Running title: Objects, space and affordances

Objects, spatial compatibility, and affordances: A connectionist study

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Abstract

In two Artificial Life simulations we evolved artificial organisms possessing a visual and a motor system, and whose nervous system was simulated with a neural network. Each organism could see four objects, either upright or reversed, with a left or a right handle. In Task 1 they learned to reach the object handle independently of the handle's position. I, in Task 2 they learned to reach one of two buttons located below the handle either to decide either where the handle was (Simulation 1) or whether the object was upright or reversed (Simulation 2). Task 1 simulated real life experience, Task 2 replicated either a classic spatial compatibility task (Simulation 1) or an experiment by Tucker & Ellis (1998) (Simulation 2). In both simulations learning occurred earlier in the Compatible condition, when the button to reach and the handle were on the same side, than in the Incompatible condition.

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1. INTRODUCTION

1.1. The role of actions in the internal representation of objects

According to the traditional view of perception, action is peripheral with regard to perception. It is sensory input that determines how the world is represented in an organism's nervous system, not the actions with which the organism responds to sensory input. This passive or contemplative view of knowledge, which has a long philosophical tradition behind it, is increasingly challenged by recent studies which suggest that visual perception and action are strictly connected (e.g., Ward, 2002) and that how the world is represented inside an organism depends on the actions with which the organism responds to sensory input rather than on sensory input per se. Experimental evidence indicates that the representation of visually perceived objects incorporates motor information. Seeing objects or pictures of objects elicits neural representations of the actions that tend to be performed with respect to them. In this perspective, the notion of affordance (Gibson, 1979) has been given new relevance. An affordance is a resource or support that the environment offers to the actions of an animal. It is one way in which a perceiver can interact with an object. Thus the notion of affordance is not an absolute one and is not an intrinsic property of objects. Different objects may provide different affordances depending on the constraints of the organism's body, the perceptual characteristics of objects, and the current context.

One way of studying how important are the actions with which an organism responds to an object in the neural representation of the object is to devise experimental tasks in which participants are shown an object and they are asked to produce an action which is in contrast with the action typically associated with the object. If the participant finds this task difficult, one can infer that objects are neurally represented in terms of the actions with which the organism normally responds to them. This type of task is called stimulus-response compatibility (SRC) tasks. In a typical SRC task participants tend to respond faster when the stimulus and the response location correspond than when they do not correspond. For example, RTs are typically shorter when the location of the

stimulus corresponds to the location of the response (e.g., left stimulus/left response) than when it does not (e.g., left stimulus/right response).

In this paper we describe some computer simulations that explore the role of the actions with which we respond to objects in the neural representations of objects. Computer simulations simplify with respect to reality but they offer some advantages in that they force us to make our theoretical ideas and explanations more clear, detailed, and complete and, furthermore, they allow us to directly examine the internal (neural) organization of artificial organisms that allows them to exhibit particular behaviors. The simulations described in this paper use two types of learning algorithms, the genetic algorithm and the back-propagation algorithm, to train neural networks to exhibit the required behaviors and they use learning success as a proxy for the reaction times (RTs) which are used in laboratory experiments. The results of experiments on stimulus-response compatibility have already been simulated in a number of published studies that will be discussed in the following pages. However, these simulations use "classical" neural networks (Rumelhart and McClelland, 1986) in which actions as sequences of movements of the organism's body (or body part) are not directly simulated. Our simulations use artificial "embodied" organisms (simulated robots) which do not only have a simulated "nervous system", i.e. an artificial neural network, but they also have a simulated body which interacts with a physical environment. This embodied simulative approach which explicitly represents motor actions and how they affect the neural network's sensory inputs appears to be more appropriate if we want to study the role of actions in the internal representation of the world.

1.2. Stimulus-response compatibility

As we have already discussed, experimental evidence shows that compatible sensory-motor mappings are easier than incompatible mappings, indicating that actions are important in the neural representations evoked by perceived objects. The advantage of compatible over incompatible mappings is preserved also when the spatial dimension is not relevant for the task. In the Simon task (Simon & Rudell, 1967; Lu & Proctor, 1995; Hommel & Prinz, 1997; Umiltà & Nicoletti,

1990; for a review see Hommel, in press; for a computational model of the Simon effect see Zorzi & Umiltà, 1995), for example, when participants have to perform a left or right keypress according to the color, shape or other dimension of a stimulus delivered either to the left or to the right of a fixation, they respond faster and more accurately if there is compatibility between the stimulus location and the response location.

