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Approaching Minimal Cognition: Introduction to the Special Issue

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This special issue highlights the work of some recent participants of a series of Minimal Cognition workshops held at the University of Wollongong in 2018. The goal of these workshops has been to showcase the interdisciplinary work being done in what might be called 'minimal cognition research.' Our aim was, and continues to be, to bring biologists, cognitive scientists, philosophers, and computer scientists into dialogue on how we might understand the minimal criteria for cognition and cognitive behavior. This special issue, titled "Approaching Minimal Cognition," is intended to open up further exchange between the different fields converging on this richly interesting area of research, and to spur debate and discussion about the roots of cognition, the indicators of cognitive behavior, collective cognition, and the possibility of life-mind continuity.

The term "minimal cognition" came into popular use thanks to Randall Beer's work on modelling what he referred to as *minimally cognitive agents* (1996, 1997, 2003; Beer and Williams 2015). As he says of this project: "The term 'minimally cognitive behavior' is meant to connote the simplest behavior that raises cognitively interesting issues" (Beer 1996). Elaborating on a relatively simple robot equipped with an eye, two motors, an arm, and a hand, Beer provides a preliminary list of such cognitively interesting behaviors. For instance, he tells us that a robot like this can organize its behavior in accordance with shapes of objects in the environment, navigate in two dimensional coordinates, observe object persistence, shift its attentional focus, and possibly even engage in cooperative tasks with other agents of the same kind (Beer 1996). Moreover, Beer used neural networks with a very simple neural architecture to show that very little was needed in the way of internal dynamics to produce behavior that might be otherwise presumed to involve information processing and the use of mental representations . According to him, the environment itself could do a lot of the work these kinds of entities tend to be posited to do (Beer 1996; Brooks 1991). Importantly, his intent was not so much to pinpoint what the minimal criteria for cognition might be, but to show how the use of models could help illuminate philosophical and scientific debates on what cognition might (or might not) be.

Beer's minimally cognitive agents are a paradigmatic example of a *minimal model*: a model that "most economically caricatures the essential" features of a system needed to generate the phenomena of interest (Goldenfield 1992, p.33). For those interested in minimal cognition specifically, though, what exactly the phenomena of interest are is not so clear. One might think of minimal cognition research as focused on finding an explanatory boundary --e.g., at what point do behaviors require a more complex explanation than pointing to chemical reactions and biological mechanisms? Or, we might think of minimal cognition research as looking to pinpoint the most fundamental components or capacities needed for an organism to exhibit some behavior we deem cognitively interesting (such as flexibility, memory, or adaptive learning). Alternatively, we might also think that discussions about minimal cognition are about approach—e.g., which tools (phylogenetic, behavioral, modelling) give us the best answers about the emergence of cognition?

Interest in these kinds of questions, a growing literature on organisms such as bacteria, plants, and even slime moulds (see Döbereiner & Nakagaki, in press; Segundo-Ortin and Calvo, 2019), and current debates about the best framework for understanding cognition have led to a convergence of interest on the level of complexity at which cognition arises. Take, for instance, the autopoietic approach, which posits cognition as continuous with the biodynamics of life itself (Varela 1979; Varela, Thompson, and Rosch 1991). Autopoiesis, also referred to as "material self-production," refers to the capacity of living systems to generate and maintain their own identity as something distinct from the environment. Varela argues that this process of self-production is, fundamentally, already cognitive, for it requires the organism to be able to distinguish what in the environment is valuable and harmful to maintain its biological autonomy, regulating its interaction accordingly. In the words of Maturana and Varela, appealing to autopoiesis enables us to see that "[l]iving systems are cognitive systems, and living as a process is a process of cognition" (Maturana and Varela 1980, p. 13).

The autopoietic approach to cognition has generated some criticism. As van Duijn, Keijzer, and Franken (2006) argue, one reason that minimal cognition is controversial is that the cognitive processes associated with minimal cognition seem to be too closely associated with biological processes, especially on the autopoietic understanding. That is, while cognition is surely a biological process, if it does turn out that cognition and living go hand-and-hand, that doesn't give us much purchase on what cognition is and how it is different from living, if at all.

Instead, van Duijn et al. (2006) propose that the starting point for cognition ought to be placed at the capacity for sensorimotor coordination. To illustrate this, they compare the operation of the "lac operon" system and chemotaxis in *E. coli*. The lac operon system allows the bacterium to metabolize lactose, and it is disinhibited in the case that only lactose, rather than the system's preferred energy source of glucose, is abundant in the bacterium's environment. As they argue, this process can be explained as a chemical reaction within the metabolic process. In chemotaxis, however, the bacterium changes its position in the environment in response to chemical gradients, "which is relevant for changing metabolic opportunities, and in this way expanding the adaptive opportunities of [the organism] to a considerable degree" (van Duijn, Keijzer, and Franken 2006, p. 164). They argue that chemotaxis, but not the activity of the lac operon, demonstrates sensorimotor coordination, and is thus a meta-metabolic, or second order, process. Sensorimotor coordination, they argue, is a better starting point for cognition, for it "subsumes a basic metabolic/autopoietic network" (2006, p. 159). Additionally, they note, this kind of cognitive activity is not only necessarily "situated" in its environment, but "the sensorimotor interaction of the minimal cognizer is constitutive of the cognitive process itself" (2006, p. 165).

