From basic adaptivity to early mind: the origin and evolution of cognitive capacities

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Abstract:

In this paper we try to understand cognition, as a specific phenomenon, that appears in motion-based multicellular organisms. This is due to the fact that when the size of the organism increases, adaptive sensori-motor coordination needs to be accomplished by an internal informational subsystem dynamically decoupled from general metabolic processes. Further increase in the complexity of this informational system (the NS) is also linked to size increase of animals. We will show that only vertebrate bauplan allows those body changes required for the emergence of new forms of cognitive phenomena such as emotions, leading to the appearance of an early form of mind.

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Key words:
Cognitive Capacities, Evolution, Body Plan, Sensori-motor Interaction, Dynamical Decoupling Autonomic Nervous System, Emotion

Outline of the paper:

I) Introduction: What is Cognition?

The appearance and development of cognitive capacities represents probably the most important event in biological evolution because it implies a tremendous increase in complexity, both regarding internal organization of living beings and their ways of adaptive interactions. The phenomenon of cognition is obviously the result of evolution, but not all living beings achieve adaptation through cognitive mechanisms. Animals and plants, for instance, show very different types of lifetime adaptability, and generally speaking, we tend to associate cognitive phenomena with the kind of adaptive interactions of the former more than with the latter, because obviously they show resemblance to our own cognitive processes (especially in some of the animals more recently evolved). But the farther we look back in evolution, the more difficult it is to identify specific cognitive processes. At the same time, it is necessary to trace them back to the most ancient evolutionary stages in order to understand the origin of these peculiar processes. This leads us to the crucial question: Which are the sensible criteria for identifying specific cognitive phenomena, as opposed to the broad biological phenomena in which they are embedded?

Now, this question is loaded by a previous problem, namely, the disagreements about what do we mean by cognition. For example, whilst for some authors the motor adaptive behavior of bacteria is already a cognitive phenomenon (Maturana & Varela 1992, Stewart, 1996) for others it is only possible to talk about cognition when we find at least some trace of consciousness or mind, which seems to happen at some stage of vertebrate evolution. In other words, we can take our own (either human or hominid) cognitive capacities as a model for identifying what is or is not cognitive. Or, alternatively, we could try to broaden the concept of cognition to include the most primitive ways of adaptive behavior. However, in neither case there is an objective justification for the chosen starting point. In the first case because, by leaving aside the whole evolutionary line that gives origin to those capacities, it is difficult to understand their functional origins or their relationship to the whole organism. In the second case because, by dissolving cognition in the broader biological phenomena, it is difficult to understand the nature and the function, even more, the evolutionary history of cognition as a specific phenomenon.

It is impossible to make a real progress in this discussion if we are not able to establish a common starting point. However, in our opinion there is one way of escaping from this dilemma: reformulating the question of the origin of cognition in radical evolutionary terms. Thus, instead of starting with such-and-such concept of cognition, based on purely intuitive criteria, we should try to understand what kind of adaptive mechanisms and under which conditions lead to more complex forms of adaptive interactions. Namely, we should ask questions like these: Which causes could explain the origin and development of bifurcations throughout the history of life in the degree of complexity within organisms and in their types of interactive adaptive capacities? What kind of (new) living organization could underlie it? And, what evolutionary implications would the development of cognitive capacities have?

If we were able to disentangle the basic milestones of the chain of causal events that lead from the most basic forms of adaptation to the first traces of mind and consciousness, we would be in a better position to substitute intuitive criteria with a more objective view of cognitive phenomena. Accordingly, in this paper we will try to sketch a genealogical explanation of cognitive phenomena. We will study the appearance and development of certain capacities, instead of from the point of view of the role they play in human cognition, focusing in what processes have brought them about, what structures have supported them and what functions they have served in the evolution of living beings. Thus, in this genealogical approach we would try to understand the different levels of cognition from a more encompassing (biological) perspective.

II) The origin of Basic Cognition

i) Adaptivity and movement in unicellulars

Any individual living being is essentially an autonomous system that interacts adaptively with its environment. Except some kinds of bacteria which live in very homogeneous and stable environments, all present day organisms posses the capacity to change in somatic time their forms of action according to different environmental conditions. Organisms have the capacity to detect those modifications in the environment that are relevant for the maintenance of their own organization and to trigger some internal and/or external processes contributing to their self-maintenance in each of these particular conditions. In order to do so, they choose one particular metabolic pathway among the repertoire available according to the particular state of the environment relevant to the functioning of the system.

The basis for adaptive action lies in the fact that organisms need to exert certain actions on their (changing) environments just to keep their metabolism going (Ruiz-Mirazo & Moreno, 2000, Christensen & Bickhard, 2002). These actions are accomplished through some functional modifications of its plastic metabolism, tuned to relevant environmental changes. In bacterial life adaptivity lies in the capacity of selectively controlling the expression of the genetic repertoire of the cell, thus enlarging its metabolic plasticity when certain external conditions occur. Despite its simplicity, this basic mechanism allows a great variety of forms of adaptive action.

Now, among the different forms of adaptive agency, motility is particularly interesting because its intrinsic relation with velocity and distance. Motility is the capacity to exert directional and *fast* movements according to *distal* conditions. Although the bacterium does not "detect" distant features, as it only "senses" the medium through certain contact proteins, its action as a whole can be interpreted as if directed by a distal goal. Bacteria such as E. Coli are equipped with mechanisms –flagella-- that allow them to move following concentrations of sucrose (Neidhardt, 1996). And this is accomplished even though it may mean a significant metabolic waste, i.e., to swim against a gradient force. This capacity would be the result of co-ordination between membrane receptors and motor mechanisms, mediated by metabolic paths in the inner cell (Losik & Kaiser, 1997, Hoffmeyer, 1998).