A powerful explanation of this effect is based on a dual route account (De Jong, Liang, & Lauber, 1994; Kornblum, Hasbroucq, & Osman, 1990; Tagliabue, Zorzi, Umiltà, & Bassignani, 2000). According to this account, an automatic fast route processes the task irrelevant dimension, whereas a slower indirect route activates the response required by the instructions. The activation of two routes explains why compatible trials, in which both routes activate the same responses, lead to a faster and more accurate performance.

In a recent study Tucker & Ellis (1998) used a SRC paradigm to demonstrate that the sight of objects elicits the affordances associated with them. They presented participants with photographs of centrally presented objects with handles, such as cups, saucepans, and knives. The objects were presented upright or upside down, with the handle extending to the left or to the right of the object. Participants had to indicate whether the object was upright or reversed by pressing a left or a right push-button. Results showed a clear effect of compatibility between the position of the handle and the location of the button, indicating that seeing an object can potentiate a certain response. The handle position, even if it was not relevant for the task at hand, influenced the response.

The results of this experiment can be accounted for in two different ways, which imply two different views of affordances. According to the first explanation visual affordances automatically elicit motor information, i.e., the object's handle automatically elicits a specific action, thus activating the ipsilateral hand. According to the second explanation visual affordances evoke an abstract response code facilitating all kinds of lateralized actions. In this view the results of the experiment can be explained as a special kind of Simon effect: the results can be due to the

activation of an irrelevant spatial dimension, i.e., to the activation of an abstract left-right coding of orientation (for a discussions on the relationship between Simon effect and affordance effect, see Cho & Proctor, in press; Iani, Baroni, Pellicano & Nicoletti, in press; Pellicano, Iani, Borghi, Rubichi & Nicoletti, in press).

To disentangle this matter, in a further study Phillips & Ward (2002) presented participants with a visual object prime such as a frying pan with a handle. The handle of the object could extend to the left or to the right of the object, or it could be in the middle. In different experiments, the prime was followed after a varying SOA by a target requiring a left or right hand or a foot-press response. In two different experiments, participants had to perform the task with the hand uncrossed or with their hands crossed. The results indicate that there was a correspondence effect between the handle orientation and the key the participant pressed regardless of the modality (hands uncrossed, hands crossed, foot response). This correspondence effect increased with SOA.

Phillips and Ward's (2002) interpretation of the results favors the idea that the affordances of an object do not potentiate a specific response code for the hand or limb more suited to respond, but activate a more abstract spatial code, which may potentiate a wide variety of responses to the afforded side of space.

This result partially contrasts with the result of a further experiment by Tucker & Ellis (1998) who did not find the compatibility effect between the handle location and the location of the key to be pressed when participants had to produce a unimanual response, i.e., when the effectors that had to provide the answer were not the two hands but a left or right finger of the same hand. Unlike the feet, fingers are too close to each other to imply a different orientation of our bodily axis towards an object located in front of us. Furthermore, fingers might be too weak to move a cup, whereas feet are surely strong enough to remove a pan by pushing its handle. Thus visual stimuli apparently evoke a simulation of the interaction with the object in which object properties are not activated per se (handle location), but in interaction with the body properties (effectors location and force) and the current situation (e.g., empty frying pan).

1.3. Aim of the study

The aim of the present study is to reproduce with a connectionist simulation an experiment using a spatial compatibility task as well as the situation explored by Ellis & Tucker (see also Parisi, Borghi, Di Ferdinando & Tsiotas, 2005). Modeling the results with a connectionist simulation has various advantages. First, connectionist simulations allow the experimenter to control the conditions in which organisms learn to perform a certain task. In this case, we first taught the organism to reach four container-like objects, which could be upright or reversed, with the handle protruding either on the left or on the right, and then we examined if the experience with the object influenced the performance in a simulated experiment.

