Embodied modeling of the organization of the brain

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Abstract

In this study embodied embedded agents are evolved in order to gain a better understanding of aspects of the distribution of cognitive functions in the brain. We found that a symmetrical body plan facilitates the evolution of two hemispheres. Furthermore, individuals with an asymmetrical body plan, which gain an asymmetrical control structure, perform better in the end than individuals with a symmetrical body. This is in line with the idea that an asymmetrical nervous system yields computational benefits since it contains less redundant processes. Finally, we found that although the symmetrical individuals show a lower performance, their development is faster. We argue that this faster development is the result of reduced complexity of the control structure in comparison to asymmetrical individuals.

1 Introduction

Our brain performs many different cognitive functions which form behavior through interaction with the body and the environment [4, 5, 17]. These cognitive functions differ, among other things, in neural location and space (i.e., the location of the function in the brain and the number of neurons involved).

For many years, these issues have had a lot of attention commonly referred to as cerebral lateralization [11, 19]. In those studies, there is a large focus on the location of brain functions. In contrast, little research is conducted on the origin of lateralized functions.

In this study we will focus on two questions that capture typical aspects of our lateralized nervous system:

1. Why does our brain consist of two hemispheres?
2. Why are some of the functions of the brain symmetrically organized whereas others are asymmetrically organized?

Regarding the first question, it is most likely that those parts of the nervous system that have to deal with sensory and motor interactions tend to be organized in a symmetrical way, since our body plan is also symmetrically organized [6]. This could have resulted in the development of two hemispheres, each one taking care of one side of the body.

In contrast, others have proposed that the development of the two hemispheres is related to the possibility of possessing duplicate functions ([7] for an overview). If the brain is damaged, the functions that are impaired can be taken over by the corresponding functions in the other hemisphere. This hypothesis is unlikely since the brain needs recovery time to adjust to its new situation. During this period the impaired animal has very little survival chances [12]. The unlikeliness of this hypothesis further directs our expectations towards a morphological influence.

Regarding the second question, it is thought that symmetrically organized nervous systems contain redundant processes since the same functions are found in both hemispheres. Therefore, there is less neural space for additional functions which could increase performance [16]. So, for the second question, it is expected that asymmetrical

[1] An earlier version of this paper has been presented at the 1^{st} NSVKI Student Conference [13]

individuals (i.e., individuals with an asymmetrical neural controller) will perform better than symmetrical individuals, since lateralization yields computational advantages [23]. Recent biological support for this hypothesis comes from [18] who have shown that fruit flies with an asymmetrical nervous system have a superior form of long-term memory compared to fruit flies possessing a symmetrical nervous system. Moreover, lateralization is found in all sorts of vertebrates [19], indicating it has evolutionary advantages. Furthermore, lateralization helps to overcome incompatible responses [1, 22]. By biasing one hemisphere over the other an adequate course of action is guaranteed.

Note that these two hypotheses contradict in the following way: on the one hand, we expect to find symmetrical control structures as a result of a symmetrical body plan; on the other hand, it is stated that asymmetry yields benefits in comparison to symmetry. As said, in all sorts of vertebrates both symmetrically and asymmetrically organized functions have been found [19]. This indicates that symmetry and asymmetry both have intrinsic evolutionary advantages. One such an advantage for symmetry may be based on the principle that symmetry is simply less complex to develop since less information needs to be integrated.

In our experiment we test these hypotheses by modelling the interactions between brain, body, and environment. Hereby we use artificial evolution of agents with different morphological structures (symmetrical and asymmetrical). From the hypotheses stated above we expect that

1. individuals with a symmetrical body plan will evolve a control structure in which there is more clustering into two hemispheres (i.e., stronger interaction between neurons in one hemisphere than between neurons in different hemispheres) in comparison to individuals with an asymmetrical body plan,

2. individuals with an asymmetrical body plan will develop a more asymmetrical control structure, which in turn results in a better performance, and

3. individuals with a symmetrical body plan will develop a more symmetrical control structure which we expect to evolve faster.

In the next sections it is explained in detail how we tested our hypotheses (Experimental setup), what we found (Results) and what the implications of our findings are (Discussion).

2 Experimental setup

As stated in the introduction, two different robots are needed: one robot with a symmetrical body plan and one robot with an asymmetrical body plan. In addition, an environment is needed in which the robots can act. Furthermore, the sensors and motors of the robots have to be coupled by a control structure that is the subject of evolution. These aspects will be discussed in detail in the next sections.