However, it isn't clear that the sensorimotor approach satisfies the criteria of those, such as Moreno and co-authors, (Moreno et al. 1997, Barandiaran, 2017; Barandiaran and Moreno, 2006), who claim that cognition must be meta-metabolic to be differentiated from biological processes. Barandarian and Moreno argue that "minimal cognition requires more than cognitive-like behavior, that it requires a particular kind of dynamic organization that adaptively sustains a behavioral repertoire and, most importantly, a capacity to reorganize and generate new dynamic structures in order to preserve its organization" (Barandarian and Moreno 2006, p. 182). So, while we might find sensorimotor coordination (which would be cognitive-like behavior) in prokaryotes, it is in the ability to sustain an organism-specific behavioral repertoire and the ability to re-organize behaviors adaptively that we should think of cognition as arising. And this, they argue, is a capacity enabled by the presence of a nervous system.

Biologists Müller, di Primio, and Lengeler, in defining minimal cognition, argue "that prokaryotes can well be described in cognitive terms and showed that some criteria normally believed to be crucial for cognitive phenomena in higher organisms apply to many phenomenon in prokaryotes" (2001, p. 93). Focusing on flexibility as a benchmark cognitive capacity, they have shown that prokaryotes exhibited a list of what they called minimal cognitive abilities (ex. modifiable stimulus-response pathway, memory, formation of expectation, adaptation, learning, etc.) that facilitated this flexibility. Interestingly, Pamela Lyon has recently shown that if we view cognition as the "capacity to flexibly generate complex behavior" (2017, p. 454) and look at the most recent research available on bacterial behaviors, then it shows that "different types of signalling systems clearly enable different degrees of response flexibility and behavioral complexity" (Ibid.) in order to cope with a more complex environment. Similar positions have been defended regarding plants (Calvo 2016; Segundo-Ortin and Calvo 2019).

Using an evolutionary approach, Peter-Godfrey Smith (2002) argues that cognition is on a continuum with, or "shades off" into, more basic biological processes such as metabolism. His environmental complexity thesis (ECT) holds that cognition is not rooted in basic biological processes, but evolved from these processes as a way for organisms to deal with increasing environmental complexity--i.e., predation. While Godfrey-Smith proposes no specific boundary, the level of environmental complexity, and associated navigational and interactive behaviors necessary for survival seems to place the evolution of cognition above the bacterial level (though he does refer to the possibility of bacteria having a kind of 'proto-cognition' (Godfrey-Smith 2002, 2016b), a notion which comes under some critical scrutiny from Pamela Lyon (this issue).

As said at the beginning, this special issue (and the workshops that preceded it) aimed to showcase part of the relevant work being done in these discussions. Given the multitude of approaches and kinds of criteria that researchers on minimal cognition are using, it is unlikely that we will see any consensus soon on what it *is* exactly, let alone where it emerges. In the meantime, the interdisciplinary aspects of minimal cognition research will be important for developing new and more precise terminology, for generating more empirical data, for developing new models, and for inspiring new philosophical questions about the fundamental nature of cognition and its emergence. Our hope is that the contributions here will help shed light on some of the controversies just highlighted, and that they will open the way for subsequent work, both in philosophy and the sciences.

Pamela Lyon's paper "Of what is 'minimal cognition' the half-baked version?" takes a critical approach to the term, distinguishing between different usages through an extensive review of the history and contemporary appearances of the term and then taking aim at what she calls the "ontological usage." Her concern is the carving out of an ontological category of minimal cognition as though this is set apart from a more fully-fledged notion of cognition, noting that this approach is unique to the cognitive sciences (in contrast to the life sciences). She points to uses of notions such as "proto-cognition*"* (Godfrey-Smith, 2002a, 2002b) as paradigmatic of this kind of usage, as they seem to point to something prior to cognition on a scale of evolution or complexity. Rather, Lyon urges us to recognize cognition (without an ontological qualifier) as a necessary function for living. Offering a detailed analysis of the intent behind the most frequent appearances of the term and a case study involving cognitive functions in protein signal transduction networks for several types of bacteria, Lyon proposes an inclusive definition of cognition intended to provide a starting point for a functional/mechanistic investigation of cognition in basal organisms.

