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Evolutionary convergence and biologically embodied cognition

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Review

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The study of evolutionary patterns of cognitive convergence would be greatly helped by a clear demarcation of cognition. Cognition is often used as an equivalent of mind, making it difficult to pin down empirically or to apply it confidently beyond the human condition. Recent developments in embodied cognition and philosophy of biology now suggest an interpretation that dissociates cognition from this mental context. Instead, it anchors cognition in a broad range of biological cases of intelligence, provisionally marked by a basic cognitive toolkit. This conception of cognition as an empirically based phenomenon provides a suitable and greatly expanded domain for studies of evolutionary convergence. This paper first introduces this wide, biologically embodied interpretation of cognition. Second, it discusses examples drawn from studies on bacteria, plants and fungi that all provide cases fulfilling the criteria for this wide interpretation. Third, the field of early nervous system evolution is used to illustrate how biologically embodied cognition raises new fundamental questions for research on animal cognition. Finally, an outline is given of the implications for the evolutionary convergence of cognition.

1. Converging on cognition

When it comes to the study of cognitive convergence, the human mind has long provided the central feature of the evolutionary landscape. The controversy between Stephen Jay Gould and Simon Conway Morris provides an illustration. Gould has in many studies—but most prominently in his *Wonderful Life* [1]—defended the idea that evolution is radically contingent: if 'the tape of life' is rerun, even a small change would result in widely diverging outcomes and the chance that humans would evolve again in such a rerun is negligible. Powell & Mariscal [2] name this Gould's radical contingency thesis: 'no important and sufficiently specific evolutionary outcomes are robustly replicable' (p. 12). When applied to the question of cognitive convergence, Gould's message would be not to expect any.

In his critique of Gould's radical contingency, Conway Morris [3,4] agrees with Gould that historical contingencies are everywhere in evolution, however:

> Put simply, contingency is inevitable, but unremarkable. It need not provoke discussion, because it matters not. There are not an unlimited number of ways of doing something. For all its exuberance, the forms of life are restricted and channeled. ([3], p. 13)

This message can be cast in terms of hill-climbing in a global search space. Only a few options within this space provide sound solutions to various design problems [5], and by travelling uphill in the direction of such optima, species will eventually acquire the characteristics of these options, irrespective of their starting position. Conway Morris argues that, given the tendency of evolution to converge on good solutions, creatures that are very similar to humans are actually to be expected once life is underway [4]. For the evolution of cognition, this implies that a human-like organization and mind constitute a global attractor on which evolutionary trajectories will converge from widely different starting conditions.

Powell & Mariscal [2] stress that Gould's position cannot be so easily dismissed as Conway Morris here suggests, a systematic study of cases of

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potential cognitive convergence will be necessary to decide this issue. In addition, the issue is not exhausted by these two options concerning cognitive convergence—either none or one—as logically there might be a multitude of possible cases and forms of cognition to converge on. For both reasons, a more detailed view of the search space relevant for cognition will be necessary. As the proposers of this special issue state: 'Any study of cognitive convergence that aims to draw broad lessons about the evolution of mind—not only in relation to its replicability, but also about the specific development and ecological conditions under which it is possible or even likely to occur—must establish and endeavour to explain patterns of cognitive convergence across a wide swath of taxa' (N. Clayton, R. Powell, C. Logan, I. Mikhalevich 2016, unpublished manuscript).

This idea is spot on. However, explaining patterns of *cognitive* convergence across a *wide swathe of taxa* implies a meaningful and coherent way to talk about cognition in a much wider sense than rejecting or accepting a human-based interpretation of cognition. Up to now, the (human) mind forms the central point of reference for talking about cognition even to the point of taking the two notions as being equivalent. Classic examples consist of human capacities like language, logic, reasoning, learning skills, counting, playing music and recognizing oneself in a mirror. Some other animals may perform some of these feats, but it remains at all times a matter of concern whether they truly do as humans do (e.g. [6,7]).

