

Developmental Pathways in the Assimilation of Non-geometric Information for Orientation in Children: a Neurorobotic Model

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Abstract

The performance of children in an orientation task involving geometric and non-geometric spatial cues presents an interesting pathway during development. At an early stage, children are able to exploit the first, but do not use the information provided by the second. This surprising result has been interpreted resorting to the presence of a geometric module in vertebrates' brain whose limitation can be overcome with the acquisition of language (Hermer and Spelke, 1996). But the described set of results is not always verified: Learmonth and colleagues (2001, 2002) have shown that children, under certain conditions, can use the information provided by landmarks. In accordance with what has been suggested in the cited study by Learmonth (2001), a crucial factor to allow the use of non-geometric information is the stability of the cue presence.

In the present work we have tried to address this question training artificial organisms, namely simulated robots, to solve the two tasks. Results show that if the non-geometric features is always present in the training procedure, the artificial organisms can use them to orient. Nonetheless, if the non-geometric information is present only for a certain period of the training, the percentage of artificial organisms that can exploit this information source varies proportionally to the length of exposure to non-geometric features. Manipulating this variable, it has

also been possible to observe different developmental pathways and, under certain conditions, to reproduce the developmental pattern observed in children.

1. Introduction

Animals display extraordinarily effective spatial behaviours in many different circumstances, for example, for foraging (the dominant feeding behavior in most species), to visit mating sites or during seasonal migration. Many animals can navigate from one location to another, even when the target location is out of range of their senses and can locate objects in the surrounding space. The ability underlying these behaviours is orientation. In finding their way in the world, we can say, simplifying, that animals rely on roughly two classes of information in the environment: geometric and non-geometric. Gallistel (1990: 212) defines them clearly:

"A geometric property of a surface, line, or point is a property it possesses by virtue of its position relative to the surfaces, lines, and points within the same space. A non-geometric property is any property that cannot be described by relative position alone".

For instance, the colour of a wall is a non-geometric property as a smell or sound coming from a corner. For the definition of these featural information, in fact, a non-geometric notion is required too.

An interesting question about this statement is the following: what pathway do animals follow in assimilating the ability to exploit these cues? Many different studies, with different animals, have been run to explore this issue, using the rectangular arena paradigm, with or without local cues. These experi-

mental settings will be described in detail in the next section.

Rats, studied by Cheng (1986) and Margules and Gallistel (1988) are able to orient in accord with geometric information, but not with non-geometric cues. Chicks (Vallortigara et alii, 1990) are able to use the non-geometric information, as happens with fish (Sovrano et alii, 2002) and rhesus monkeys (Gouteux et alii, 2001).

A great number of studies have seen humans as experimental subjects, both in adult age and during development. Hermer and Spelke's (1996), Hermer-Vazquez and colleagues' (1999) and Gouteux and colleagues' studies (2001) have tested adults that proved to be able to use both kinds of cues. In children a particular responses pattern emerges: in the experiments with children of about 2 years, the subjects could use the geometric information in almost every condition, but could use the non-geometric information only in some conditions (Hermer and Spelke, 1996; Learmonth et alii, 2001; Wang et alii, 1999; Hermer-Vazquez, 2001). When children grow older, at about 6 ages, the primacy of geometric information is overcome and they can use the non-geometric information consistently (Learmonth et alii, 2002).

The results regarding children have been interpreted in different ways. Hermer and Spelke (1996), considering other experiments in which the performance of adults was impaired by verbal tasks interference, have hypothesized that the language plays an important role in overcoming the geometric primacy. On the other side, between other things, Learmonth and colleagues (2001) suggest that an important factor that leads to different results is that in Hermer and Spelke (1996)'s study, the children knew landmarks were movable, while, in Learmonth et alii (2001)'s experiments, the landmarks looked permanent and children never saw them move.