However, in the primitive forms of life motility is not substantially different from other forms of adaptability. For example, when the prokaryote *Caulobacter* lives in a very humid medium it persists fixed to the soil like a vegetal type, whereas, in dry periods, it reproduces and the new cells grow a flagellum capable of transporting them to a more humid environment. So, the interactive loops established by the most primitive organisms with their environment are always contrasted and evaluated according to the effects they have upon their basic capacity for self-construction (or self-maintenance), which is their main normative goal. In fact, in eukariotic cells, body movement could be considered as just an extension of the set of mechanisms that are required for a minimal metabolism. So, capture of food by means of body movement (as opposed to exploitation of primary energy resources or fermentation processes) does not entail qualitatively important differences in adaptation mechanisms. At this level, the underlying organization of behavior and of morphological change is basically the same.

Now, this situation of indistinguishability begins to change as the size of organisms increases. Unlike other forms of adaptivity, at bigger sizes the organization of motility faces new problems raised by the need of fast internal coordination between detection and action. Accordingly, when eukaryotic cells appeared, motor responses had to be organized in a different manner than in small prokaryotes. Instead of organizing functional changes only by means of diffusion processes, eukaryotic cells are equipped with mechanisms allowing a precise and speedy distribution of substances. These --comparatively-- big[1] cells are capable of rapid movement because they possess microtubules, which contribute not only to chemical channeling and plastic reorganization of selected parts of the internal structure of the cell, but also to external movement by means of undulipodia[2]. External eukaryotic organs for movement, like cillia or flagella, are much more complex structures than prokaryotic flagella, and adequate coordination between detection and motor tasks also requires more complex internal organization. But this new organization conveys a conflict between simultaneous movement and reproduction (Buss, 1987, Maynard-Smith & Szathmary, 1995). This conflict is already pointing to an organization problem that will become more critical with the appearance of bigger organisms in evolution: the increasing difficulty in organisms of bigger sizes for the basic metabolic organization to efficiently support quick and versatile sensori-motor actions. As the size of the organism increases, the energetic and material costs for the metabolic organization to provide a rich and plastic enough system of internal patterns for supporting fast

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[1] The size of eukaryotic cells is around 10.000 times bigger than that of prokaryotic cells.

[2] In some cases, fast movement is accomplished thanks to symbiotic association with certain prokaryotes, like spirochaeta.

sensori-motor coordination tasks become incompatible with the accomplishment of the very function of self-maintenance.

ii) The appearance of the neural organization as an autonomous level

The appearance of multicellular organisms was a critical point for the organization of motility. At this size it becomes impossible to organize, based on metabolism alone, quick and versatile sensori-motor actions. There are two causes of this problem: the enlarged internal distance between parts of the body, which need to be connected in short delays (so that the organism can move fast); and the need to selectively modulate the organization of connections (to get the adequate sensorimotor correlations). Hence, if metabolic network plasticity were the only mechanism for accomplishing adaptive interaction and self-maintenance, the behavioral repertoire would probably be very limited at the multicellular size[3].

The situation changed when in the development of some metazoans (the so called eumetazoans, which already developed tissues, mouth and digestive cavity) a new kind of cell –the neuron-- started to differentiate. The neuron is a cell specialized in connecting sensorimotor surfaces in a plastic, fast, and (metabolically speaking) cheap way. Neurons differentiated as cells capable of forming branches, which may be interconnected through ion channels (controlled either by the electrical potential over the membrane or by ligand) in their membranes. These interconnected cells led to the establishment –about 600 mya-- of a network able to manage an efficient coordination between sensor and motor/effector structures in multicellular organisms (Llinás, 2001). These networks were highly plastic because of the specific bio-chemical properties of neurons that permit stimulated dendritic branching on short timescales, entrained assembly depolarization, and a host of like basic properties.

Since the very beginning of its evolution, this neural organization appeared as an extended network capable of producing a recurrent dynamics of specific patterns. Unlike chemical signals circulating within the body, which directly interact with metabolic processes, chemical or physical interchanges among neurons make recurrent interactions within the very Nervous System (hereafter, NS) possible, thus generating a new domain of patterns, specifically informational[4]

What makes neural interconnections so special is that they create an incredibly rich and plastic internal world of patterns of fast connections, dynamically *decoupled*[5] from the metabolic processes (Moreno et al, 1997). The nervous interactions obey a dynamics (or a set of rules) not governed by the general metabolic organization: it constitutes a new, autonomous, level producing new phenomenology.

However, the possibility of this autonomy lies in the embodiment of the NS in a self-maintaining organization interacting in a given environment. Thus, the autonomy of the NS is both required and limited by its functional role. Ultimately, the logic of the activity of the NS

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[3] The case for plants with quick movement capacity is obviously a marginal case. Quick plant movements can be considered a consequence of coordination mechanisms that are not essentially decoupled from general metabolism, For example, in Dinee plants, rapid closing movements of the leaves involve changes in water pressure controlled by metabolic mechanisms (Simons, 1981). As a consequence, this form of motility lacks flexibility and plasticity, and therefore there is no possible an evolutionary increase in the complexity of the motor response.