Second, connectionist studies allow ruling out particular explanations. We simulated an organism whose brain is not characterized by hemispheric specialization or asymmetry and we explored a situation in which the space partitioning is due solely to the kind of movement the organism can perform with its arm. Consider, in addition, that our simulated organism has a single arm. If we find compatibility effects, it is plausible to predict that the presence of two different limbs is not necessary to obtain such effects. The prediction derived from simulations should obviously be further empirically tested. There is convergent experimental evidence indicating that it is the spatial location of the response rather than the effector used that is responsible for the compatibility effect. Third, connectionist simulations allow us to analyze the internal organization of the neural system which is responsible for the obtained results.

Even though the specific experiment we model has not been simulated, other connectionist models of the Simon effects have been proposed. We will briefly address the major features of two of the most recent ones. Zorzi and Umilta' (1995) reproduce the Simon effect using a network with 2 response nodes linked by hardwired positive connections to 2 nodes representing position (left, right) and by weight-modifiable connections to 2 feature nodes. The response system incorporates a competitive mechanism: each node might send lateral inhibition to the other node. After stimulus

onset, the system works until there is a winning node: reaction times are assumed to correspond to the number of cycles necessary for the system to settle.

Kornblum, Stefans, Whipple and Requin (1999) use a model composed by an input and an output layer, each consisting of at least one module composed by 2 units, representing the relevant stimulus dimension in the task (i.e., the color). When there is Stimulus-Stimulus and Stimulus-Response overlap, there are automatic connections between the 2 respective modules – the connections between the corresponding units of each module (for example, the left stimulus and the left response) are positive (excitatory), the connections between non corresponding units are negative (inhibitory). Differently from Zorzi and Umilta' model, this model does not have inhibitory connections between units of the same module (the response one) but only between different modules, for simplicity sake. In addition to the automatic connections, there are controlled connections, simulating a "decision" based on the instructions, linking the relevant stimulus module to the response module. The real advantage of this model consists in the capacity to decompose RTs into a stimulus processing and a response processing stage. The first stage starts from the stimulus onset to the moment in which the activation of one (or also two) input unit reaches a given threshold. When this occurs, a positive value is sent to the appropriate response unit. Before some input unit reaches the threshold, no processing takes place in the response module. The response processing stage starts from the beginning of response processing to the time when activation in one of the response units reaches threshold.

Compared with these models of the Simon effect, our model has some peculiarities due to the fact that we used an "embodied" approach (for similar work, see Tsiotas, Borghi & Parisi, 2005; Caligiore, Borghi, Parisi & Baldassarre, 2009; in press). Namely, we decided to model not just a behavior performed by a decontextualized brain simulated through a neural network but to reproduce the behavior of a robotic organism, i.e. an organism endowed not only with a brain but also with a body. The organism we simulated lives in a simplified environment where different objects are present and is a member of a population of organisms. Each individual organism is the

product of a given genetic heritage. In fact, we used a genetic algorithm to find the weights who lead to a correct performance. This choice allows us to avoid any a-priori hardwiring of inhibitory or excitatory connections between or within modules. The other major difference with respect to previous models consists in the fact that we reproduced the real structure of the experiment we aimed to simulate – we modelled actual button reaching behaviors and the spatial positions of the object handles and of the button to press.

We believe that using "embodied" models represents an advantage by itself but that these models are particularly useful in this specific case, as we are interested in the effects of object affordances on reaching movements and the Simon effect. For example, a brief review of the literature on the Simon effect shows that there are controversial results concerning the effects of crossing hands on compatibility. There is evidence showing that the effect is of the same magnitude when the response to the stimulus is executed with uncrossed and with crossed effectors (Wallace, 1971; see also Bradshaw, Willmott, Umiltà, Phillips, Bradshaw, & Mattingley, 1994). However, Nicoletti, Umiltà and Ladavas (1984) found longer RTs with the hands in uncrossed position and attributed it to a conflict between the two spatial codes related to the effectors, the locational code which is linked to the location of the responding hand in space, and the anatomical code which is linked to the side of the body with which the hand is connected (Nicoletti & Umilta', 1984). Riggio, Gawryszewski and Umiltà (1986) showed that the effects of crossing might not be due to the position of the hand but to the position of the response goal. Participants manipulated response keys with sticks that were either crossed or uncrossed. Independent of the hand location, they found an effect of spatial correspondence between the stimulus location and the location of the end of the stick, i.e. the location of the response goal. Hommel (1993) confirmed the effect of correspondence between the stimulus and the intended action; however he showed that other correspondences' effects (e.g. stimulus to hand location or to anatomical mapping of the hand) give an additive contribution to the resulting Simon effect. As the literature on hand crossing shows, the role played by anatomical factors in compatibility effects is controversial, and therefore it is crucial to use a

