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On the integration of biological constraints into the evolution of artificial neural systems

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Abstract

The combination of evolutionary computation and artificial neural networks is increasingly reduced to a specific optimisation problem. In this work, we will propose to aim more at the integration of new principles from evolutionary neurobiology than at the mere formalisation of existing methods. We will outline several findings from neurobiology and single out the incremental development of neural systems as a principle which is worth translating into the design of artificial neural systems. Furthermore, we will argue that learning could be understood as a direct consequence of such a development process. The properties of a simulation system to test the propositions made in this paper will finally be outlined.

1 Introduction

Technically the tuning of the different parameters and of the structure of artificial neural systems[1] can be seen as a mixed parametric/combinatorial optimisation task. Therefore, the application of evolutionary computation as a particular optimisation tool to these problems, seems to be a logical approach. Indeed over the last decade this application has covered a wide range of neural computation, e.g. parameter adaptation and initialisation, specification of the structure or the architecture, feature selection and rule extraction, see [1] for a recent survey of the literature. At the same time, most of these applications have only dealt with "simple" neural systems in the sense of size, flexibility to dynamic environments, task complexity, etc. Indeed this restriction was the reason why indirect encoding methods for the evolution of neural networks were proposed as early as 1990 by Kitano [2]. In addition to the scalability problem, the sole formalisation of the combination of evolutionary computation and neural networks into various classes of mathematical optimisation problems bears the risk of leaving no room for new biologically inspired paradigms. After all, the biological paragons for artificial neural systems, the brains are organs of computation that were built by evolutionary processes. The ever larger and more specialised brains enabled improvement of the organism's performance and the ability to adapt to changes in the environment [3].

The aim of this paper is to draw attention to some findings from evolutionary neurobiology[2] which could serve as a basis for new properties of and constraints on the evolutionary development of artificial neural systems. We want to re-awake the discussion on which of these principles should be incorporated into the evolution of artificial neural systems to be able to handle more complex tasks.

In this work, we will concentrate on the developmental aspects of the biological brain both during the phylogeny and the ontogeny. We believe that constraints from the development can be used to shed more light on the properties of the neural information processing with respect to

- the *interaction between evolution and learning* [5] both regarding the evolution of learning and the "distribution of responsibilities" between both mechanisms. Although very different in their physical realizations, the processes of evolution and learning are similar when analysed at an abstract level as processes which extract information from the environment to design and optimise structures;
- *architectural properties*, like strong modularity and the hierarchical organisation of the system. In particular modularity is usually seen as a result of an indirect encoding scheme or

[1] The term "neural systems" explicitly includes non network based paradigms like neural fields.

[2] To which extent information on the formation of the neural structure and function is genetically determined is still an open questions. However, for some parts of the brain the specification might be more detailed than generally assumed, as Gierer [4] comments: *This line of thought bears on the "nurture versus nature" issue in supporting a considerable though structurally hidden genetic contribution towards "fine tuning" of neuronal connections.*

genotype-phenotype map [2, 6, 7], which however always poses constraints on the evolutionary process;

- *flexibility and plasticity of the design.* It has been shown that both during phylogeny and during the individual lifetime some parts of the brain can be assigned to different tasks within certain restrictions.

On the one hand, we believe, that the identification of the properties of the development of neural systems [8] will be beneficial or even necessary to understand the functional structure of the brain. On the other hand the constraints, which are apparent from the biological evolution of the human brain, can be integrated into the artificial evolution of neural structures and reduce the dimensionality of the search space. Thereby, a gradual development of robust artificial neural systems for the generation of behaviour can be enabled. Therefore, the identification of developmental aspects from evolutionary neurobiology in the next section, will be followed by the translation of these aspects into technical constraints and by a proposal for a simulation environment to verify their usability for artificial evolution in Section 4.

2 Notations from the biological evolution of the human brain

One important principle for the development of the nervous system during phylogenesis is that "old" proved structures of the brain are not abolished in higher developed species [9]. Contrarily, they stay active and perform their functions, being in close connection with newly evolved parts of the nervous system.

Already in 1908, Edinger [10] proposed that the brains of all vertebrates can be subdivided into two fundamental functional units, the phylogenetically old palaeencephalon and the neencephalon. The palaeencephalon is the oldest part of the central nervous systems and is the seat of all reflex mechanisms and innate instinctive behaviour. Fish posses only a palaeencephalon, however in higher animals (amphibian, reptilian, mammalian), new parts of the brain have been developed and the palaeencephalic reflexes and instincts became increasingly subordinated to neencephalic associative and intelligent processing. A related idea was formulated by MacLean [11]. According to his theory of triune brain, the brain of higher primates is composed of three formations reflecting an ancestral relation to reptiles, early mammals and late mammals. Again, in the highly developed primates, the old (reptilian) parts of the brain remain preserved. Thus, brains of vertebrates are built on a common basic plan, however show large structural variability in later emerged parts of the brain, depending on the special environmental influences and the species-specific behaviour of the animal.