In the present paper we would like to start from this issue: it seems to be relevant that non-geometric information such as the colour of a wall or some panels posed in the corners, are more or less stable. In other words, while geometry is very stable, other sources of information can be stable at different degrees. Depending on this stability factor, organisms could rely on this information with different involvement. If an animal knows that a certain landmark is always present and it always occupies the same position, it can rely on it to orient. Otherwise it is better not to take into account it, because it could be misleading. This is not a strange or wrong idea: if I have to remember where to turn to reach my uncle's house that lives abroad, I will try to consider something that doesn't move, like a church, a monument or the arrangement of a square rather than a concrete mixer that is in a certain location for roadwork and will be likely displaced.

Considering the issue in these terms, perhaps it is not necessary to hypothesize the existence of a geometric module (Cheng, 1986), in the sense of Fodor (1983) and it is not useful to address the question of cues relevance opposing geometric and non-geometric cues. Perhaps it is better to concentrate our attention not on the nature of the information source (geometric vs. non-geometric), but on the reliability it offers. Geometric information, especially in the experiments we considered, is stable, thus providing a reliable information, while non-geometric information is not, at least not as much as geometry.

In this paper we have investigated the issue of spatial cues role, as it emerges from the studies on children posing us this question: if non-geometric information is stably present, is it used as much as the geometric one? Is it possible to replicate the developmental pattern observed in children manipulating this variable?

We have tried to answer this question using artificial organisms. We have tried to answer this question using artificial organisms. In fact the validity of this hypothesis is difficult to assess with natural organisms, because it is virtually impossible to control all the potential information sources (visual, olfactory, vestibular, proprioceptive, sense of direction, internal compass, etc). An alternative possibility is to use artificial organisms (Langton, 1995), whose input patterns can be thoroughly controlled by the experimenter, and whose internal organization can be analyzed at a level of detail difficult to obtain with more traditional methods. Moreover, using artificial organisms permits to model the phenomenon in quantitative terms, to carry out experiments that would otherwise be impossible for evolutionary, ethical or practical reasons and to get insights into the implicit assumptions underlying biological and ethological research. Since researchers have to "build" their own artificial organisms, they are forced to define the links between dependent and independent variables clearly, thus reducing bias. In brief, here we propose the hypothesis that observed stages in the spatial orientation abilities development may reflect changes in the exposition frequency to different stimuli classes. We test this hypothesis using evolutionary robotics' techniques to train a population of simulated robots to solve orientation tasks. The robots are controlled by an artificial neural network, whose weights are selected by a genetic algorithm. Through the genetic algorithm we aim at exploring the solutions' space, an n-dimensional space whose dimensions are the connections' weights of the agent neural controller, represented by a point in this space. Methodologically this process, even if is intrinsically genetic, resembles in the essential respects a learning/development process on the individual level. We then study both processes jointly, con-

sidering the common aspect they share: the modification of behaviour (determined by the connections' weights) in interaction with the environment. With this approach, the way robots can acquire a new capability is through a dynamical evolutive process. There is no "learning" or "development", no modification occurs during lifetime. This is, obviously, a hard simplification. For the abilities involved in the task we considered, in the case of rats and fish, it's not possible to state if a significant role is played by modification that occur during lifetime because there is not data about the performance in the task at different age. On the contrary in human beings it is clear that development plays a vital role in the acquisition of new skills in spatial orientation. However, what is important from our point of view is not the time-scale (evolution or development) along which new abilities are acquired but the mechanisms and the variables which guide the process, in other words the dynamical structure. What we have tried to do in the present contribution is to identify the stages in which a new ability is acquired without considering the distinction between the individual and the species. We have focused our attention on the search in a learning space, metaphor that which is applicable both on development and evolution level. By manipulating the frequency with which the robots come into contact with different classes of spatial information, we have tried to observe the different "developmental pathways", intended in wide sense as the steps of a way to certain ability and if it was possible to reproduce in the artificial agents the pattern observed in human beings.

2. Materials and Methods

2.1 The Tasks

In the present work we will consider, in particular, 2 experimental situations: the Open Field Box and the Blue Wall task. These settings, that we will shortly describe in detail, have been used to investigate if the experimental subjects can exploit various information sources to orient. In fact solving the first requires the use of geometric information, while solving the second requires the joint use of geometric and non-geometric information.