[4] In a neural network certain physico-chemical events such as spikes and patterns of spikes can be described in informational terms for the following reasons: First, neural states can switch body states by configurational rather than energetic means (Cariani 2001). And second, being dynamically decoupled from metabolic processes, these configurations can recursively operate on themselves, producing a kind of “formal processing”.

[5] A phenomenon of decoupling appears when a system gets organized in such a way that 1) a part of this system constitutes a new level of interactions which operates according to a set of rules independent of the dynamics of the low level (the remaining system) and 2) both levels become causally connected in such a way that they depend on each other. Thus, each level appears as a relatively autonomous system, though, as we have stressed, both are mutually dependent.

depends on its participation in the logic of the global maintenance of the animal (its metabolism requires an adequate sensorimotor activity). And, in turn, metabolic organization supports NS´s construction, functioning and maintenance. Thus, NS and metabolism are connected in such a way that their respective maintenance (and therefore, existence) depend upon one another.

iii) A new organization of the body

The rich plasticity of the NS allows for a qualitative increase in the complexity of the adaptive behavior of multicellular organisms. As a result, individual adaptability does not rely mainly on changes in body structure, but in the neural network. Thus, for these organisms --animals-- behavior, understood as functional body movement, is the most important way of adaptability: their metabolic self-maintenance is mainly produced through neurally controlled secretions and motor actions.

Now, in addition to allowing quick and efficient motility for organisms with body masses bigger than protozoans, the appearance of the NS opened up new, qualitatively different, modalities of adaptive interaction. Already at early stages of NS evolution, we can see some rudimentary learning, categorization and memory capacity (Arhem & Liljenstrom, 1997). We tend to identify the main significance of the appearance of the NS in terms of the development of these capacities --and very soon new others, such as associative learning, communication and social cooperation-- because they begin to appear as specifically cognitive[6] (insofar as these capacities apparently show increasing similarities with ours). However, from an evolutionary perspective, the importance of these new capacities lies mostly in the cascade of changes that they opened. The appearance of the NS enabled new radical changes in the body design, but its further development was only possible when new, very specific, body changes appeared.

Therefore, it would be an error to see the problem of evolution of cognitive capacities as a question concerning only the construction of increasingly complex and broad neural networks coupled to more complex sensorial and motor structures. Animals are much more than sophisticated robot-like systems, since their NSs, instead of controlling only sensori-motor organs (as in robots), are embedded in a biological (metabolic) organization. For example, the NS indirectly participates in the functioning of metabolism through the so-called neuroendocrine system[7]. And in turn, metabolism ensures the adequate maintenance of the NS (construction, repair, and adequate energetic supplies). This fact is not only important for their mutual maintenance, but for the constraints that each other imposes in their respective evolution. The organizational and structural consequences of the constraints that the evolution of each subsystem imposes on the other can account for many important aspects of the cognitive phenomenology. Hence, the basis of cognitive phenomena does not lie ultimately only in a special subsystem --like the NS-- but in the functional relationship between this one and the whole organization of the animal.

Accordingly, the potentialities of the NS cannot be developed independently of changes in the general organization of the body. On the contrary, as Chiel and Beer (1997) have pointed out, the appearance and development of more complex kinds of adaptability is the result of

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[6] These phenomena can be explained as the result of the development of the NS as a recursive network of informational patterns that control sensori-motor actions so as to achieve certain goals required for the survival of the organism. As has been shown in the last 20 years, simulations of the dynamics of interconnected idealized neurons (Neural Networks) can account for a variety of tasks considered as cognitive ones (such as categorization, memory, pattern recognition and associative learning). All these capacities are possible thanks to the almost unlimited potentiality for internal configuration processing that these neural networks possess.

[7] In comparison with NS, the functioning of neuroendocrine system is slower and more durable. As we will see in next section, in certain animals, in addition to the neuroendocrine system, there is also a direct takeover by the NS of some body functions.

interactions and constraints between the dynamics of the NS, the rest of the body, and the environment. In an animal, body organization is configured or shaped by the very evolution of the NS (and conversely), so that, to a high degree, both the NS and body organization are complementary. For example, not only has the muscular system been developed by evolution in a narrow interrelation with the increasing in complexity of NS, but the organization of internal circulation, the system of fixation, and even the body shape have as well.

Thus, basic potentialities of the NS to support complex forms of adaptive behavior cannot be unfolded only on the basis of more complex neural networks, if these are not accompanied by new ways of organization of body structure (bauplan). However, once fixed, a body plan becomes a constraining factor in the evolution of a given line of animals, since adaptations only take place inside the architectonic limits of the ancestral body plan (Hickman et al., 2001).

III) The origin of Mind

i) Size, motility and body plans

By the early Cambrian, a rapid development of both NS and body plans took place (Raff, 1996), and a variety of relatively complex adaptive behaviors appeared. From the beginning, the evolution of the NS –as of other important features of the body plan-- has taken two different paths. On the one hand, there is the line of protostomes, where the neural cells assemble themselves in a ventral nerve cord. The evolutionary trend of these NSs has tended towards accumulating neural cells into groups (ganglia) distributed along the body. On the other hand, there are the deuterostomes, whose NS has evolved into a process of first assembling neurons in a dorsal tube and later centralizing the bulk of these neurons in one mass, near the sensorial organs (encephalization). In fact the more complex development of the NS appears only in the second line (the deuterostomes), from which vertebrates have evolved.