This mind-based interpretation provides a very fickle way of demarcating cognition, as individual cases may move across this boundary depending on the latest experiments. In addition, it does not self-evidently deal with the obvious continuity of the many capacities that humans do share with many other organisms, such as perception, memory and action, and that should be taken into consideration when dealing with cognitive convergence. Third, it tends to preclude an integrated way of referring to the intelligent capacities of organisms coming from a wide swathe of phyla and kingdoms that are very far from the human paradigm (as discussed in §3). All in all, we just cannot take it for granted that human-style intelligence provides the centre of all possible forms of intelligence that occur within the biological world. The systematic study of evolutionary patterns of cognitive convergence would be greatly helped by a clearer and more robust conceptual demarcation of cognition that can be confidently applied to a broad variety of cases, including, but not limited to, humans.

A radical way forward at this point is to explicitly question and disband the paradigmatic status given to the (human) mind as the yardstick of both cognition and intelligence. This option is supported by work in embodied cognition, which interprets cognitive processes in terms that apply to an array of systems that do not exhibit mind in any standard sense. Also, from a biological perspective, many organisms exhibit forms of intelligence, even when applying the notion of mind to these organisms remains far-fetched. In the following, I will develop this idea by presenting a new conceptualization of cognition that dissociates cognition from the mind: cognition will be conceptualized as referring to an empirical domain centred on the various ways in which organisms deal with their environment in ways that systematically further their existence and reproduction. I will refer to this interpretation as *biologically embodied cognition* (BEC).

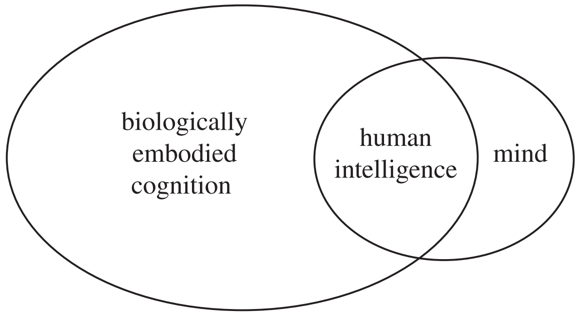

Figure 1. Human intelligence is here positioned in two different conceptual contexts that can be dissociated from one another. BEC refers to a broad domain of biological cases of intelligence as designated by embodied approaches to cognition. Mind refers here to the intuitively ascribed common-sense notion of an abstract entity or set of processes that is only loosely (or not at all) tied to physical systems.

The opposition between the two interpretations is sketched in figure 1, which shows how human intelligence can be placed in two different conceptual contexts. One consists of mind, a classic concept that is not tied to biology but applies to entities ranging from humans to angels, ghosts, artificial minds and God. This conception tends to exclude, or at the very least to question, many biological cases that exhibit various forms of intelligence. The second context consists of BEC. Here, human intelligence is placed within a wider biological domain, highlighting connections between human cognition and biological organization.

The central idea here is that one can set the concepts related to mind aside, while developing an independent parallel account of cognition that builds on the many biological cases of intelligence. This parallel domain can accommodate forms of intelligence that are very different from human and animal examples, not only allowing a continuum of cases along a single axis of more to less complex but also opening a way to think about radically different forms of intelligence. BEC provides a congenial conceptual context for interpreting various forms of cognitive convergence and divergence. I will also argue that BEC can catalyse new research questions that move beyond the conceptual options allowed within a mind-based conceptual framework. In all this, human intelligence becomes one, although special, case among many others.

The paper is structured as follows: §2 introduces the background of the conceptual proposal for a biologically embodied interpretation of cognition and develops this proposal in some more detail. Section 3 discusses how BEC extends the cognitive domain as it applies to a broad range of lifeforms, including bacteria, plants, fungi and animals. This emerging interdisciplinary research domain, in turn, lends plausibility to the biologically embodied interpretation of cognition proposed here. Section 4 illustrates how BEC invites new and fundamental conceptual questions concerning cognition using the evolution of early nervous systems as an example. Finally, I will return to the possible implications for cognitive convergence.

2. From mind to biologically embodied cognition

Cognitive science evolved as an amalgam of several scientific enterprises concerned with studying the human mind [8]. The concept of mind as an inner domain of thought and consciousness derives from long-standing philosophical traditions such as Cartesianism and British Empiricism. Its connection with dualism made it an increasingly problematic notion during the twentieth century until cognitive science came into existence with its promise to keep the mind while discarding the dualism. The notion of cognition became subsequently a useful way to signal this more respectable view of the mind, while also acquiring a face of its own.