2.1.1 The Open Field Box

In the experiments described in the following section we have replicated an orientation task in a rectangular open field box. The task we studied is often used in the study of spatial behaviour. In the human version of the experiment a subject is placed in a rectangular room with white walls. In one corner, the experimenter places a very inviting object (a reward). In the training phase the subject is allowed to

see the reward, which the experimenter then hides. In the testing phase, the reward is buried. After a disorienting procedure, designed to eliminate the subject's inertial sense of direction, the experimenter asks him/her to find the reward. At first sight the subject has no way of distinguishing between the four corner, but in reality they are not equivalent. Considering the only information available, namely the shape of the room, he/she can identify two corners: the first one is the reward zone and the second one is the corner that has the same geometric characteristics and is perceptually equal to the correct one. If the arena is rotate of 180 degrees the two corners are coincident. This corner is referred to as rotationally equivalent and its choice rotational error.

Of course the subject has no way of distinguishing between them. So, if the subject takes into account the information provided by the geometrical arrangement of the arena, he/she will choose with almost equal frequency the correct corner and the rotational equivalent, committing a systematic error. Briefly the task is solved if the frequency of choice of the 2 corners is similar, above chance and significantly higher than the frequency of choice of the other 2 corners. The Open Field Box task has been used with many different species: rats (Cheng, 1986; Margules and Gallistel, 1988), chicks (Vallortigara et alii, 1990), pigeons (Kelly et alii, 1998), fish *Xenotoca eiseni* (Sovrano et alii, 2002), rhesus monkeys (Gouteux et alii, 2001), humans (e.g. Hermer and Spelke, 1996).

2.1.2 The Blue Wall Task

In the Blue Wall task the experimental procedure is exactly the same but the arena that is used is different only in this respect: one of the walls is blue coloured. In this case, if the subject considers both geometric and local information he/she will search for the reward just in the correct corner. Otherwise if the only information exploited is geometry he/she will search in the wrong (rotationally equivalent) as well as in the correct corner. Performing the task correctly requires subjects to integrate shape information with other non-spatial information such as the colour of the wall.

The Blue Wall task has been used with a number of different species including rats (Cheng, 1986; Margules and Gallistel, 1988; Benhamou and Poucet, 1998), chicks (Vallortigara et alii, 1990), pigeons (Kelly et alii, 1998), fish *Xenotoca eiseni* (Sovrano et alii, 2002), rhesus monkeys (Gouteux et alii, 2001), humans (e.g. Gouteux and Spelke, 2001).

In our experiments, we used the same experimental setting defined by Sovrano et al. (2002) We then used the EvoRobot simulator (Nolfi, 2000; Nolfi and Floreano, 2000) to get a population of artificial or-

ganisms (software robots) with the ability to solve the Open Field Box and the Blue Wall tasks.

2.2 Artificial Organisms

Each artificial organism consisted of a physically accurate simulation of a round robot, the Khepera robot (Mondada et alii, 1993) with a diameter of 5.5 cm. Each robot is equipped with 8 infrared proximity sensors (capable of detecting objects within 3 cm of the sensor) and a black/white linear camera with a receptive field of 270 and 6 metres range. The robots moved using 2 wheels (one on each side of the robot) powered by separate, independently controlled motors. The control system was an Artificial Neural Network (a perceptron) with 18 input neurons: 8 units for the infrared sensors, 8 for the camera and 2 bias units. These units are always active, so their activity is not influenced by the interaction with the external world. Nonetheless they are very useful to allow the robot to produce a behaviour even in absence of external stimulation, because they transmit a certain activation to the output neurons. The perceptron also owns 3 output neurons (2 units for the wheels, 1 "decision unit"). All input units are connected to all output units.