This divergent line of evolution of the NS poses an important problem. The origin of phenomena such as emotions and awareness, tightly related to other cognitive capabilities such as complex self-directed learning (Christensen & Hooker, 2000) and mental representations, is linked to the second aforementioned evolutionary line. Now, since relatively simple forms of the NS seem to be sufficient for allowing complex and diversified behavior patterns, what kind of role a bigger neural development would play? What kind of causes would explain the appearance and development of these new phenomena? And why do this development have occurred only in a particular evolutionary line (that of vertebrates)?

As we shall see, here again, the answer is related to the issue of size. As happened before when multicellular organisms appeared, new increases in size posed serious problems to the organization of versatile and strong motility. In fact, in bigger animals control of movements gives rise to structural and organizational problems: Let us mention just three examples: first, movement of big body masses requires some surface for muscles to be inserted in. In invertebrates this is accomplished to some extent through the external skeleton, but for bigger body masses it would have to be too heavy, and body growth would also be constrained by this external rigid cover (Storer et al,, 1979). Second, whereas small animals do not require special means in order to distribute nutrients and oxygen, or in order to collect their residual substances from catabolism as all their cells are close to nutrient sources and environment, bigger animals need more complex and closed circulatory systems (Nilsson & Holmgren, 1994). And third, the time needed for motor reaction increases. Whereas small animals can modify their movements very quickly (for instance, certain flies can change their flight within a few milliseconds (Downer, 1988)) animals with bigger body masses usually require much longer response times.

There are several reasons that explain why invertebrates bauplan precludes versatile motility at big corporal size.

- Skeleton: Invertebrates lack internal skeleton, which poses a problem (for big size animals) since there is not adequate place for seizing muscles that have to realize quick and forceful movements. Vertebrates, on the contrary, possess an internal skeleton, allowing for more powerful muscles, which in turn allows for more efficient movement. An internal skeleton is also important for allowing a more complex and precise control of movement. From the evolutionary point of view, its origin seems to be related with a progressively predatory way of feeding --which requires strength in several muscles of the body-- instead of feeding through substance filtering (Purnell, 2001). An internal skeleton also has more capacity to attain larger sizes than an external skeleton.

- Circulatory system: Invertebrates usually have open circulatory systems: blood is pumped into a body cavity (hemocele) and then runs freely through tissues. This system is not very efficient for bigger animals, as there is not enough blood pressure that can move blood rapidly through tissues. As a consequence, this system cannot provide the energetic supplies needed in each particular part of the body quickly and efficiently. Though big invertebrates have closed circulatory systems, this is far from vertebrate´s circulatory systems, in which blood circulates through a complicated pipe system that distributes it to every corner of the body at proper conditions of pressure and flow, which translates into speed and efficiency at the level of motor actions (Storer et al, 1979). What invertebrate closed circulatory systems lack is a fine tuned mechanism for controlling the conditions of the flow at each place and time. Efficient and versatile motor control at bigger sizes requires proper pressure and flow of nourishing blood, which in turn requires not only that the pipe-system is closed, but also a control system to regulate this pressure and flow depending on different internal and environmental circumstances. This is achieved by a system of receptors distributed along the blood vessels, which detect pressure of blood, oxygen concentration, and acid level (Sherwood, 1997). These receptors are connected to the NS, but the link is through the so-called Autonomic Nervous System (ANS), that we will describe latter. The ANS can then modify pressure and flow of nourishing blood in different body areas and organs by means of a direct neural control of contraction or dilatation of vessel wall or of hearth functioning. This kind of closed cardio-circulatory system allows for proper working of the muscles in a quicker and more efficient way, which improves animal movement. Therefore, only a circulatory system such as this allows the muscular system to mobilize a big body mass with speed and strength. This also implies fine control (through a highly efficient circulation of hormones, peptides and other regulatory substances) of the metabolism of other internal organs (viscera), so that there is fine modulation of different organs and their functions: digestion, respiration, sexual activity, immune defense.

- Immunity. Invertebrates do have a primitive immune system that lacks capabilities for memory and specificity (Beck & Habicht, 1996). Such a system becomes inadequate as the complexity of the circulatory system increases. Vertebrate’s circulatory system requires a new type of immune system. As the distribution of beneficial substances is facilitated, toxins and potentially harmful substances have more ease to enter into distant and vital parts of the organism. This is why a complex system of defense circulating along the vessels is needed, that is, the cellular immune defense system with its capacity for immune memory.

As a consequence, big size invertebrates (pogonophores, giant cephalopods and others now extinct[8]) are exceptional, and the ecological niches they occupy are also marginal. Even middle-size invertebrates, like octopuses, live in the limits of the functional capacities of their body plan. For instance, octopus’s circulatory system only allows them to perform short time

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[8] Other big invertebrates, such as the giant millipedes that existed during the mid Paleozoic, disappeared as soon as land predators appeared.

muscular efforts. Lacking fine tuned control of blood circulation, they tire easily and their vascular system is forced to work close to its physiological limits (Abbott, 1995).