In its original usage, cognition came to refer to complex forms of internal information processing. Information processing provided a way to explain various forms of problem solving and decision-making, with examples like playing chess, reasoning and the interpretation of visual scenes being prominent. The central idea here was that computational information processing provided an internal mechanism that could manipulate representations, which in turn enabled reasoning, decision-making and planning. Here is Neisser's well-known description:

> The term 'cognition' refers to all processes by which the sensory input is transformed, reduced, elaborated, stored, recovered, and used. It is concerned with these processes even when they operate in the absence of relevant stimulation, as in images and hallucinations. ([9], p. 4)

This cognitive science interpretation was taken up widely and for example also used by Shettleworth in her classic textbook of comparative psychology where she applies it to animals in general:

> Cognition refers to the mechanisms by which animals acquire, process, store, and act on information about the environment. These include perception, learning, memory, and decision making. ([10], p. 5)[1]

Interestingly, if cognition is literally held to be equivalent to internal information processing as stated here, any computer would be a cognitive system. Most researchers and philosophers active within cognitive science are unwilling to accept this conclusion and additional requirements are standardly used to bar this possibility. Shettleworth [10] explicitly limits her definition to animals, for example. However, as all animals exhibit forms of perception, learning and so on, this restriction may be considered insufficient. After all, a major question within cognitive ethology and comparative psychology concerns whether certain animals 'really' have cognitive features that include, for example, a self-concept or intentions (e.g. [7,11,12]). The presence of high-level mental functions remains a central requirement for what most researchers in cognitive science are willing to call cognition. Cognition remains firmly tied to mind here.

In addition to this inner information-processing interpretation, other views have sprung up of which two are central here: embodied approaches within cognitive science and a biological interpretation from philosophy of biology. Embodied approaches to cognition have for many years now criticized the idea of cognition as inner information processing. Rodney Brooks' [13] work in robotics in the late 1980s was an early example. He stressed the central role of ongoing bodily interactions with an environment as a way to minimize the need for inner information processing and move the field of robotics forward [13]. In addition, authors like Van Gelder [14], Beer [15] and Chemero [16] presented the mathematical framework of dynamical systems as a new way to describe and understand the ongoing perception–action relations between agents and their environments. Rather than being peripheral to intelligence, sensorimotor interactions became seen as the key feature of the processes that make us intelligent.[2]

In this embodied perspective, minimal forms of cognition are present in complex agent–environment interactions rather than inner information processing [15]. Problem solving itself often depends on the manipulation of an environment, while the sensorimotor tasks that animals routinely accomplish are actually highly complex—just try to make a robot that does the same—rather than basic behavioural responses. More complex inner information processing, such as involved in various forms of memory, learning and planning, fits in this picture as a way to extend the behavioural capacities of basic embodied agents. Still, the latter would be sufficient to talk about a form of cognition: the presence of perception–action relations is the key feature for basic forms of cognition here.[3]

Biological readings of cognition depart from the two previous views in an important way. Within cognitive science, cognition is treated at an abstract functional level where biological brains and bodies, and computers and robots are both considered as perfectly legitimate *realizers* of cognitive phenomena. Conceptually, neither the mind nor its derivative cognition is necessarily connected to biology. As philosopher Andy Clark [21] once phrased it: thinking otherwise would be succumbing to 'mere bio-chauvinistic prejudices'. By contrast, biological readings take a living biological organization as a precondition for cognition, thus making an important additional claim.

Such biological interpretations come in various forms. One highly influential, though controversial, approach goes back to the work of Maturana & Varela [22], who stated that 'living systems are cognitive systems' because of the complex ways in which self-maintenance depends on successful interactions with an environment. Another important influence here is the philosophical work of Godfrey-Smith [23] and his idea that cognition 'shades off' into other biological functions without any clear boundary between the two. More recently, Lyon [24] proposed a *biogenic approach* to the study of cognition that starts from general biological principles rather than from human-based criteria, which she calls an *anthropogenic approach*. In all these cases, cognition is related to the various complex ways in which organisms interact with their environment to maintain themselves and to reproduce.