The most progressive development of all parts of the brain shows the forebrain: whereas amphibians have only a small "anlage" of the cortex, the evolution led to an amazing increase of size and specification of the cortex in higher animals. Also for the cortex is has been shown that phylogenetically old parts remain active even in the highly developed brains of primates. For a long time, it was assumed that the primary sensory and motor areas appeared first in evolution and the associative areas of the cortex developed later. However, by systematic comparative neurological studies Bishop found that [12], on the contrary, the areas with the highest architectonic and functional specialisation, the primary areas, present the most recent stage in cortical evolution. Additionally, "successive waves of circumferential differentiation" away from two phylogenetically old cortex areas (hippocampal cortex and paleocortex), could be demonstrated [13]. Based on such insights and his own research, Sanides [14] proposed a new interesting theory that was further specified by Pandya and Yeterian [15]. The main statements are shortly elucidated in the following. Based on comparative studies of cortical architecture (lamination, connectivity, myelinization, etc.), it was suggested that all cortical regions have evolved from two prime moieties in the root of the forebrain of early vertebrates. The one moiety (paleocortical) is thought to be tied to the issue of "what", i.e. sensory processing, and the other moiety (hippocampus-derived) to the "where", i.e. to spatial processing crucial for effecting behaviour. From these two moieties other cortical areas developed, which remain either tied to the processing of aspects of "what" or of "where" (including control of action and behaviour).

The architecture of the new cortical areas is not identical to the architecture of the moieties or the previously developed areas, but it changed during evolution resulting in more and more specialised areas with an increasing number of neurons.

- One important trend of cortical evolution is increasing lamination, starting with the 2-3-layered moieties and culminating in the primary sensory regions having up to 10 layers in V1. Additionally, the general myelin content of the intracortical projection and association fibers increased while proceeding from the cortices of origin, resulting in the necessary larger velocities of conduction in the ever longer connections between related cortical areas in the expanding brain.

- Whereas the phylogenetically old cortical areas get inputs from all modalities (olfactory, visual, somatosensory, etc.), the more recent

stages of development process only information of a single modality [16]. Thus, from the single multimodal moiety for analysing the sensory input ("what"), several specialised cortical regions for processing of visual or acoustic or somatosensory information developed during evolution, each with several hierarchical levels.

- Within the modality-specific sensory areas several sensory representations in the form of maps are found. The "younger" the area, the finer is the respective map. Thus, the phylogenetically young areas became increasingly specialised, both with regard to modality and resolution. However, the "older" areas with their very crude maps remain substantial and seemingly are in charge if very fast decisions are necessary.

For instance, also men and monkeys posses an ancient visual area, called area prostriata, which is activated by visual stimuli with very short latency [17]. The map of this area is only a coarse one, but this is seemingly enough for the specific behaviour which is dependent on activation of this area. Via direct connections to an ancient motor area, area prostriata can induce fast manual responses (catching something) or fast contraction of facial muscles (fast closing the eyes) [18]. Such "simple" functions, based on coarse analysis and rapid decision, might be more important for survival of the individual than very fine analysis of the sensory input.

It may be relevant for understanding evolutionary processes to know that only the older cortical regions have intense connections with important structures of the limbic system, like amygdala and hippocampus which are related to emotions and memory formation, respectively [19]. Amygdala controls the emerging cortical areas and probably modifies development according to the drive and the needs of the animals, whereas hippocampus "organises" the memory formation in these areas. In this context it may be important that robust long-term synaptic modifications, which are the basis for learning, are most easily induced in hippocampus, amygdala, and the surrounding phylogenetically old cortical regions.

In developed animals the highly specialised (modality specific) cortical areas can process sensory information and solve many tasks independently. However, for the cortex the phylogenetically older areas remain substantial and seemingly take control over processing under certain circumstances. They may be crucial

- if the speed of a reaction is more important than exact knowledge about the stimulus (escape, hunting).
- if processing of multimodal information is necessary for optimal decision.
- if the situation is highly loaded with emotions (for instance, fear) or drive (hunger).
- if the task is very complicated or several alternative responses are possible (For instance, recently it has been shown that in humans the old cingulate cortex was activated in tasks that elicited competition among alternative decisions [20].).

During the evolutionary formation of the specialised areas, the ancient parts continue their development. The relative size of old cortical areas may also increase during evolution [9]. Moreover, recently it has been shown that men and apes have unique projection cells in the phylogenetically old cingulate cortex, never seen before in lower animals [21]. This is understandable if we accept that "old" cortical areas can control or modulate the newer ones by the emerging new connections between them. Thus, evolutionary processes adapt the "old" areas to their tasks in controlling and modifying the performance of phylogenetically new areas.