2.3 Training environments

In our experiments, we used two distinct training environments: the first one was a *purely geometric arena* that reproduced the setting used by animal psychologists in the Open Field Box Task. Its walls are all white. The second one was a *coloured arena* that reproduced the setting used for the Blue Wall task. In this arena one of the long sides was coloured, thus providing an additional, non-geometric information. Both environments were rectangular in shape (56.8*25.6 cm); in both environments the "target area" (the reward) was located in the top-left corner.

2.4 Training procedures

The artificial organisms were trained using a Genetic Algorithm (Mitchell, 1997). At the beginning of each experiment, we created 100 simulated robots with random connection strengths. We then tested each robot's ability to find the target location. The robot was positioned at the centre of the arena facing in a random direction and allowed to move around for 1500 computation cycles (100ms per cycle). Every time the robot reached and "identified" the target (activation of the decision unit greater than 0.5) it received a one point reward. Each robot was tested 100 times and assigned a final score consisting of the total number of points received during the tests. At the end of this procedure, the 80

robots with the lowest scores were eliminated (truncation selection). The remaining twenty robots were then cloned (asexual reproduction). Each "parent" produced five "offspring". During cloning, 35% of neural connections were incremented by random values uniformly distributed in the interval $[-1, +1]$. The testing/selection/cloning cycle was iterated for 100 times.

To investigate the effects of landmark stability on spatial abilities diachronic acquisition, we performed two families of training experiments. To the first class belong the training procedures that have been run in only one setting (Open Field Box setting or Blue Wall task setting): this means that the non-geometric feature was never or always present. The second family, that we will refer to as *alternation procedure*, instead, includes 3 training procedures in which organisms were trained in both settings, with different rate of presence of the non-geometric cue (25%, 50%, 75%). Each experiment consisted of 20 simulations with identical parameters. Each simulation began with different, randomly generated connection weights.

3. Results

3.1 Training process

Figure 1 shows the average and the standard deviation in reward scores for the 20 individuals (the best of each replication) in time. The training process was run exclusively in the Open Field box task.

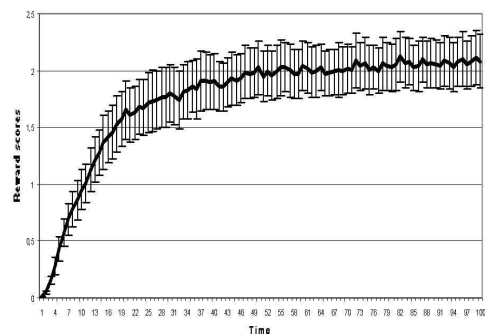


Figure 1: Open Field Box Setting. Reward scores for the artificial organisms: average and standard deviations in reward scores for 20 individuals (the best of each replication) in time.

Figure 2 reports the same results, this time regarding the training process in the Blue Wall task. This setting provides, together with the information about the shape of the environment, the non-geometric information of the coloured wall in a stable way.

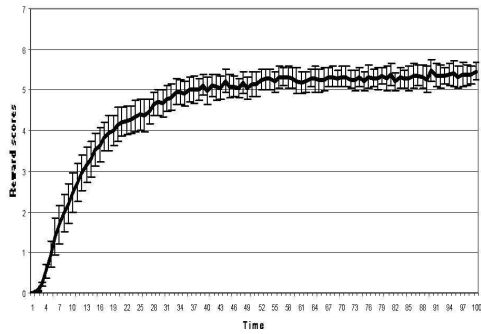


Figure 2: Blue Wall Task. Reward scores for the artificial organisms: average and standard deviations in reward scores for 20 individuals (the best of each replication) in time.

As it is evident from the graph, organisms learn progressively to behave correctly in their own environment, both in the Open Field Box and in the Blue Wall task setting.

It is important to underline that, if the non-geometric features is always present, thus constituting a reliable source of information about the general arrangement of the environment, the artificial organisms can use them to orient.