So, in summary, radical changes in body organization were required to produce bigger animals, capable of motor versatility and efficiency. The appearance of animals whose body plan permitted these changes –the chordates-- happened very early. From these animals evolved the primitive vertebrates, nearly 500 my ago, and the basic structure of the vertebrate brain was established by 480 my ago (Miklos et al. 1994). Ultimately, however, all this was the result of the appearance, about 525 my ago (that is, during the Cambrian radiation), of a new bauplan –that of chordates-- whose latent potential became progressively unfolded through an evolutionary process of interplay between the appearance of some of the aforementioned features and subsequent evolutionary changes. As we will see in the next section, these body changes will both require and make possible critical changes in the NS organization and complexity. At the same time, these changes opened up a process of reorganization of the relations between body and NS, leading to the appearance of new forms of cognitive agency.

Next we are going to see the origin and consequences --both organizational and structural-- of these changes.

ii) Implications for the NS.

One of the most significant aspects of the evolutionary history of vertebrates is the process of encephalization, namely, the increasing concentration of neurons in the head. This process was probably the result of a complex set of causes that operated in different evolutionary stages and on different kinds of vertebrates. Although a complete study of these causes is out of the scope of this paper, we will try to understand here in terms of the body design, which factors have allowed a process of encephalization. Thus, from this perspective, the development of a new, fine tuned circulatory system was fundamental because it provides fine blood input regulation for the adequate functioning of big neural concentrations. In turn, these neural concentrations –through the ANS-- allow for a fine control of the circulatory system. Thus, there is a kind of feed-back between the evolution of the NS and the above mentioned changes in body organization. Vertebrate’s ANS controls an adequate blood flow and pressure (through rhythm and strength of the heart and contraction/dilatation of the walls of the vessels) that maintains nutrient and oxygen intake in tissues far away from the external surfaces of the animal. This, again, requires more neural resources.

The increasing complexity of the NS in vertebrate evolution is also facilitated because it is embriogenically developed around the walls of a cylindrical cavity and is therefore favored by nourishment from the inside, as well as from the outside limits. In invertebrates neural concentrations are just accumulated one over the other with less room for nourishment structures. Even with a closed, efficient circulatory system, a fine energetic maintenance of this kind of increasingly big neural concentrations would be difficult (Montalcini, 1999). Last, but not least, in vertebrates, the conduction of electrical impulses through axons is facilitated by myelinization, which is absent in invertebrates.

However, the key difference of the vertebrate’s NS lies in its internal organization. Whilst the NS of invertebrates is fundamentally a distributed network of neural sets (ganglia) devoted to the organization and coordination of sensori-motor activity (besides an indirect control of metabolism-viscera through the neuroendocrine system), in vertebrates an important part of neural resources is devoted to control the metabolism (through direct neural modulation of the functioning of different viscera, like circulatory and respiratory systems), and this task becomes decoupled from sensori-motor control tasks[9].

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[9] The basic way for the NS to control the functioning of the body is through the neuroendocrine system, which operates through highly specific substances (hormones) distributed by the circulatory system. Instead of the

In invertebrates clusters of ganglia usually at the anterior end of the animal make up the brain. These ganglia exert control over the body segment ganglia. It is well known that in certain invertebrates the brain could reach a considerable development. Of special interest is the case of cephalopods, which constitute the most developed case of encephalization[10] in invertebrates. According with this development of their brain, certain cephalopods show remarkable learning capacities and other forms of complex behavior (for instance, in some cases they use their capacity to control changes of skin texture and color either for mimicking different fishes appearance or for social communication (Griebel et al, 2002)). However, this seems to be the limit of neural complexity in invertebrates, since further evolution in their cognitive capacities would require a different bauplan (capable for example, to support at the same time large body masses and big variety and versatility of sensori-motor interactions in terrestrial environments). But this would require a radical change in the organization of the NS, including some structure capable to exert a fine tuned neural control on the functioning of the viscera. So, eventual evolutionary increases in the size and complexity of invertebrate's brain could not be functionally recruited[11].

Thus, the importance of the ANS for the evolution of vertebrates cognitive capacities lies in the fact that it is a key element in a new organization of the relation between the body and the NS. The ANS is a subsystem of the NS that receives information from all the viscera, integrates it by means of its own control centers, independently from the rest of the NS, and sends efferent instructions back to viscera so as to maintain adequate homeostasis. The rest of the NS --NS less ANS-- is now increasingly specialized for control of sensori-motor activity independently of coordinating metabolism, and we shall refer to it hereafter as the Somatic Nervous System (SNS)[12].

Together with the SNS, there are the structures which provide a coordination mechanism between sensori-motor cognitive tasks brought about by the SNS, and internal organ control tasks brought about by the ANS. Coinciding with the appearance of reptiles (about 310 my ago) appeared a specific structure in the brain labeled as Limbic System, which is a system of interconnected nuclei that bridge the ANS and the SNS (Gloor, 1997). This system organizes the flow from the ANS to the SNS of both neural connectivity and secretion of peptides, and other neuromodulator substances that can modify qualitative aspects (such as speed) in the operation of many brain circuits. Limbic system organizes the flow back from the SNS to the ANS as well, by means of neural connectivity. In addition to that, limbic system also organizes secretion of hormonal substances in the blood stream that affect functioning of viscera.

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neuroendocrine system, which is based on diffusion and is largely distributed, vertebrate's ANS is a centralized system which operates mainly through direct, fast neurally channelled control.

