg and Linda B. Smith. "Letting Structure Emerge: Connectionist and Dynamical Systems Approaches to Cognition." *Trends in Cognitive Sciences* 14 (2010): 348–356.
- McLaughlin, Brian. "Systematicity Redux." *Synthese* 170, issue 2 (2009): 251–274.
- Michaels, Claire F., and Claudia Carello. *Direct Perception*. Englewood Cliffs, New Jersey: Prentice-Hall, 1981.
- Mithöfer, Axel, and Wilhelm Boland. "Plant defense against herbivores: chemical aspects." *Annual review of plant biology* 63(2012): 431–450.
- van Gelder, Tim. "Compositionality: A connectionist variation on a classical theme." *Cognitive Science* 14 (1990): 355–384.

Norman, Joel. "Two Visual Systems and Two Theories of Perception: An Attempt to Reconcile the Constructivist and Ecological Approaches." *Behavioral and Brain Sciences* 25 (2002): 73–144.

Pollack, Jordan B. "Recursive distributed representations." *Artificial Intelligence* 46 (1990): 77–105.

Reed, Edward. "James Gibson's Ecological Approach to Cognition" In *Cognitive Psychology in Question*, edited by Alan Costall and A. Still, 142–173. Sussex: Harvester Press, 1987.

Richardson, Michael J., Kevin Shockley, Bret R. Fajen, Michael A. Riley and Michael Turvey. "Ecological Psychology: Six Principles for an Embodied-Embedded Approach to Behavior". In *Handbook of Cognitive Science: An Embodied Approach*, edited by Paco Calvo and Antoni Gomila, 161–190. Oxford: Elsevier, 2008.

Rock, Irvin. *The Logic of Perception*. Cambridge, Mass.: MIT Press, 1983.

Rock, Irvin, ed. *Indirect Perception*. Cambridge, Mass.: MIT Press, 1997.

Ronacher, Bernhard, and Rüdiger Wehner. "Desert ants *Cataglyphis Fortis* use Self-induced Optic Flow to Measure Distances Travelled." *Journal of Comparative Physiology A* 177 (1995): 21–27.

Schenk, H. Jochen, Ray Callaway and Bruce Mahall. "Spatial Root Segregation: Are Plants Territorial?" *Advances in Ecological Research* 28 (1999): 145–180.

Schogler, Benjamin, Gert-Jan Pepping and David N. Lee. "TauG-guidance of Transients in Expressive Musical Performance." *Experimental Brain Research* 198 (2008): 361–372.

Smolensky, Paul. "The constituent structure of connectionist mental states." *Southern Journal of Philosophy* 26 (1987): 37–60.

Smolensky, Paul. "Tensor product variable binding and the representation of symbolic structures in connectionist systems." *Artificial Intelligence* 46 (1990): 159–216.

Srinivasan, Mandyan V., Shaowu Zhang, Monika Altwein and Jürgen Tautz. "Honeybee Navigation: Nature and Calibration of the 'Odometer'." *Science* 287 (2000): 851–853.

Stoffregen, Thomas A., and Benoît G. Bardy. "On Specification and the Senses." *Behavioral and Brain Sciences* 24 (2001): 195–261.

Symons, John. "Explanation, representation and the dynamical hypothesis." *Minds and Machines* 11, 4 (2001): 521–541.

Symons, John. *On Dennett*. Belmont: Wadsworth, 2002.

Symons, John. "Understanding the Complexity of Information Processing Tasks in Vision." *Philosophy and Complexity: Essays on Epistemology, Evolution, and Emergence*. Edited by Carlos Gershenson, Diederik Aerts, and Bruce Edmonds, 300–314. Singapore: World Scientific, 2007.

Travieso, David, and David Jacobs. "The Ecological Level of Analysis: Can Neogibsonian Principles be Applied Beyond Perception and Action?" *Integrative Psychological and Behavioral Science*, 43 (2009): 393–405.

Tresilian, James R. "Visually Timed Action: time-out for 'tau'?" *Trends in Cognitive Sciences* 3, no. 8 (1999): 301–310.

Trewavas, Anthony J. "Aspects of Plant Intelligence." *Annals of Botany* 92 (2003): 1–20.

Trewavas, Anthony J. "Plant Neurobiology: All Metaphors have Value." *Trends in Plant Science* 12 (2007): 231–233.

Trewavas, Anthony J. "Aspects of Plant Intelligence: Convergence & Evolution." In *The Deep Structure of Biology: Is Convergence sufficiently Ubiquitous to give a Directional Signal*, edited by Simon C. Morris, 68–110. West Conshohocken, PA: Templeton Press, 2008.

Turvey, Michael, Robert Shaw, Edward S. Reed and William Mace. "Ecological Laws for Perceiving and Acting: A Reply to Fodor and Pylyshyn." *Cognition* 10 (1981): 237–304.

Tye, Michael. "The Problem of Simple Minds: Is There Anything it is like to be a Honey Bee?" *Philosophical Studies: An International Journal for Philosophy in the Analytic Tradition* 88 (1997): 289–317.

Verbrugge, Robert. "Language and Event Perception: Steps towards a Synthesis." In *Event Perception*, edited by William Warren and Robert Shaw, 157–93. Hillsdale, NJ: Lawrence Erlbaum, 1985.

Visscher, P. Kirk. "Animal Behaviour: How Self-organization Evolves." *Nature* 421 (2003): 799–800.

von Frisch, Karl. *The Dance Language and Orientation of Bees*. Cambridge, Mass.: Harvard University Press, 1993.

Vygotsky, Lev. "Interaction between learning and development." In *Mind and Society*, 79–91. Cambridge, Mass.: Harvard University Press, 1978.