In their contribution, **Felix Woolford** and **Matthew Egbert** take an approach more in line with the initial explorations of minimally interesting cognitive behaviors pioneered by Beer (1996, 1997, 2003). Using an organizational (Varela 1979) rather than a functional approach, Woolford and Egbert employ a simplified IDSM (Iterant Deformable Sensorimotor Medium) controller to investigate self-sustaining sensorimotor behaviors, which they call a NB-SMM (Node-Based SensoriMotor Map). In this model, the nodes denote a pattern of response to environmental features. Parameters of the nodes of one and two node systems were varied to investigate the resulting senrorimotor dynamics between robot and environment. Their results, they argue, demonstrate that the behavioral variety arises from the constraints (assigned parameters) of the embodied robot-environment interaction. They surmise that there would be an increase in behavioral complexity not only through the addition of more nodes, but also if the robot were given a dynamic environment—demonstrating that even a minimal sensorimotor-to-motor map can produce cognitively interesting behaviors that a functional analysis might be inadequate to explain.

Patrick McGivern's contribution examines the suggestion that simple physical systems can serve as *minimal models* for cognitive behaviors. While most work on minimal cognition focuses on behaviors found in living systems, many of the same types of behavior can also be found in non-living systems. For example, Lagzi et al. (2010) describe maze-solving behavior in chemotactic oil-drops, where simple oil drops are able to find the shortest path through a maze given an appropriate chemical gradient. Similar behaviors involving autonomous motion and environmental sensitivity are often cited as paradigmatic cases of minimal cognition when they occur in living. Drawing on recent discussions of minimal models in physics, McGivern considers the suggestion that these cases should be viewed as minimal models of cognition. He argues that the concept of a minimal model carries with it significant implications concerning the nature of the behavior being modelled and the constraints that systems exhibiting that behavior must satisfy. One consequence of this is that the claim that a non-living system is a minimal model of cognition is more difficult to establish that we might expect: there is more to being a minimal model than just its simplicity. Another consequence is that it is difficult to justify a distinction between living systems as genuinely cognitive and non-living systems as 'mere models'. McGivern suggests that the domain of minimal cognition should be understood very broadly, rather than being restricted to the domain of living things.

The contribution of **Lachlan Walmsley** also explores the implications of modelling in minimal cognition, though in this case modelling of the slime mould *Physarum polycephalum* is used to show the compatibility between mechanistic models and enactive approaches to cognition. Enactive approaches consider cognition to be constituted in the relationship between an organism and their environment, rather than the more standard cognitivist view of cognition as the processing of representations. Walmsley argues that the branch known as Radical Enactivism (REC) (Hutto and Myin 2017) in particular adheres to an explanatory monism, accepting only dynamical explanations, when it ought to be adopting an explanatory pluralism about cognition. Instead of rejecting mechanistic models outright, Walmsley provides evidence through a description of the modeling of slime moulds for what mechanistic models can offer for radical enactive explanations of cognition, without it being necessary for enactivists to adhere to the primacy or fundamentality of mechanistic explanation (as advocated for by new mechanists).

Jules Smith-Ferguson and **Madeleine Beekman** also look at the slime mould *Physarum polycephalum*. In their paper, Smith-Ferguson and Beekam use *P. polycephalum* as a case study for exploring minimally cognitive capacities through the lens and methods of behavioral ecology. In particular, they discuss evidence for memory, habituation, and irrational decision-making in *P. polycephalum*, in this case to better understand the emergence and evolution of information processing mechanisms across phyla. This empirical focus is combined with a defense of the so-called "biogenic" approach to cognition (Lyon, 2006). This is an inherently evolutionary approach that conceives of cognitive capacities as phylogenetic traits evolved to enhance the organism's capacity to adapt to their environment. Adopting this approach, they contend, can help illuminate questions such as why an organism *x* has some specific cognitive capacity while other organisms do not. For example, in light with the empirical evidence concerning learning in *P. polycephalum*, Smith-Ferguson and Beekam hypothesize that even though non-associative learning (habituation and sensitisation) is essential for *P. polycephalum*, it might have other mechanisms that make the evolution of more complex forms of learning (associative learning, non-elemental discrimination, and so on) unnecessary.

Sidney Carls-Diamante's paper takes issue with chemical self-recognition in octopuses, examining how it connects to debates about minimal cognition in different organisms. Self-recognition is broadly understood here as "the capacity of an organism to identify its body and body parts as its own and not of a conspecific or another entity" (p. 2). Chemical self-recognition is a well-known phenomenon in other species (e.g., urine sniffing in dogs), and consists of determining whether the phenotypic signals contained in a specific chemical stimulus belong to the organism itself, to a conspecific, or to another organism or entity. Based on empirical finding regarding the inhibition of sucker responses when presented with octopus skin, Carls-Diamante provides an account of how chemoreceptive mechanisms in the peripheral nervous system of octopuses may contribute to the system's overall capacity for self-recognition. After this, the author offers reason as to why this form of self-recognition should be considered a middle ground between a purely reactive, non-cognitive activity, and a sophisticated, representation-based, cognitive capacity.

As the papers included in this special issue show, the research about minimal cognition has been growing consistently and surprisingly fast in recent years, attracting the attention of philosophers and scientists alike. We believe this special issue can contribute to enrich the current state of arts, and that it will become a useful source for information for those interested in investigating *where*, *how*, and *why* cognition starts.

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