model that maps the anatomical structure of the human body in order not to miss some important point that may account for spatial compatibility effects.

2. SIMULATIONS

We simulated an artificial organism possessing a visual and a motor system (see also Borghi, Parisi & Di Ferdinando, 2005; Di Ferdinando & Parisi, 2004). The visual system allows the organism to see different objects, one at a time. The motor system consists of a single arm composed by two segments. By moving the arm the organism can reach with the arm's endpoint (the hand) different spatial locations. The arm sends proprioceptive information to the organism's brain specifying the arm's current position. The behaviour of the organism is controlled by a neural network (see Figure 1). The network architecture consists of 3 layers: one input layer with 3 different groups of units, one layer of 4 hidden units, and one output layer of 2 units. In the input layer 15 units encode the perceptual properties of the objects, 2 proprioceptive input units encode the current value of the two angles between the shoulder and the arm and between the arm and the forearm, respectively, while the 2 remaining input units encode two different tasks. (For the description of these two tasks, see below.). The 2 output units encode the actions performed by the organism: namely, they encode the variation of the previously mentioned angles. As shown in Figure 1, the visual input units and the task units are first connected with the hidden units, while the proprioceptive input units are directly connected with the output units.

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Insert Figure 1 about here

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On each trial the organism sees an object. The object represents a container with a handle which protrudes either on the left or on the right of the object (see Figure 2). The object can be presented in 4 different manners: upright or reversed, with the handle on the left or on the right.

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Insert Figure 2 about here

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To find the connection weights which allow the organisms to perform correctly the task we used a genetic algorithm (Holland, 1992). We first assigned random connection weights to the neural networks of an initial population of 100 individuals. Then we tested each of these 100 individuals on 20 randomly selected trials. In each trial an individual starts with a randomly chosen arm's position and sees one of the four objects. At the end of the 20 trials we assign each individual a fitness value reflecting the individual's ability to perform the task (reaching the handle of the object or pressing the right button). Each individual has a genotype encoding the individual's connection weights. We used a direct one-to-one mapping: each gene encodes a different connection weight as a real number. The 20 best individuals are selected for (nonsexual) reproduction and each of them generates 5 offspring inheriting their parent's genotype with the addition of some random mutations (mutation rate = 10%). The 20x5=100 individuals thus obtained represent the new generation. The process is repeated for a sufficient number of generations so that at the end the organisms are able to execute the task.

Genetic algorithms have the advantage of being biologically plausible. Differently from the previously described models, however, our model is a model of learning across a number of generations rather than a model of trial-by-trial responses. Whereas other models reproduce response times on the individual trials of an experiment, our model hypothesizes a correspondence between number of generations and response times. Using genetic algorithms we model individual learning through evolution, and we draw a correspondence between the number of generations required to learn performing a task and the task difficulty. Given that in this study we do not have trial-by-trial-responses, it might be objected that we do not reproduce response times. However, we reproduce errors, and the compatibility effect found in the experiment by Tucker and Ellis, i.e. the interaction between response hand and handle location, was significant in both response times AND errors.

Given that in the literature there are controversial results as to whether compatibility might depend on learning or on innate factors, we decided to run the same simulations using both genetic algorithms and a classical learning algorithm, the back propagation algorithm. As our aim was not to simulate physiological learning mechanisms but to analyze the effect of learning on two different conditions (Compatible and Incompatible conditions), we used back propagation. Even if it is not considered a biologically plausible algorithm, it is an efficient learning algorithm.