2.1 Robot Design

For the experiment we used a simulation of the Lego Mindstorms platform [14, 15, 20], in which we designed a symmetrical and an asymmetrical robot. Both types of robots are equipped with two light sensors facing the floor, outputting a continuous value from 0 to 100 which is divided by 100 and used as input in the control structure. In addition, one pressure sensor is placed on the robot's front, which provides the input layer of the control structure with a binary value, zero or one. Two motors are used, symmetrically arranged on the left and right side of the robot which make the wheels turn according to a continuous input between -100 and 100.

As can be seen in Figure 1, the symmetrical and the asymmetrical robot differ in two ways: the placement of the light sensors, and the activation of the two motors. For the symmetrical body plan, the light sensors are placed symmetrically at the front of the robot. For the asymmetrical body plan, one of the light sensors is placed on the side of the robot. The motors of the symmetrical robot have a direct connection with the two output units of the neural controller. In contrast, in the asymmetrical robot, the output of one output neuron of the control structure codes for the rotation component of the velocity (*rotation*, motors turn in opposite direction) and the other one for the forward component of the velocity (*velocity*). Equation 1 shows how this signal is transformed into a suitable signal to activate the two motors.

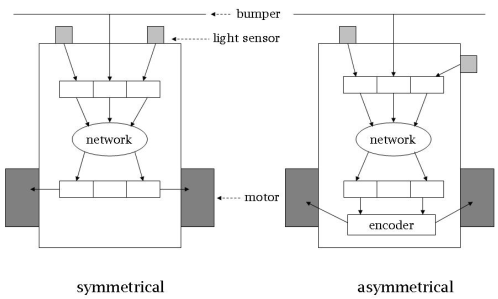


Figure 1: Schematic overview of the morphology of the two different robots.

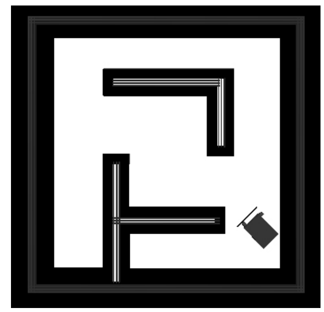


Figure 2: Ecological Niche. The floor is shown in black and white, the walls are grey. The asymmetrical robot is shown.

$$\begin{aligned} v_{left} &= (velocity - rotation) \cdot 100 \\ v_{right} &= (velocity + rotation) \cdot 100 \end{aligned} \tag{1}$$

The velocity and the rotation are values of the output neurons in $[-0.5, 0.5]$. So the values v_{left} and v_{right} for the motor input are in $[-100, 100]$.

2.2 Task & Ecological Niche

A task is devised in which the robots have to move around a kind of maze (Figure 2) as fast as possible without bumping into walls. A band of black surface is placed on the floor around the walls to help the robots, whereas the other parts of the floor are white.

This is a task the robots should be able to perform with the sensors available to the robot. Furthermore, the task is likely to cause a sensory-motor interaction in which all sensors and motors have to participate. The bumper is needed in order to detect walls and with the light sensors the robot can avoid bumping into the walls. In order to obtain a measurement of the robot's performance a fitness function is defined according to equations 2 and 3. In equation 2 n is the number cycles (1000 in this experiment) and the $penalty$ for every bump was 50.

$$fitness_{total} = \sum_{cycle=0}^{n} (fitness_{cycle}) - (penalty \cdot bumps) \tag{2}$$

$$fitness_{cycle} = \begin{cases} \sqrt{v_{left} \cdot v_{right}}, & \text{if } v_{left} > 0 \text{ and } v_{right} > 0 \\ -\sqrt{v_{left} \cdot v_{right}}, & \text{if } v_{left} < 0 \text{ and } v_{right} < 0 \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

If for one cycle both motors turn forward, the fitness of that cycle is positive. If the motors both turn in a backward direction the fitness of the cycle is negative. The maximum $fitness_{cycle}$ is $\sqrt{100 \cdot 100} = 100$. Therefore, the maximum $fitness_{total}$ is $n \cdot 100 = 10^5$. This value can only be obtained in a world where the robot can go forward with maximum speed during all cycles. In our world the maximum fitness obtained by a robot was ca. 21000. These formulas show that the higher the output to both motors, the higher the fitness will become. The higher the output to both motors the more distance the individual covers that cycle. This is in accordance with the task we formulated above; the individuals have to move trough the environment as fast as possible while avoiding bumping into walls.