In fact, at the end of the training, we conducted a testing session on the best organisms and, on the total of 20 replication, the 100% of subjects solved the task in the setting where it had been trained. In particular, in the Open Field Box setting the organisms chose with almost equal (very high) frequency the correct corner (51.1% of the trials) or the rotationally equivalent one (49.7%), while in the Blue Wall task setting they disambiguated completely the problem choosing correctly the rewarded corner (99.2% of the trials.)

We then tested the robots in the setting they had not experienced during training: they did not behave correctly in the unknown condition, thus proving not to generalize.

3.2 Behavioural Strategies

To understand the behavioral strategies and the type of neural processing underlying the results presented above, we analyzed the behaviour of the best performing individual (the individual with the highest reward score) from all the replications in the Open Field Box arena. The strategy it employed is represented in Fig.3.

The organism trained in the purely geometric arena adopted a simple but extremely effective behavioral strategy. Analyzing the behavior displayed in Figure 3, we can describe the robot's strategy as

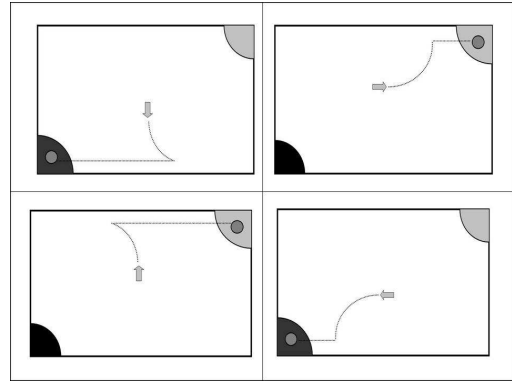


Figure 3: Trajectory of the best performing individual (represented in the diagram above by a grey circle) from the training trials in the purely geometric arena. We consider four different starting points: facing south (up on the left), facing north (below on the left), facing east (up on the right) and facing west (below on the right).

follows: first, the robot identified a long side and moved towards it. Upon reaching the wall, the robot turned to the right and followed the wall until it came to a corner. This corner is necessarily either the correct corner or its rotational equivalent. In actual fact, the robot could not distinguish the long from the short sides. In the absence of coloured objects, which could be picked up by the on-board video camera, the only sensors actively available to the robot were the infrared sensors. These sensors could only identify obstacles within a distance of 3cm. Therefore, the robot received no information from its sensors until it was very close to a wall. Even when the sensors were active, all they told the robot was that it was near an obstacle. In this way, the robot could know nothing about the colour or length of the wall. So how was it able to move towards the long side? Simply by finding appropriate connections between the bias units and the motor units (see Materials and Methods section). The configuration that evolved produced a differential activation of the two motors. This led the robot to follow a curved trajectory. The radius of the curve was such as to guarantee that the robot would automatically hit one of the long sides. In the Blue Wall task setting the robot's strategy is nearly perfect. Regardless of its initial direction the robot rotates until the black wall is on its right. At this point the reward area is exactly in front of the robot, which now moves towards the target in a straight line. A specific pattern of infrared sensors tells the robot it has reached a corner.

At this point it activates the place unit. By effectively coordinating sensor input and behavior the robot completes the task flawlessly. Summarizing, the strategies for solving the task are different for the robots trained in the 2 different settings: while

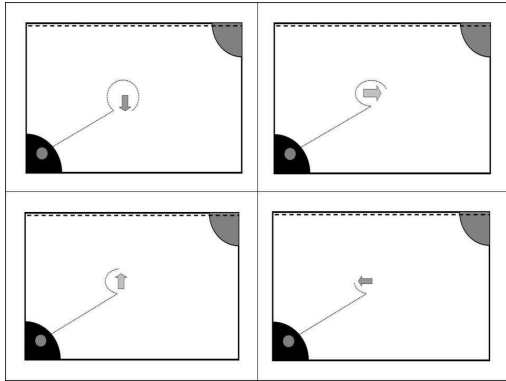


Figure 4: Trajectory of the best performing individual (represented in the diagram above by a grey circle) from the training trials in the arena with additional non-geometric information. We consider four different starting points: facing south (up on the left), facing north (below on the left), facing east (up on the right) and facing west (below on the right).

in the first case they exploit the constraints of the arena, adapting their trajectory to the characteristics of the arena (that is its rectangular shape, its size), in the other case they do use both information (geometric and non-geometric), thus arriving directly to the reward area.