Biological and embodied approaches to cognition are suitable companions. Embodied cognition provides a conceptual understanding of intelligence that starts with the interaction between an agent and its environment, highlighting the intricacies of sensorimotor relations and the ways in which higher-level forms of cognition derive from and lean on perception–action relations: cognition is here a much broader phenomenon than internal, human thought and self-evidently applies to most organisms. Biological approaches add to this embodied conceptual framework in many ways. Foremost, they provide a huge domain of potential cases to which this framework applies and where thinking in terms of embodied cognition will be helpful. Consider a crab that negotiates its environment, searching for food and avoiding predators. Doing this, the crab relies on many features—perceiving, moving, judging—that are definitely within the cognitive domain for an eye attuned to embodied cognition. These biological cases with their wealth of detail, their variations between both species and individuals, and their complexity provide a perfect empirical domain for embodied cognition to sink its teeth into.

At this point, I propose to combine embodied and biological interpretations of cognition even more intimately and turn them into a single view. Here, biology provides the empirical domain where an embodied conceptualization of cognition applies and can be further developed in ways that enhance our understanding of this domain. Most importantly, in this conceptual proposal cognition is no longer a notion that acquires its meaning from its connection to mental concepts or what we now consider as common sense. Cognition is cast as an empirical concept the interpretation of which will change on the basis of what science brings us. The notion will become similar to other common concepts that acquired a specific technical interpretation in biology such as species, organisms or plants, all of which have been reinterpreted and acquired new meanings on the basis of biological research. I refer to this proposed interpretation as BEC.

This proposal has various positive features. First, this proposal explicitly accepts and addresses the wide range of possible cases the living world provides when it comes to cognition and that deserve attention in a systematic way. Second, it allows us to deal with cognitive phenomena independent from the human case, suggesting instead the possibility of a broad variety of cognitive phenomena, as well as the option of a continuum from relatively simple to much more complex forms of cognition. Third, in this way BEC provides a suitable conceptual framework for the study of cognitive convergence across many and widely separated taxa. Fourth, as the proposal includes humans it will provide a wider context for understanding the basic organization and operation of human cognition and brain processes, most of which we share with other mammals. Fifth and final, this proposal allows a lot of conceptual and scientific freedom in rethinking what cognition is and how it can be best explained, given the empirical findings.

The last point may also be read as a criticism as the proposal allows the study of cognition to move away from existing views on cognition that keep it as an equivalent of mind. Is there a guarantee that the result will provide a suitable account of our own minds? The answer here must be radical: there is no such guarantee and there should not be one. Providing an account of mind—as presently conceived at least—is not a concern for this proposal. As shown in figure 1, this proposal dissociates the study of cognition from the study of mind: the study of cognition—now conceptualized as intelligent phenomena as they occur in living systems—should be conducted on its own accord and develop the necessary concepts and research strategies to further this aim. While one may question whether the crab mentioned above has a mind, it does definitely perceive, act and judge in some form, all of which are definite targets for a biologically embodied cognitive science. Whether or not the notion of mind applies to such cases is not an issue that will be addressed within this scientific project.

While the disconnection from the mind may sound radical within the context of current cognitive science, it actually fits a lot of long-standing and ongoing research on non-human intelligence where the notion of mind plays hardly any role. For example, in her textbook Shettleworth [10] discusses the connections between behaviour and cognition in a way that easily fits within BEC. In the next section, more examples will be given of research that addresses the domain just sketched. The present proposal aims to articulate and integrate these often diverse research efforts by providing them explicitly with a common label that highlights the relevance of this research for understanding intelligent phenomena and that provides a common ground that includes all these cases, including the human one.

Some readers may wonder why the domain targeted by BEC should be called *cognition*—even if used as a technical term. Why not use a different technical term that may cause less confusion? I must stress that a different word could be used, although it is unclear which one. Using the word cognition for the present proposal is just very fitting: embodied and biological approaches to cognition have shown that a lot of human cognition consists of processes that are present in many other lifeforms, even when our common language is rife with the conceptual distinction between mind and mere matter. To stress the need for a clear scientific approach of this common ground, it is a sensible strategy to challenge the standard—mind-related—usage of cognition and to acknowledge the relevance and importance of many organisms with respect to phenomena that we willingly call cognitive in humans. Using the word cognition beyond its current comfort zone will reinforce this message.