2.3 Neural Network

The neural network we use as a control structure consists of three layers of neurons: an input layer, a hidden layer of four units, and an output layer. These three layers are connected by feedforward connections. The neurons within the hidden layer are fully connected to each other. This neural network structure was chosen for a number of reasons. First, with this neural network the individuals should be able to complete the task. Second, the fully connected hidden layer enables the possibility of integration of information, but also the development of a left and right cluster. Finally, the symmetrical form of the network has some useful properties for analyzing clustering and symmetry.

Activation spreads through the network summing the product of the inputs and their weights and the bias for every neuron in the network. The neurons are activated using the activation function defined in equation 4. So, they have an activation value in $[-0.5, 0.5]$.

$$activation_i = \frac{1}{1 + e^{-(inputs_i + bias_i)}} - 0.5 \tag{4}$$

2.4 Evolutionary process

In order to develop the control structure we used an evolutionary process which evolves the weights and biases of the network. The evolutionary process is based on generations consisting of 20 individuals represented by 20 genotypes. A genotype contains a weight for every connection and bias for every neuron, resulting in a vector of 41 values. With each generation the ten individuals with the highest fitness are selected. Their genotypes are copied to the next generation, in which ten new genotypes are formed from the ten copied genotypes. The new genotypes are the result of mutations over the genes of the ten copied genotypes. Every value in the genotype has a five percent mutation probability and, if selected for mutation, is mutated according to the equation

$$genotype_{new,i} = genotype_{old,i} + r \cdot 0.3 \tag{5}$$

where r is a random value from a Gaussian distribution with mean 0.0 and standard deviation 1.0. This way, sometimes larger mutations are encountered but most of the time the weights and biases are slightly mutated. The factor 0.3 is based on pilot tests.

3 Results

In this section we discuss the results of the experiment. We will first go into the fitness, after which we will look at clustering and how this was measured. Finally, the symmetry of the resulting control structures will be compared.

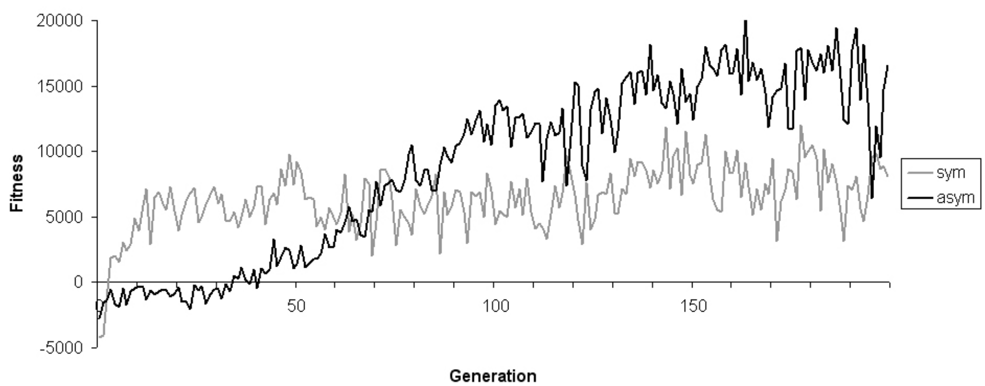


Figure 3: Development of mean fitness for the symmetrical and asymmetrical group

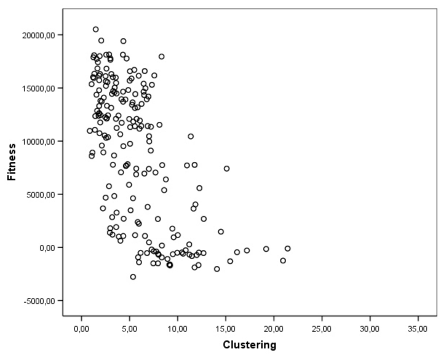


Figure 4: Correlations between clustering and fitness show a strong negative correlation in the asymmetrical group.

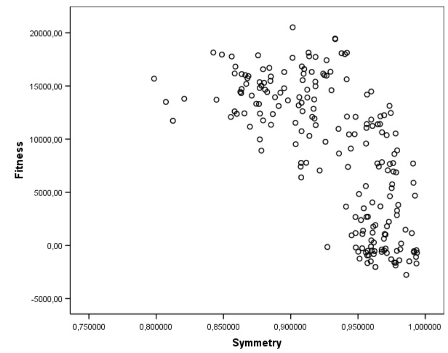


Figure 5: Correlations between symmetry in the resulting control structure and fitness show a strong negative correlation in the asymmetrical group.