3.3 Correlation between stability of non-geometric cue and its exploitation

In the previous section we have observed that, if the coloured wall was always present, the artificial organisms used the information it provided. But what happens if this cue is present only sometimes? To answer this question we have considered the robots that had been trained with the *alternation procedures*. We have tested the behaviour of the subjects belonging to each of the procedure (coloured wall in 25, 50 and 75% of the trials) and then we have counted how many of them did solve the Blue Wall task. The coefficient of correlation between the number of trials during which there is the coloured wall and number of agents that choose the correct corner significantly more often than the others, thus solving the Blue Wall Task, was:

$$r(3) = 0.987, p < 0.01$$

These variables presented a strong positive correlation: in other words when the number of trials in presence of the coloured wall increases, the number of agents that do consider this information source increases proportionally. The more the cue provided a stable information, the more the agents exploited it to orient.

3.4 Acquisition pathways

In order to understand which acquisition pathways the robots had actually followed, we have concentrated our analysis on the robot that had been exposed to the non-geometric feature for the half of the trials (*alternation procedure*). In this condition robots were exposed with equal frequency to the two experimental settings, an edge condition for the exposition to the 2 different environmental conditions. It is now necessary to stress a methodological assumption we made. All the agents share the same morphological and neural characteristics, but differ in a significant respect: their connections' weights are randomly assigned at the beginning of the procedure. The genetic algorithm holds as starting points different positions in this space, defined by the random initialization. The modifications that occur during the process are indeed a search in the solutions' space that we metaphorically assimilated to a learning/development process of 20 different individuals. First of all we concentrated on the performance of the artificial agents at the end of the procedure. Between the 20 artificial organisms that had been trained, 7 were able to behave correctly in both arena, solving both the Open Field Box task and the Blue Wall Task, while 5 showed a correct behaviour only in the first task and 8 only in the second one. This was the situation at the end of the process, but we were interested in understanding what these final outcomes corresponded to during the acquisition of the abilities to solve the 2 tasks.

For this reason we decided to test the 7 robots that, at the end of the process, solved both task, at precise steps along the training too. We have checked that after 20 iterations (generations on a species scale or trials on a individual scale), robots solved at least one of the tasks, so this is the first time lapse we have taken into account. We then tested the organisms in the 2 tasks every 20 iterations.

The figure above deserves an explanation: on the x axis there are the iterations, while on the y axis we find 3 different behavioural abilities: solving the Open Field Box Task, solving both tasks and solving the Blue Wall Task. In brief, at each time step, indicated by the number below, the robots can 1. solve only the Open Field, 2. solve only the Blue Wall task, 3. solve both tasks. The lines represent the acquisition pathways for robots that are able to solve both tasks at the end.

Various acquisition sequences are possible: 2 robots learn both tasks at the same time, since the 20th trial the 2 spatial abilities emerge together. Instead, in the others 5 robots that at the end of training procedure do solve correctly the two tasks, an ability emerges before the other. As the exposition to the 2 tasks is similar, the two options are both present: someone (3 robots) acquires the ability to

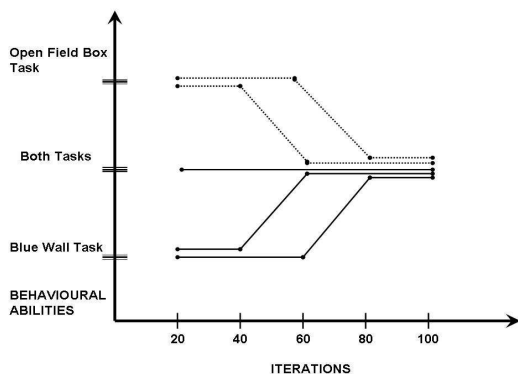


Figure 5: Representation of the ability acquisition pathways to solve the Open Field Box and the Blue Wall task in the alternation procedure with 50% of trials in the Open Field Box Task setting and 50% in the Blue Wall Task setting.

solve the Open Field Box task before (the dotted lines in the graph) and some (2 robots) later (the continuous lines in the graph). In the first case the artificial organisms follow the same route of human children: at an earlier stage they can solve correctly the Open Field Box task and later acquire the ability to take into account non-geometric information too, thus solving the Blue Wall task.