2.1. Baseline simulation

In the baseline simulation we reproduced the experience of learning to reach the objects' handles. As shown by Creem & Proffitt (2001), grasping the handle of common objects such as hammers in an appropriate way requires the activation of the long-term memory, which contains the objects' affordances reflecting our previous experience with the objects. In our simulation the organism has to learn to react appropriately to the object's affordances: it has to learn that, when it sees an object, it has to reach with its hand the object's handle, i.e., the point in space where the object's handle is located, independent of the position (upright or reversed) of the object. This reflects exactly what we typically do in real life: we learn to react appropriately to objects' affordances.

2.1.1. Results

We repeated the simulation 10 times, starting with different sets of initial connection weights. All the results presented are the average of the 10 replications, each of which lasted 3000 generations. In the first analysis, we calculated the percentage of correct responses in performing the task. At the end of the simulation (generation 3000) the best individual responded correctly in almost 10 out of 10 trials, while the population average was below 4 out of 10 trials. The population average might seem low, but this depends on the chosen mutation rate (10%) (see Figure 3). As it can be seen in Figure 3, similar results were obtained also with the back-propagation algorithm, in which the learning speed was higher: in less than 500 generations the task was learned.

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Insert Figure 3 almost here

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2.2. Simulation 1

After being trained for 3000 generations with the baseline simulation, the organisms were trained for 5000 more generations with 2 different tasks. The two tasks are localistically encoded in the 2 "task demand" input units.

As in the baseline simulation, the organism could see an object which could be upright and reversed, with the handle oriented on the right or on the left. However, now there were two buttons located below the object's handles. Depending on the activated task unit, the organisms had either to reach for the object's handle or to press one of the two buttons below. In order to be sure that the organisms did not "forget" what they had previously learned, one of the two tasks was the one learned during the baseline simulation, i.e., the organisms had to reach the handle of the object. The other task was a Stimulus-Response spatial compatibility task, in which the location of the handle was relevant for response selection. In fact, the organism had to press the button located on the same side of the handle or on the opposite side, i.e., in a position which is either compatible or incompatible with the handle location.

We devised 2 different conditions.

(1) Compatibility. In this condition, the button to press was located below the handle. The organisms had to press the right button when the handle of the object was on the right, the left button when it was on the left. Thus the handle location and the location of the button to press were compatible.

(2) Incompatibility. In this condition, the button to press was located below the object but on the opposite side with respect to the handle. The organisms had to press the left button when the handle of the object was on the right, the right button when it was on the left. Thus the handle location and the location of the button to press were incompatible. In order to disentangle the effects of distance between handle and button and of spatial compatibility, we made sure that the distance

between the handle and the button in condition 1 (Compatibility) was the same as the distance between the handle and the button in condition 2 (Incompatibility).

2.2.1. Results

We calculated the percentage of correct responses in performing the task in the 2 conditions. All the results presented are the average of 10 replications, each of which lasted 5000 generations.

At the end of the simulation (generation 5000) the best individual responded correctly in almost 10 out of 10 trials in the compatible condition and in almost 9 out of 10 trials in the incompatible condition (see Figure 4). The difference between the two conditions appears after 500 generations, that is, when the organisms have learned the second task requiring them to press the buttons. As it can be seen in the figure, the same results were obtained using back propagation. Learning occurred much faster in the compatible condition than in the incompatible condition.

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Insert Figure 4 about here

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In order to detect what kind of neural organization underlies the ability to perform the tasks, in each replication of the simulation we selected the network of the best organisms of the last generation (generation 5000) and analyzed their hidden units' activation patterns. The organisms were presented with the 8 different conditions they had learned (task 1 vs. 2, upright vs. reversed object, right vs. left oriented handle) and the activation pattern of the hidden units of their network was determined. In Figure 5 the 4 columns represent the 4 hidden units and the rows represent the 8 conditions (Task 1 vs. Task 2, Upright vs. Reversed Objects, Left vs. Right Handle). So, for example, row 1 represents the pattern 'Task 1, upright object, right oriented handle', row 2 represents the pattern 'Task 2, reversed object, right oriented handle', and so on. In interpreting the figures, note that there are 3 kinds of units: the bias units, which in the figure are always white, the null units, which are always black, and a third kind of units, which may be active (white) or non active (black).