[10] In certain big octopuses like the Red Octopus of North Pacific, the brain can attain a considerably large size, containing more than 170 millions of neurons (Wells, 1978). However, the potential cognitive capacities of this increase in the size of brain are strongly restricted by the low conductivity due the lack of myelin: Cephalopods compensate this inconvenience by increasing the diameter of the axon, but this strategy precludes the development of more complex brains.

[11] We cannot discard that something functionally similar to the ANS could have appeared in the evolutive history of invertebrates. However, the potential functional advantage of such invention would only be recruited if other changes in the organization of the body would occur simultaneously, so that a feed-back between ANS and new, more complex bauplan were established.

[12] Under the word Autonomic Nervous System some authors consider only the peripherical nerves that connect viscera and the central nervous system. However, we consider, following A. Damasio (1994) as well as Shepherd's (1994) ideas, the ANS as including the control nuclei for these peripherical nerves and we thus follow this critical functional division of the nervous system between the Autonomic (dedicated to homeostasis) and the Somatic, which is in fact the bulk of the NS and is more related to interaction with the environment by means of sensorial and motor phenomena. Some authors will even conceptualize both the Autonomic and the Limbic systems under one system.

As Edelman (1992) points out, both the Autonomic and the Limbic systems constitute "a system of the interior" as opposed to the "system of the exterior" that would be constituted by the SNS. According to this author, the system of the interior is composed of different structures that were selected during evolution to match the body, more than to match that large number of unanticipated signals from the outside world. These systems evolved to take care of body functions and are connected to body organs. On the other hand, the system of the exterior would have evolved to receive signals from sensory receptors and to give signals to voluntary muscles. It evolved to permit increasingly sophisticated motor behavior.

In summary, vertebrates have developed a complex visceral system, with its own fine-tuned control mechanisms, thanks to the aforementioned reorganization of their NS in two structural and functional separated parts. Although the origin of this separation remains unsolved, a feedback between the organization of the body and that of the NS took place very soon in the evolution of vertebrates. This process was probably one of the crucial factors explaining the process of encephalization in vertebrate's evolution[13]. It is tempting to suggest that the development of the ANS and the appearance of the Limbic system is related with the colonization of a terrestrial environment, since aquatic environment seems less favorable for the evolution of cognitive capacities than terrestrial one (terrestrial life faces a far more stressful range of environments than marine life (Raff, 1996)). This hypothesis is congruent with the fact that certain reptiles (i.e., crocodiles) show also a more evolved SNS (a first form of neocortex).

iii) A new decoupling

Among all the changes that the appearance of vertebrate's bauplan has conveyed, the reorganization of the NS in two separate parts was particularly crucial. As we have pointed out at the beginning of this part, the importance of this reorganization lies in the fact that it allowed a feedback between the development of more complex circulatory systems and an increase of neural concentrations in the brain. However, another non-less important consequence of this reorganization was the fact that the ANS has to be, to same extent, independent of environmental circumstances, and hence independent of sensori-motor activity, although coordinated with it. In that sense, whilst the SNS works according to complex decision-making processes, the ANS works according to relatively more simple thermostat-like reflexes, in order to maintain basic homeostasis in the organism (Kandel, 1995). This functional independence of the ANS is the fundamental element that will allow for a new line of evolution on the basis of a new body organization, since it frees the SNS from the increasingly complex tasks of controlling internal functions.

Thus, the ANS is dynamically decoupled from the rest of the NS in the sense that it is a network whose components change independently of sensori-motor interactions. The ANS constrains the flow of neural information in such a way that the maintenance of the metabolism is ensured, together with a successful behavioral action. In turn, the SNS ensures, through the control of (sensori-motor) behavior, the recursive maintenance of the ANS. Interestingly, the relation between these two decoupled neural systems is mediated through the metabolic organization (Figure).

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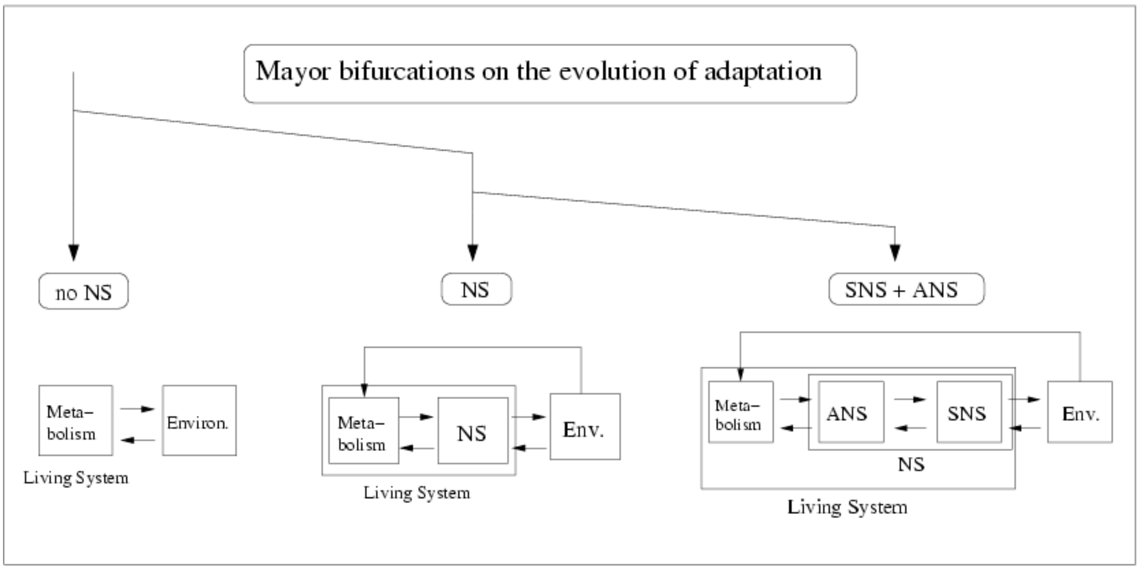
[13] However, this process was not an automatic result of the new bauplan, since it required the participation of many different causes (like, for example, the colonization of terrestrial niches). Thus, our point is that the new bauplan *permitted* the encephalization process, whereas the remaining ones, for different reasons, precluded this process.