Cutting cognition loose from the conceptual context provided by the mind runs the risk of leaving this new interpretation in a conceptual limbo where it becomes unclear what the notion means or refers to. Two considerations should lay this worry to rest. First, by cutting the connection cognition does not suddenly lose its current meaning. Compare it to cutting the rope between two ships that were tied together. Initially, their positions will not be too different, even when it becomes possible to move in different directions. In addition, using current knowledge and considerations it will be possible to formulate a preliminary and modifiable list of features for what we take BEC to be. Lyon [25] provides an example in the form of 'a basic cognitive toolkit' that gives an indication of what such a list could look like.

— *Sensing/Perception* The capacity to sense and recognize (re-cognize) existentially salient features of the surrounding milieu.
— *Valence* The capacity of an organism to assign a value to the summary of information about its surroundings at a given moment, relative to its own current state.
— *Behaviour* The capacity of an organism to adapt via changing its spatial, structural or functional relation to its external or internal milieu.
— *Memory* The capacity to retain information about the immediate (and possibly distant) past, and to calibrate the sensorium to take account of this information, for example via signal amplification.
— *Learning* The capacity to adapt behaviour according to past experience, enabling faster response time.
— *Anticipation* The capacity to predict what is likely to happen next based on an early stimulus.
— *Signal integration* (*decision-making*) The capacity to combine information from multiple sources, because all organisms appear to sense more than one thing, and some bacterial species are equipped to sense dozens of different states of affairs.
— *Communication* The capacity to interact profitably with conspecifics, including initiating collective action, which may or may not include an explicit method of differentiating 'us' from 'them'. ([25], p. 4)

A list such as this one must be considered preliminary and open to revision on the basis of what is discovered in the living world. For now they will suffice to guide research into the right direction.

3. The phylogenetic spread of biologically embodied cognition

How does this proposal for BEC impact on the study of cognitive phenomena? In this section and the next one, I will discuss two different ways in which thinking along the lines of this proposal links up with empirical developments. In the next section, I will illustrate the proposal's potential for conceptual innovation by discussing with the example of early nervous systems. In this section, I will sketch how BEC dovetails with ongoing empirical work that renders such cognition extremely widespread or even universal within the living world. The concept of BEC highlights the many ways in which organisms organize their interactions with their environment, using the capacities named in Lyon's toolbox and possibly others. As successfully interacting with its environment is an essential requirement for any organism, BEC can be expected to be very widespread. Here, I will discuss research on a broad variety of organisms in order to assess the plausibility of this implication.

Animals are the obvious group of organisms that comes to mind when thinking about cognition. Given their complex multicellular bodies, any animal sensing, moving and judging can be considered a cognitive system. While there are enormous differences in complexity and organization between bonobos and pill bugs, the bottom line is that even a humble pill bug has a complex sensorimotor system and an array of normative constraints to respect in order to stay alive and reproduce. No animal is a mechanical stimulus-response machine, unless it is manipulated to behave like one. Once one starts looking with the eyes of a roboticist, all 'simple' sensing and behavioural features show up as major evolutionary accomplishments [18,26].

Bacteria provide much more radical and exotic examples of intelligence, ranging from a wide array of cellular adaptations to environmental circumstances, tracking environmental features and complex social interactions [25,27–29]. The case of chemotaxis in *Escherichia coli* [30] is perhaps most often used as an example for the psychological relevance of bacteria [31,32]. The bacterium can detect a chemical gradient by comparing the amount of a substance at two points in time, by using a two-component signal transduction system that operates as a short-term memory enabling the bacterium to coordinate its behaviour with respect to the gradient. Other examples are the way in which *Pseudomonas aeruginosa* switches between two iron acquisition processes in a way that optimizes cost–benefit ratios or how *Bacillus subtilis* comes to the decision to transform into a state where it is able to take up DNA (both discussed in [29]). Galperin [33] provides a more systematic approach to bacterial cognition by initiating a quantitative genomic approach to assess the number of bacterial signal transduction proteins available in different prokaryote organisms. He argues that the number of encoded signal transducers can be used as a measure of the organism's *bacterial IQ*: its ability to adapt to diverse conditions, while it usually correlates with the phylogenetic position of the organism, its lifestyle, and typical environmental challenges it encounters [33]. All in all, there is a lot of research related to the ways in which bacteria deal with their environment in intelligent ways, and according to the biologically embodied reading of cognition this suffices to consider them as parts of this wide cognitive domain.