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Insert Figure 5 about here

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In Figure 6 the activation patterns of the hidden units of one organism at the end of the Baseline simulation (Figure 6a) are compared with the activation patterns of the same organism observed at the end of the Compatible (Figure 6b) and at the end of the Incompatible simulation (Figure 6c). After the Baseline simulation, in which the task consists in reaching the object's handle, the units of the fourth column (i.e., fourth hidden unit) are active or not active depending on the handle position: they are white in correspondence with the left handle and black in correspondence with the right handle. Consider now what happens at the end of the Compatible simulation: the activation pattern of the fourth column is the same as that of the Baseline simulation. But now also the third column is used to identify the kind of task to perform - more specifically, to decide whether to go upwards or downwards, to reach the handle or the button below the handle. Figure 6c represents the activation pattern of the hidden units after the Incompatible simulation. In this case the first 4 rows, representing Task 1, do not differ from the Baseline simulation, but in rows 5 to 8 the network has reorganized itself and other units are used, i.e., column 1 and 2, to encode the new information. Thus the network becomes modular: column 1 and 2 encode Task 2, while Column 3 and 4 encode Task 1.

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Insert Figure 6 about here

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2.2.2. Discussion

The results replicate the results obtained in spatial compatibility tasks with humans. In fact, they show that an artificial organisms learn more quickly (in terms of number of generations) when the handle location and the button location are compatible. The difference between the 2 conditions

is due to a spatial compatibility effect, as the distance between the Stimulus and the Response location was controlled.

Consider that, since our simulated organism has just one arm, the difference between the 2 sides of the body is not due to the presence of 2 arms, but simply to the movement the organisms perform to reach the target. Hence, the compatibility effect is purely due to movement.

The advantage of the Compatible over the Incompatible condition can be explained by analyzing the activation pattern of the hidden units. In fact, in the compatible condition the network can maintain the same activation patterns used in the baseline simulation and a new unit is simply added to encode the new task. On the contrary, in the incompatible condition the network has been re-organized, it becomes modular, and different units are used to encode the 2 tasks.

2.3. Simulation 2

After being trained for 3000 generations (Baseline simulation), as in Simulation 1, the organisms were trained for 5000 more generations with 2 different tasks. As in Simulation 1, depending on the activated task unit, the organisms had either to reach for the object's handle or to press one of the buttons below the object. Simulation 2 differed from Simulation 1 only because task 2 was not a spatial compatibility task; rather, the organisms were required to perform a task similar to that devised by Tucker and Ellis (1998). That is, depending on the activated task unit, the organisms had either to reach for the object's handle or to perform the experimental task, that is to press one of the buttons below the object in order to indicate whether the object was upright or reversed. They had to press the right button to indicate that the object was upright and the left button to indicate that it was reversed. We used also the opposite condition (pressing the right key to indicate that the object was reversed and the left key to indicate it was upright) and obtained similar results. Consider that we paid attention to mapping exactly the experimental procedures. Whereas typically spatial compatibility and spatial incompatibility tasks are submitted to different participants in order to avoid confusion, this was not the case for Tucker and Ellis's experiment. In

order to reproduce exactly the experimental procedure we did not block compatible and incompatible trials but mixed them.

2.3.1. Results

Again, we repeated the simulation 10 times and all the results presented are the average of the 10 replications.

In order to determine whether learning occurs earlier (in terms of number of generations) in the compatible than in the incompatible condition, we calculated the number of correct responses, and the fitness for the best individual and for the average individual each 500 generations, i.e., for generation 0, 500, 1000, 1500, etc. In order to determine whether they had learned, we submitted each organism to a generalization test in which each pattern was presented 20 times. This allowed us to determine how many patterns were responded to in a correct way and whether the compatible patterns were learned more easily (earlier) than the incompatible ones.