3.1 Fitness

The control structures of both groups are evolved for 200 generations after which the fitnesses of both groups seem to settle. When looking at the behavior of the final generations it is seen that they perform their task quite well.

In Figure 3 it can be seen that the symmetrical group starts with a higher fitness, however after about 75 generations the fitness of the asymmetrical group has risen above the fitness of the symmetrical group.

Over the first 50 generations the performance of the symmetrical group ($\overline{fitness_{sym}} = 5.0 \cdot 10^3$) is better than the performance of the asymmetrical group ($\overline{fitness_{asym}} = -0.29 \cdot 10^3$). An analysis of variance between the two groups over the first 50 generations shows that there is a significant effect on mean fitness between the symmetrical and the asymmetrical group ($F(1, 98) = 1.6 \cdot 10^2$, $p < .001$). In contrast, over the last 50 generations the performance of the asymmetrical group ($\overline{fitness_{asym}} = 15 \cdot 10^3$) is about twice as high as the performance of the symmetrical group ($\overline{fitness_{sym}} = 7.7 \cdot 10^3$). An analysis of variance over the last 50 generations shows that this difference is also significant ($F(1, 98) = 2.3 \cdot 10^2$, $p < .001$).

3.2 Clusters

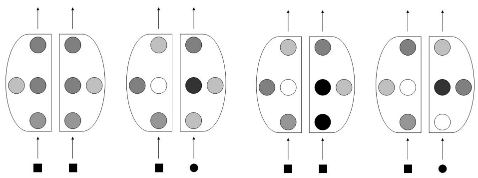
Additionally, we want to gain insight in the development of hemispheres. For current purposes, a hemisphere is seen as a set of neurons which interact more strongly with each other than with other neurons in the network. We used techniques described by [8] and [21] to measure these kind of clusters. This resulted in a cluster index (CI) indicating the amount of clustering. A higher cluster index indicates more clustering.

In order to compute this cluster index, tracking of the different states of the network is needed. Two possible states, which depend on the activity of the neuron, are defined and measured for each neuron at each cycle: an active state ($activation < -0.2$ or $activation > 0.2$) and almost inactive state ($-0.2 < activation < 0.2$). In our experiment we found values for CI between 0 and 35.

There is more clustering in symmetrical individuals ($\overline{CI_{sym}} = 6.5$) than in asymmetrical individuals ($\overline{CI_{asym}} = 3.9$). With an analysis of variance it is shown that this effect of body plan on clustering is significant ($F(1, 98) = 15$, $p < .001$). Moreover, for the asymmetrical individuals there is a strong negative correlation between clustering and fitness ($r(200) = -0.619$, $p < .01$). With more clustering, the fitness decreases (see Figure 4). In contrast, no significant correlation for the symmetrical individuals was found.

3.3 Symmetry

We performed an additional analysis to determine whether the developed control structures are symmetrically or asymmetrically organized.



(a) Symmetrical control structure (b) Asymmetrical control structure

Figure 6: Symmetrical and asymmetrical processing inside the control structure with symmetrical and asymmetrical stimuli. The grey value of the neurons indicates their activity. The circles and squares represent different input values.

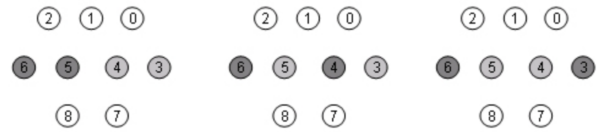


Figure 7: Because it is unclear which neurons in the hidden layer form each other's counterpart all three possibilities are measured during the symmetry analysis. The most symmetrical couples are selected.

Symmetry inside the nervous system originates from symmetrical connectivity between the neurons. So in the case of a symmetrical control structure, a symmetrical stimulus will result in symmetrical neural activation patterns. This means that if the left and the right sensor of the robot encounter an equal stimulus, the activation patterns in the left and right part of the control structure should be similar. In Figure 6 the typical behaviour of a symmetrical and an asymmetrical control structure is illustrated.