4. Discussion

The goal of this work was to verify if *stability* could be a relevant variable in the spatial abilities assimilation, as this aspect is not, in our opinion, adequately regarded in the study with natural organisms. In brief, we have tried to understand if stability plays a role *beyond* the nature of the information (geometric vs. non-geometric).

Thanks to the use of artificial organisms whose brain could not build an explicit representation of geometry or non-geometric cues, we could concentrate on stability: a variable that, in our opinion and in the point of view of Embodied and Situated Cognition may be relevant in this (probably also in others) kind of spatial tasks.

Results we have shown in the previous section can be interpreted in the theoretical framework of Embodied and Situated Cognition (Clark, 1997; Thelen and Smith, 1994; Varela et alii, 1991). Behavioural data (Fig.1, 2, 3 and 4) show, in fact, that, even with a simple perceptron as brain, the artificial organisms we studied can exploit the information provided by the coloured cue, if it is always present during the training. In this case the coloured wall provides a reliable information about the environment, it becomes something the robots can count on: as during training they adapted to the environment they expe-

rienced, they learn to respond adaptively (efficiently) to this environmental cue too.

The developmental results can be summarized this way: if the non-geometric information is present only for a certain lapse of time of the training the percentage of artificial organisms that can exploit it varies proportionally to the length of exposure to non-geometric features. In this case the Embodied and Situated Cognition interpretation is fit too: the more the cue is stable, the more robots use it, because the adaptation to the environment forces to consider the increasingly stable cue.

Manipulating the variable *stability*, (Fig.5) it has also been possible to reproduce the developmental pattern observed in children. When the coloured cue is present only in half of the trials, some of the robots display the same developmental pattern observed in human children: first they solve the Open Field Box task and the ability to solve the Blue Wall task emerges later. Also in this case the robots assimilate these abilities thanks to the interaction with the environment. These results go against Hermer and Spelke's (1996) hypothesis that demand that, for merging geometric and non-geometric cues, an high-level cognitive process (language) is required. On the contrary we can suggest, as Learmonth and colleagues (2001-2002) do, that this variable is relevant also in the case of children. As we have suggested before, it is not wrong to believe that they could adapt before to geometric, presumably more stable, information and only later to non-geometric information, that is present and important but not totally reliable.

Of course these results don't pretend to provide a direct evidence for what happens in children. In the human beings, in fact, may be the assimilation of geometric information can indeed be made through a module, process that becomes more flexible with the language acquisition.

On the other hand, between the robots we studied there is also the opposite pathway that has not been observed in nature (could we shyly whisper that this happens because geometry is always predominant?). The results we present here derive from a genetic search, so the interpretation in terms of developmental sequences can be accepted under the condition that we consider it as a metaphor of the exploration of the solutions' space. In choosing this methodology, in fact, we took inspiration on Edelman's theory of neural Darwinism (Edelman, 1987) according to which groups of neurons are selected during development through the interaction with the environment. In this study selection was not operated on multiple groups of neurons in a single agent, but on multiple groups of neurons tested sequentially on the same agent. This way, the best neural controllers could emerge thanks to the interaction with the envi-

ronment. Using evolutionary techniques (that could be also another learning algorithm) to find a neuro-controller that can solve our specific tasks and by analyzing how these tasks are solved, we could suggest something about the structure of the task.

In particular the results lead us to suggest that the way in which natural and artificial organisms acquire their (spatial) abilities can be explained, in principle, just resorting to the adaptation on the precise characteristics of the ecological niche in which they develop.

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