A similar story can be told for plants. Plant scientists have found many cases of intelligent behaviour in plants and they are actively promoting the idea that we should see plants as intelligent organisms (e.g. [34–37]). Some even argue that various characteristics of nervous systems are present in plants [38]. Van Loon provides a succinct overview of what plants do:

> They are able to perceive the progress of the seasons, as well as the presence of neighboring plants that may outgrow them, and they adjust their growth rate and morphology accordingly. Plants can 'smell' the volatile fragrances that are produced by other plants of the same or different species in response to, for example, insect attack, as well as gaseous compounds produced by root-colonizing micro-organisms in the soil, and thereupon mobilize appropriate defenses to withstand such potential invaders. Plants can 'taste' which nutrients are present in the soil and react with the development of more or fewer lateral roots. ([37], p. 286, references in the original not included)

Plants easily fulfil the requirements for BEC [39].

For fungi, there is less of an outspoken group of mycologists arguing systematically that fungi are intelligent as is the case for bacteria and plants, the exception being work on the collective behaviour of slime moulds (giant unicellular amoebae rather than a fungus) and some fungi. However, when one looks at the literature with this question in mind, many cases can be found that put fungi on a par with the other groups. The tips of fungal hyphae (tubular filaments that are the basic growth form of a fungus) are capable of invading substrates, show directional growth that is sensitive to various environmental circumstances and are capable of signalling from the tip, which receives the earliest information about ambient conditions to the nucleus that controls development [40]. The interactions of symbiotic fungi with the roots of plants can provide a huge benefit to both, but this depends on elaborate signalling between fungi and plants, where the plant allows the fungus to grow specialized organs inside appropriate plant cells in a way that is highly sensitive to the specific plant structures they invade [41]. The growth structure of fungal mycelia (the fungal network constituted by the hyphae) is very complex, involving sophisticated ways of sensing, decision-making and intercellular communication, all of which are tailored to forage for scarce resources and distribute them across the mycelium [42,43]. Such fungal mycelia are also capable of traversing labyrinths in an efficient way [44,45]. In this way, they may very well perform similar to the strategies used by slime moulds [46,47]. Finally, various fungus species are carnivorous. They catch and eat nematodes in ways that are more sophisticated than any carnivorous plant. These fungi use adhesive knobs and nets, or constricting rings that trap nematodes like rabbits in a snare. Such rings are grown when the fungus detects nematode pheromones [48,49]. In some cases, they develop active adhesive zoospores that move about, functioning like self-moving sticky mines hunting for nematodes [48]. Once the nematode is trapped, or contact made, thread-like hyphae invade the worm and turn the cytoplasm of the worm into fungus. Even when the mycologists do not seem to have advocates explicitly arguing for the intelligent characteristics of fungi, given the capacities of fungi as just discussed, they should be treated as a group that exhibits (wide) cognition.

To conclude, various forms of intelligence that fit the proposal for BEC are very widespread and biologists are beginning to appreciate these findings as a cohering set of phenomena that can be grouped and studied together [50]. This is no coincidence as the proposal was formulated with these findings in mind, as well as the perceived need to find a way to refer to these varied cases in a more systematic way, and the desideratum to position human intelligence in its natural context. Many biologists are reluctant to talk about intelligence, leave alone cognition in non-human organisms. They work with scare quotes when using psychological terms outside the human range, avoid any hints of anthropomorphism, and invoke Morgan's canon to counter undue psychological interpretations. A wide, biologically embodied reading of cognition is cut free from the mental domain and explicitly targets biological cases that exhibit features like sensing, behaving, valuing, memorizing, learning and so on. Very few creatures can do without such skills. As the kind of studies discussed are only now starting up in a more systematic way, it is to be expected that this domain will expand rapidly in the near future, bringing together many new findings and connections between these varied cases. Such developments will have major implications for the study of cognitive convergence.

4. Biologically embodied cognition's take on early nervous systems

Accepting the proposal for BEC implies that phenomena which we can scientifically designate as cognitive are very widespread and basically universal within life. In addition, BEC invites scientific thinking on problems that have so far escaped attention by mind-oriented interpretations of cognition. As an example, I will discuss ongoing conceptual and empirical work on nervous systems that target the problem how animal multicellularity—the foundation of animal cognition—came about.