Therefore, in order to measure symmetry, we calculate the differences between the activations of different neurons in the network when the input is symmetrical (i.e. when both light sensors have a value higher or lower than the black/white threshold of the floor). It is unclear which neurons are each others symmetrical counterpart, so all three possible comparisons in the hidden layer are made (see Figure 7). Such a comparison is done by summing, at each cycle, the differences between the activation of three couples of neurons (i.e. the output neurons and the neuron couples in the hidden layer neurons). The most symmetrical comparison is selected. So for the case in which the couples are (a_4, a_5), (a_6, a_3), and (a_7, a_8) the symmetry is measured as given in equation 6.

$$Sym = 1 - Asym = 1 - \frac{1}{3n} \sum_{cycle=0}^{n} |a_4 - a_5| + |a_6 - a_3| + |a_7 - a_8| \tag{6}$$

This way, for every individual the amount of symmetry in the control structure is measured in $[0, 1]$. Over the final 50 generations there is more symmetry in individuals with a symmetrical body plan ($\overline{Sym_{sym}} = .95$) than in individuals with an asymmetrical body plan ($\overline{Sym_{asym}} = .90$). An analysis of variance over the final 50 generations shows that this effect of body structure on symmetry in the control structure is significant ($F(1, 98) = 1.1 \cdot 10^2, p < .001$). Moreover, for the asymmetrical individuals there is a strong negative correlation between symmetry in the control structure and fitness ($r(200) = -0.514, p < .01$). With more symmetry, the fitness decreases (see Figure 5). In contrast, there was no significant correlation for the symmetrical individuals.

3.4 Conclusion

In the first place, the cluster analysis shows that there is more clustering in individuals with a symmetrical body plan than in individuals with an asymmetrical body plan. As stated above, the clusters can be thought of as hemispheres. To conclude, we would say that these results support evidence for an influence of body plan on the origin of the two hemispheres.

Furthermore, from the symmetry analysis of the control structures, it is clear that the individuals with a symmetrical body plan develop a more symmetrical nervous system than the individuals with an asymmetrical body plan.

Finally, it is seen that the robots with a symmetrical body plan evolve faster (see Figure 3). In contrast, the asymmetrical group evolves slower but performs better in the end. This difference might be the direct causal result of the structure of the body plan. In contrast, it could also be the case that the clustering and symmetry of the control structure are causal intermediates in this relation. These possibilities will be further discussed in the following section.

4 Discussion

4.1 Symmetry with Asymmetry

The results show that asymmetrical individuals, which have a more asymmetrical control structure, perform better than the symmetrical individuals. This could mean that an asymmetrical body plan has direct advantages in the model we used (e.g., the environment might be better suited for the asymmetrical body plan). However, this does not relate to nature very well since almost all animals possess a symmetrical body plan [9]. Furthermore, a symmetrical body plan has been shown to have clear adaptive advantages [2, 10]. Instead, the better performance of the asymmetrical individuals is better explained by the presence of an asymmetrically organized nervous system. Asymmetry in the control structure positively correlates with higher fitness. This is in line with the hypothesis that an asymmetrical nervous system yields computational benefits.

Although asymmetrically organized functions are found in the human nervous system, the nervous system also contains a lot of symmetrically arranged functions. We want to propose that cerebral symmetry has evolved due to its lower degree of complexity. We will illustrate this by considering a simple Braitenberg Vehicle [3]. Its control structure has a typical symmetrical architecture with only two connections directing the robot towards or away from a stimulus. If this control structure would be organized asymmetrically (e.g., like the example in this study, with one output neuron coding for rotation and one output neuron coding for velocity), the control structure would need more connections for the integration of information. This results in increased complexity of the control structure which makes it a configuration less likely to appear during the process of evolution. This fits the findings from our experiment in which the asymmetrical control structure evolves slower, and might also be the adaptive advantage leading to the current symmetrical structures in the human nervous system.

A remaining issue is the relation between the development of a symmetrical organization of the nervous system and the evolution of the two hemispheres. In our experiment the symmetrical individuals developed a more clustered control structure. This leads us to believe that symmetry facilitates clustering. We believe that the same relation holds for natural systems. Therefore, it is likely that the bihemispherical configuration emerged from a symmetrical nervous system. Subsequently, asymmetry evolved with the need for more complex cognitive processing. Asymmetry provides the required neural space.

4.2 Embodied Embedded Brains

This study shows that embodied cognitive modelling can contribute to research on cerebral lateralization. Regarding this contribution, it is important to consider the validity of the model in relation to a natural system.

The simulated model used in this study is by no means a valid equivalent of a natural system. One should therefore be very careful in generalizing the results from the simulation to the human nervous system. On the other hand, this research can be valuable in the sense that it can provide supporting evidence for conclusions drawn from studies dealing with natural systems. Furthermore, it can lead to new ideas and insights, and may result in original hypotheses.

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