In the progress of evolution, biological neural networks (brains) increase in size (in number of areas and number of units) and develop areas for more and more specialised processing. However the ancient areas are preserved and may influence the later developed parts of the brain by the parallelly developed associative connections between them. As a result of this evolution, there is a set of phylogenetically old areas that are widely shared among vertebrates. Additionally, every species developed more specialised (phylogenetically younger) areas, depending on the specific environmental influences and requirements [22]. The developed brains with their combination of phylogenetic old and young areas enable a multifarious repertoire of behaviour with the ability to create adaptively organised relationships between sensory information and behaviour.

The outlined notations from phylogenetic development can be conferred to the ontogenetic development, as it is a well known rule that ontogeny roughly re-capitulates the phylogeny. Indeed, it has been shown, that phylogenetically older cortical areas have adult-like patterns of responsiveness earlier in ontogeny than younger areas like the primary sensory and motor areas [23, cited in [24]], [25]. Recently it has even been shown, that after stroke, specific features of brain functions revert to those seen at an early stage of development, with the subsequent process of recovery re-capitulating ontogeny in many ways, particularly in the motor system [26].

3 Hypotheses for new constraints on the development of artificial neural control structures

The findings from evolutionary neurobiology, which we outlined in the last section, contain many starting points for considering new principles for the evolution of artificial neural systems. However, some key features can be identified:

Incremental development Phylogenetically old structures are re-used during evolution, the process is inherently incremental. There seem to be two prime roles which are assigned to the old structures. Firstly, the organisation of behaviour where speed is the issue and not fine analysis, e.g perception based reflexes. Secondly, the control and coordination of the new structures, which in turn are responsible for higher sensory processing. The relation between old and new neural parts is shown schematically in Figure 1 together with the two different pathways: fast but coarse, Fig. 1(a) and fine but slow, Fig. 1(b).

Specialisation The latest additions to the neural system are the most specialised ones. In this context specialisation refers to both the environment and to specific parts of the sensory input.

Information decomposition Sensory information is decomposed and handled in parallel in different pathways in addition to the fast action/perception like system which remains active.

In particular, the principle of incremental development raises several questions to why it is so deeply inveterated into the neural evolution; how the old structures can be combined with the additional functionality of the systems and how they are able to take up their role as "control entities".

3.1 Why incremental?

The phylogenetically and ontogenetically incremental approach can be related to the "constructability" and to the safety or stability of the systems. The term "constructability" refers to the possibility that a system can be build. Although an incremental approach might not necessarily lead to the system with the best performance, it might be the only strategy to develop a complex system at all. In this sense it is an evolutionary interpretation of the "divide and conquer" principle. At the same time, the incremental approach is safe and stable in the following sense. If old structures remain fully operational, i.e. a pathway persists which is independent from recent neural innovations, then the impact of possible shortcomings of the new structures is minimised, the system is safe. The same argument holds for changes in the environment, thus

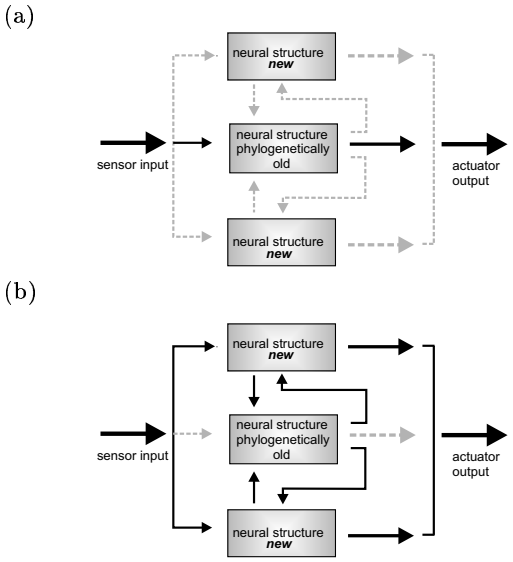

Figure 1: The integration of old structures into a new functional system and the realisation of two different information pathways: (a) fast but coarse excluding new structures and (b) fine but time-consuming with old structures acting as control systems for new components.

the system is stable. It is interesting to note that this is also an important issue in technical systems, where standard neural networks are often excluded from safety sensitive control tasks because stability and safety are difficult to guarantee for online learning networks.

At the same time, the environment must be structured in such a way that an incremental organisation is possible. Thus, it must be possible to decompose problems hierarchically so that task complexity grows alongside system complexity and vice versa. This decomposition has to embrace the selective pressure towards solving problems of higher complexity. An example could be the visual system, where a hierarchical organisation of a coarse to fine analysis can be coupled to a selective pressure. The fast differentiation between predator and prey could be refined to a more time-consuming differentiation between high and low nutritious prey. This incremental problem complexity can be reflected by an incremental evolutionary approach. For the ontogenetic development such a combined growth process of problem and network complexity has been proposed in [27].