First, BEC encourages one to look at a broader picture than animals alone. As Maureen O'Malley [51] stresses, life is at heart microbial, while multicellular macrobes such as animals, plants and fungi are the exception. Animals do not constitute a prototypical 'natural' form of life that will self-evidently evolve. They are not basic lifeforms but extremely advanced multicellular organisms that evolved rather late. For a very long time, microbial life existed on Earth without any animals and, as far as we know, life could have gone on perfectly well without them until this very day. The presence of animals on Earth is therefore not a starting point but a problem: How did such often horrendously complex multicellular organizations first evolve and what role did nervous systems play?

Modern-style animals with 'complex active bodies' (CABs) [52] have been around roughly since the Cambrian, starting 542 million years ago [53]. CABs are defined as having articulated and differentiated appendages; having many degrees of freedom of controlled motion; distal senses (e.g. 'true' eyes); anatomical capability for active, distal-sense-guided mobility (e.g. fins or legs); and anatomical capability for active object manipulation (e.g. a mouth, hands or tentacles). Coordinating CABs requires a nervous system, and the origin of nervous systems must therefore be sought in the Precambrian [54–56]. At present, there is a lot of tentative knowledge but not yet a clear picture as to when, why or even how many times nervous systems evolved.[4]

CABs require nervous systems to control the animal's interaction with its environment, but this is not the only function of nervous systems, nor is it self-evidently true that this was their central function at very early stages of nervous system evolution [60]. To systemize thinking about early nervous system evolution, Jékely *et al.* [61] formulated a conceptual option space that sketches two explanatory models and distinguishes three different functions for nervous systems—control of behaviour, of physiology and of development. The two models are input–output (IO) models and internal coordination (IC) models. The models are compatible but emphasize different control tasks for early—and modern—nervous systems.

IO models fit classic information processing, most notably by stressing the role of nervous systems in dealing with sensory information, processing it and producing some form of motor output. Such models easily fit CAB-level animal organizations, as well as the standard interpretation of nervous systems as information-processing devices [10,60,62]. IO models apply more widely though, and Jékely *et al.* provide examples of IO-based regulation also in animal development and physiology.

IC models are less known and focus on the various internal coordination problems that arise when many cells have to work together to act—in the animal case—as an integrated multicellular unit [61]. When life—and BEC—is at heart microbial, the multicellular animal organization cannot be taken as a basic starting point. An account is required that explains how the constituting cells came to cooperate in the specific ways that are typical for the animal organization [63]. Nervous systems can be presumed to play a central role in generating the multicellular unity of animals and IC models address the question how nervous systems contribute to such internal coordination. Chris Pantin [64] provided an early IC model when he argued that early nervous systems were essential to organize and coordinate muscle contractions involving a large number of contractile cells. Keijzer *et al.* [60] provide a modern version of this idea.

As nervous systems are deeply involved in cognition, the presence of both IO and IC features raises important conceptual questions. Given that nervous systems are central to controlling activity both within and outside the body and that both functions involve complex forms of information processing [61], the question must be asked how these functions are related. It is basic biological knowledge that physiology and sensorimotor activity are connected in many and intricate ways. This suggests that the two functions may be better taken together, and that we should ask whether it remains useful to exclude physiological control from the cognitive domain. When we follow common sense, this suggestion may seem absurd: physiology and sensorimotor activity are very different, only the latter being related to cognitive functions. From the perspective of BEC, it is an open issue where to draw such demarcations as they must depend on what we encounter in Nature. As the history of science testifies, being in line with common sense is hardly a way to move science and understanding forward. Thus, one general conceptual merit of BEC is the way in which this interpretation challenges us to be more open to changes in our interpretations of intelligence in the light of new findings and ideas.

Another example from the same context where BEC encourages thinking in new directions consists of animal sensing and the role played by nervous systems here [65]. Sensing itself is present everywhere in the biological domain: each individual cell can monitor its environment in often complex ways. Multicellular sensing as achieved by animals is a different ballgame though. Animal senses tend to consist of extended sensor arrays made up from many individual receptors in a spatial arrangement—for example the skin or retina—allowing animals to perceive macroscopic, spatially extended patterns of pressure and light, and to integrate these patterns into the higher-level perception of surfaces and objects. The important question here is: how do such huge collections of cells come to act together to constitute unified sensory devices, as well as an integrated nervous system that controls the animal's behaviour?