Figure

But, actually, which is the reason for visceral control tasks to require the appearance of a functionally autonomous subsystem, instead of just a more complex centralized brain? When body organization became more complex, the NS had to take faster and finer tuned control over the organization of internal tasks. But since this system is implicated in the control of both movement and metabolism, as both tasks increased in complexity, the functioning became less and less efficient and increasingly unreliable. In fact, sheer coordinative burden reduction will require a new decoupling (this time within the NS) because it provides increased behavioral and thermodynamic efficiency. When a certain complexity threshold is reached, the only operative solution for controlling very different tasks requires a decoupling of the initial system into two different systems, whose respective dynamics each control a different kind of process (although this requires establishing a coordination system at another level).

The ANS, due to its relative autonomy from the external environment and due to certain physiological characteristics of its neurons and circuits (which are capable of becoming polarized and depolarized spontaneously) form the basic drive from which initial activation of the NS is derived (Peters, 2000). Now, this initial activation is necessary for the NS in order not to be completely driven by the environment. The organism needs to adapt to the environment, but sometimes it also needs to activate itself on its own.

An indirect consequence of this feature is a change in the functional relation of the NS with the body. As the ANS is sensitive to internal changes induced by stimulii originated in the viscera, it monitors need states that selectively control cognitive functions. This allows for a much more complex modulation of cognitive activities than in invertebrates. Thus, there is an indirect coordination between the ANS and the SNS through metabolism.

iv) Emotions. Their functional role.

As we have already mentioned, the creation of two relatively independent structures in the NS requires new forms of coordination between them. Since the main control tasks of both Autonomic and Limbic systems are related with the functioning of viscera, at least part of the relations between the SNS and the Limbic and Autonomic systems is mediated by the viscera. Accordingly, the connection between the (nervous) system of the “interior” and of the “exterior” implies a constant feed-back between (both structures of) the NS and the internal organs. As Damasio (1994) has pointed out, this coordination between the "cognitive" and the "visceral" NS implies an understanding of emotional phenomena as an ongoing feedback between the environment, the SNS, and the ANS, mediated by changes in visceral and metabolic states, so that the mutual coupling can be fast and precise enough and so that these viable interactions become patterns to be remembered. Thus, according to this view, emotional processes happen not only in moments of stressful circumstances with high level of arousal of the organism, but also at any time.

Due to the fact that emotions arise at the level where this connection occurs, they play an essential role in reorganizing and selectively evaluating highly complex options of behavior. Therefore, emotions will play an important role in strictly cognitive tasks: they allow some kind of perception of hypothetical future consequences for the body according to different behavioral options. This means that the animal will be able to anticipate consequences of motor behavior on the visceral part of its body and general metabolism. This anticipation will also require the use of some kind of mental representation[14]. These representations or internal models are not directly connected to motor organs, but linked first to internal viscera by means of emotional phenomena. They will be fundamental for (the specification of) complex behavior and their role for behavior control seems to be in vertebrates much more complex and indirect than the role of neural configurations that control stereotyped behaviors in invertebrates. These representations will also require, in order to be translated into behavioral actions, some kind of high order processing. Basically, it will be needed to evaluate possible consequences of internally anticipated behaviors, taking into account emotionally remembered or perceived experiences of the past. A similar idea has been pointed out by Bickhard (2000) who holds that emotions play a crucial role to handle uncertainty of environmental highly complex situations. According to this author, emotions would be a special kind of internal process, which consists of interactions with the animal’s own internal uncertainty about how to proceed and to anticipate the interaction with the environment. Thus, in complex situations, the animal interacts with its own uncertainty, instead of directly interacting with the environment.

As Dennett claims (Dennett, 1996), emotional mechanisms include simulating and rehearsing behavior trials not in the external environment, but in the internal environment of the animal, that is, in their own body. This process would generate emotional feedback signals to the brain which are used as evaluative mechanisms for those behaviors. Thus, an emotional experience would typically start with the perception of an external stimulus (can also be internal) by sensory regions of the brain (SNS). It is followed by some analysis by other SNS structures, regarding stimulus qualities. From here signals are sent to limbic structures. These are relay structures from where other signals are sent through the ANS to the viscera of the body, such as the heart, stomach, etc. These signals have some pleasant or unpleasant consequences in the functioning of these viscera, which are signaled again to the brain. Here we have further analysis by SNS structures, and finally some kind of response to the original (external) stimulus (Ledoux, 1996).