3.2 Integrating the old structures into new functional systems

In order to combine old structures with new functionalities of the system, it is likely that changes on all levels will be necessary. The design of the new parts is straightforwardly defined by the new task, e.g. refined sensor/motor behaviour, and the need to make a common interface available to

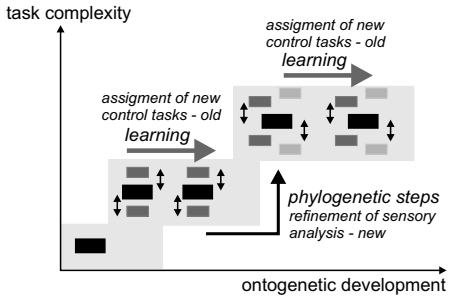

Figure 2: The coupling between new phylogenetic steps and learning of additional functional roles of existing structures during ontogeny in order to process increasingly complex tasks.

the existing system. However, the changes of the existing system are more difficult to realise. Firstly, the possibility that these changes are a result of the evolutionary process are limited, because the system is already part of the whole processing structure and the important constraint, that the basic functioning of the existing structure should not be altered, has to be fulfilled. Secondly, the old parts seem to take up the role of the control structure of the system as a whole. At first sight, partially reconfiguring the old part in such a way that they can accomplish this task seems to be more difficult than the evolutionary design of a new part[3]. The alternative would be to design a method which can assign new functional roles to existing subsystems during ontogeny. In this way, the "control burden" would be lifted from the evolutionary design of a new part; the safety issue of the existing system could be genetically fixed and the control of the new structures could be organised in a strictly task driven way during development. Of course this design method is nothing else than *early learning*. Therefore, we postulate that learning is not just a convenient method to increase the flexibility of the system and to allow adaptation on a short time-scale, but that it is an essential property to enable the observed development of the neural system. Thus, the phylogenetically incremental approach might be a direct reason for developing "learning" systems independent from other beneficials. This proposition is schematically shown in Figure 2, where a new *phylogenetic* developmental step is accompanied by a learning based configuration of interfaces to existing systems during *ontogeny*. Of course this proposition also raises additional questions like as to how in detail a learning process itself can evolve and as to why the old structures have sufficient potential to fulfil all the additional tasks which they face after the main part of their evolutionary development has already been completed. At the same time, in [7] it was shown that an incremental process during ontogeny and the utilisation of old structures in new systems can be beneficial for the design process of artificial neural systems.

[3]It should be noted that the opposite developmental principle, where the new systems enslave the existing structures, can also be observed during the neural development. The interaction between both principles is a fascinating topic, which however goes beyond the scope of this paper.

4 Properties of a proposed simulation system

The incremental, task driven phylogenetic and ontogenetic development of a neural system combined with learning was motivated in the last two sections both from recent neurobiological results as well as from considerations on how new and existing systems can be integrated into one enhanced control structure for behaviours under the various existing constraints. Both the transferability of the neurobiological findings as well as the validity of our consideration have to be tested in appropriate simulation environments. The aim of such an analysis, however, should not necessarily be optimisation, but systematic design of complex neural systems. We should find out whether the proposed development of a neural system is possible, whether it is beneficial and whether the proposed logical consequences, e.g. learning, can be observed. At the same time, there are constraints which we have to pose onto the simulation environment.

- The possibility of a hierarchical problem decomposition which can be reflected by the neural architecture and a strong selective pressure towards such a decomposition.
- The selective need to realise a neural fallback system in the form of the basic functioning of the old structure.
- The distinction between a fast and a slow neural process during the interaction with the environment.

It is our future aim to realise these constraints in a simulation environment for a humanoid robot concentrating on the simulation of a vision system as an example for the sensor side and on the evolution of a biped movement on the actuator side.

5 Conclusion and summary

The aim of the paper was to outline new possible constraints on the evolution of artificial neural systems which are based on recent findings from neurobiology. This is a formidable task because of the large number of neurobiological publications which usually offer great detail but hardly any governing principles. Since these principles are often very much speculations, this is understandable, but of course it leaves the designer of artificial systems

very much in the dark. In this paper, we singled out the incremental approach as such a principle, which seems to be inherent in the development process at least on two levels, the phylogenetic and the ontogenetic level. Additionally, we discussed system properties, e.g. learning, which we believe are logical consequences of such an incremental approach. In the introduction, we stated that one of the aims of this paper is to trigger a more intense discussion in this area where most people seem to have settled with the fact that we deal with a standard optimisation task. At least the findings of Section 2 should indicate that the evolution of neural systems still holds a lot of surprises. The proposed properties of the simulation system in Section 4 will hopefully help to reveal some of them.

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