Our current best answer, information processing, remains vague on issues relating to how such an extremely complex multicellular organization maintains its coherence over time, allowing it to function. When it comes to internal coordination, our understanding of nervous systems remains limited [66–72].

Focusing on the origins of nervous systems provides a route towards understanding the operation of nervous systems that targets IC problems more directly. For example, IC models allow a different approach to animal sensing that uses an animal's body movements produced by muscle contractions as a means to detect environmental structure at the scale of the animal's body [65,73].[5] The animal's body itself becomes a multicellular effector and sensing device in one. Early nervous systems may not have constituted an IO device but a controller of spatially organized activity enabling moving and sensing at the same time. While this particular proposal remains very preliminary, it illustrates how thinking in terms of BEC suggests new questions and directions for research that are easily overlooked otherwise.

5. Converging on cognitive convergence?

BEC constitutes a new interdisciplinary domain that targets many different lifeforms and greatly extends the domain that is relevant for cognitive convergence. At this stage, it is impossible to predict in any detail how wider interpretation of cognition would impact on the study of cognitive convergence. Here, I will discuss some general implications that seem to be relevant for further consideration.

— The human mind should not to be taken as the yardstick for cognitive phenomena. There are too many phenomena that do not involve mind in its traditional sense while they fit plausible criteria for intelligence.
— Cognition turns out to be a universal feature of life that can be expected to have diverged into a wide array of forms and levels of complexity rather than a single continuum from simple to complex. It seems very unlikely that there is a global point of cognitive convergence as suggested by Conway Morris [4].
— Cognitive convergence can be assumed to take place (or not) in more specific, restricted areas within the general cognitive domain where, for example, the study of cognitive convergence on human-like characteristics can remain perfectly valid.
— The study of cognitive convergence becomes wider: BEC involves a huge domain of unicellular organisms where specific lifestyles may evolve that provide important targets for convergence studies. At this level, many or even most potential cases of convergence must be presumed to take place at the levels of molecular and cellular organization. For example, the notion of a bacterial IQ [33], or derivatives thereof, may be used as an indicator of cognitive convergence initiated by the need to deal with niches that require a complex lifestyle. In addition, it will be an interesting issue whether all features of Lyon's [25] cognitive toolkit, or of its updates, will be equally widespread or whether there are systematic convergences on particular combinations.
— There is a major organizational shift involved in the transition to multicellular organisms, which will have many repercussions for cognitive convergence. For example, the number of independent transitions to multicellularity is presently set at around 25 [76], while the lineages with complex multicellular organizations remain restricted to three: fungi, animals and plants. The small number of such transitions—even 25 is not a large number—suggests that the route to multicellularity may be highly contingent and could even constitute a bottleneck for the evolution of macroscopic forms of cognition.
— For the three lineages that did make the transition to complex multicellularity, new macroscopic forms of BEC arose, each with their own options for evolutionary divergence and convergence.
— As discussed for the animal case, a differentiated multicellular organization requires complex forms of internal coordination that we might come to consider as a part of BEC.

This short list is just a very tentative indication of possible options for research on cognitive convergence, given BEC. In all these cases, there are new options—and challenges—for articulating possible instances of cognitive convergence that are not constrained by common-sense interpretation of the cognitive domain.

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Endnotes

[1]The same text can be found in the second edition from 2010.
[2]The field has diversified a lot since these early developments. Most of these developments are not directly relevant, but for good overviews see Calvo & Gomila [17], Pfeifer & Bongard [18] and in particular Barrett [19], who discusses the field as a comparative psychologist and behavioural biologist.
[3]An extensive discussion on defining cognition has been triggered by the claims made for an environmentally extended view on the mind (e.g. [20]). The call for a definite 'mark of the cognitive' has become prominent, but this debate is too extensive to discuss here.
[4]For recent reviews of the early evolution of nervous systems see Bucher & Anderson [57] and Strausfeld & Hirth [58] and the references therein. Moroz [59] defends the idea that nervous systems evolved several times independently.
[5]The basic idea derives from sensorimotor theories in embodied cognition where sensing is based on systematic sensory changes brought about by self-initiated motility [74,75].

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