Last, but not least important, external expression of emotions gives rise to the need of perceiving, interpreting and reacting to other organisms´ emotions (and hence, behaviors) thus contributing to a new way of communicative and social behavior (Shepherd, 1994). It will constitute the fundamental basis of nurturing behavior. It also plays an important role in predatory behavior as well, and in general in both competitive and collaborating aspects of social behavior. These kinds of behavior, at the same time, produce pressure for cognitive complexification. They are closely correlated with (and contribute to) the development of vertebrates limbic system (Gloor 1997) and further in evolution, also to a special part of the ANS related to control of facial muscles (cranial or social autonomic nervous system (Porges 1997)), which is very important for nonverbal communication (movement of lips, muzzles,

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[14] Though a serious analysis of the problem of representation is out of the scope of this paper, the following is just a brief comment suggesting a direction for further exploration.

scalp and external ear flaps, for example). This mentioned cranial or social component of ANS is developed in mammals.

v) Summary

Let us now summarize all these issues. We have intended to analyze how the decoupling within the NS itself enables a qualitative increase in the complexity of cognitive capacities in evolution. In the course of the evolution of vertebrates an increasing part of neural processing becomes decoupled from direct behavior control, because it is devoted to the internal visceral control tasks and to coordinate all this with a sensori-motor activity. Some time, probably when vertebrates were capable of complex and fast terrestrial movement and their brain attained a certain threshold of complexity[15], this neural activity devoted to the control of behavior through emotions became the basis of what will constitute the "mind", understood as a kind of slower, second-order neuro-somatic activity by means of which the animal is able to perceive a basic sense of self. This sense of self or basic awareness would be linked to new and more complex forms of coordination between the Limbic system and the SNS (Edelman 1992) or even involving the viscera (Damasio 1994, 1999)[16]. Thus, instead of a fast, reactive, kind of adaptive agency, mind appears as a non reactive (anticipative) control of sensori-motor behavior, based on a kind of neural processing, which implies an ongoing feed-back between the environment, the SNS and the ANS mediated by changes in visceral and metabolic states. This non-reactive kind of agency is probably a consequence of the fact that in the animal some neural configurations, instead of being directly used to control action, contribute to build internal models of reality (virtual interactions with the environment (Coterill, 2001)). These internal models, assisted by emotional phenomena, allow for more complex ways of anticipatory behavior, like self-directed learning, and probably also for some form of awareness.

IV) Concluding remarks

In this paper we have attempted a travel from the most primitive forms of adaptive behavior until the earlier manifestations of the mind in animals, trying to understand from an evolutionary point of view the specific nature of cognition.

As we have argued, any form of life based on motility has to develop more complex forms of agency if, given sufficient time and conditions to evolve, its size increases significantly. But as a specific capacity, the origin of cognition is related with the functional organization of movement in multicellular organisms through NS, conceptualized as an internal subsystem supporting sensori-motor interactions, dynamically decoupled from metabolic processes. This decoupled system is necessary for the maintenance of these organisms through control of functional behaviors, but at the same time it is built, maintained and evaluated by the metabolic network. Cognition emerges then as a special kind of

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[15] For reasons that are not yet well known, in mammals was produced a significant increase in the neocortex. It has been suggested that during the long nocturnal period of mammalian evolution there was a growth in olfaction and a change in the thalamic pathway for visual processing, leading to a complexification of the neocortex (Aboitiz, 1992). This phylogenetic process was produced exploiting the ontogenetic capacity of neurons for migration and formation of new pathways in the central NS (Gerhart & Kirschner, 1997). Thus, according to these authors, it is possible that simply removing a constraint on growth may have been all that was necessary for neocortex evolution.

[16] According to this author being aware of something (stimulus or own action) would be the process of linking the sense of self to that stimulus or action. That is, an animal is aware that its actions and perceptions are related to its own body. Thus, the animal needs a continuous feedback from viscera and other homeostatic detectors in order to have a sense of self, that is to be aware of the state of its own body, potential dangers or its state of pleasure or needs at any moment. So awareness means a bidirectional link, on the one hand towards the viscera and in general to the metabolic side of the body through emotional phenomena, and on the other hand to the environment trough sernsori-motor coordination.

adaptability through macroscopic movement decoupled from metabolism (behavior). And this decoupled internal system, constituted by informational processes, is what supports the progressive emergence of a new kind of interactions: the cognitive interactions.

The entangled relation between the basic biological processes and the cognitive ones brings about a new, qualitatively different evolutionary process. Within this frame, the development of cognition appears as a strongly embodied process, where the potentialities and limitations of various basic body designs proved to be enabling or necessitating for further evolutionary development of new cognitive capacities, while others hit apparent ceilings. Cognition generates organisms whose maintenance is progressively more dependent upon their behavioral actions, which become, on their side, progressively complex. From this fundamental organization, increase in body size, among other factors, will lead to the development of new ways of decoupling affecting the NS itself, which imply different relationships with the rest of body organization. This new decoupling within the NS happens in vertebrate evolution, where a part of the NS, the Autonomic NS, controls viscera and indirectly controls metabolism, whilst the rest controls sensori-motor interactions. This second decoupling is going to be the fundamental element that has allowed for a new line of evolution on the basis of a body organization able to support versatile and rapid bigger organisms, and at the same time, capable of allowing a self-sustaining process of encephalization, producing the emergence of new levels of cognitive phenomena, such as emotions and awareness. These complex forms of animal cognition, which can be labeled as Mind, require a globally integrated organization based on dynamically decoupled (informational) levels of organization.

We are still far from an understanding of the complexity of Human Mind. But we think that such a goal will require an understanding of the evolutionary processes leading to higher forms of cognition. We hope that this paper will contribute to this research.

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