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Insert Figure 7 almost here

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As can be seen in Figure 7a, the average number of correct answers in all the generations tested in the Compatible condition is greater than the average number of correct answers in the Incompatible condition. Several ANOVAs were performed, one for each tested generation. In the ANOVAs we had the 10 seeds (the replications) as random factor, and the compatibility (Compatible vs. Incompatible condition) as a within participants variable. The dependent variables were the number of correct answers and the fitness. The results indicate that, in all the generations tested, the average number of correct answers and the average fitness of both the best and average individuals was higher in the Compatible than in the Incompatible condition. As to the number of correct answers, the difference between the Compatible and the Incompatible conditions reached significance ($p < .05$) at generations 1500, 2000, and 4500. The differences in fitness between the Compatible and the Incompatible conditions reached significance ($p < .05$) at generations 500,

1500, 4000, 4500, and 5000. As in Simulation 1, we used also the back propagation learning algorithm. In Figure 7b is reported the percentage of correct responses in a generalization task performed each 100 generations until generation 1000. As it can be seen, the result is straightforward and even stronger than that obtained with the genetic algorithm: learning is faster in the compatible than in the compatible condition.

As in Simulation 1, we analyzed the hidden units' activation patterns of the best organism of generation 5000 in the different replications. In Figure 8 the activation patterns of the hidden units of the best organism of one replication of the Baseline simulation (Figure 8a) are compared with the activation patterns at the end of Simulation 2 (Figure 8b). As can be seen in Figure 8b, the first 4 rows, representing Task 1, do not differ in the Baseline simulation and in Simulation 2. However, similarly to what happened in the Incompatible condition of Simulation 1, in rows 5 to 8 the network reorganizes itself to perform the task and another unit (column) is used to encode the new information. As in the Incompatible condition of Simulation 1, the network becomes modular: column 1 and 2 encode Task 1, while Column 4 encode task 2.

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Insert Figure 8 almost here

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2.3.2. Discussion

Our results confirm the findings of Ellis and& Tucker. Even if the handle location is irrelevant for the task at hand, the sight of the handle activates the movement compatible with its location. When the handle location and the button to press are spatially compatible, learning occurs earlier (in terms of number of generations required to reach an optimal performance) than when they are not. The results clearly replicate the behavioural ones. A potential limit of our model, however, is that it does not take into account the neural underpinnings of the behavioural effects.

The results found by analyzing the activation patterns of the hidden units are compatible with the dual route account. According to this account, one route processes the task irrelevant

dimension, i.e., the spatial compatibility between the handle and the button to press, whereas another route activates the response required by the instructions, consisting in deciding whether the object is upright or reversed. The activation of two routes explains why in compatible trials, in which both routes activate the same responses, learning occurs earlier. (for a sophisticated, neural-based computational model of the competition occurring in the prefrontal cortex between two different possible responses, one of which triggered by the instructions, see Caligiore, Borghi, Parisi & Baldassarre, in press).

However, the results do not allow to decide at what stage response selection occurs. In fact, they are compatible with two different explanations. According to the first explanation, when the stimulus appears, in the compatible condition a movement is immediately programmed, whereas in the incompatible condition a new program has to be prepared after stimulus identification (Hietanen & Rämä, 1995). According to the second explanation (Rubichi, Nicoletti, Umilta & Zorzi, 2000), the Simon effect occurs at the response selection stage, regardless of whether the response is a key-press or an aimed movement, and the effect is attributed to facilitation or interference.

Consider, however, some important differences between the results of Tucker and Ellis and our results. First, differently from Tucker and Ellis we can be sure that the compatibility effect is not due to a perceptual asymmetry but it depends on the fact that seeing the handle of the container potentiates the action schema associated with it. In fact, as underlined by Bub, Masson, and Bukach (2003) the results of Tucker and Ellis are ambiguous as it is not clear on which aspect of the stimulus the compatibility effect depends. In fact, the handle of a container can either define the object part that is grasped during use or it can indicate a perceptual asymmetry. So, the effect found by Tucker and Ellis might depend either on the potentiation of a motor affordance or on a perceptual asymmetry.

On the contrary in our simulation the visual input is not topographically organized. Accordingly, the partitioning of the space into a right and a left side is entirely based upon the

movement performed by an organism. Thus, these simulations indicate that in order to explain the results it is not necessary to invoke the perceptual asymmetry of the object - i.e. the fact that it has a protruding handle. The only information concerning the left or right handle location is derived from the movement used to reach for the handle. Consistent empirical evidence by Di Pellegrino, Rafai and Tipper (2005) suggests that the effect of the handle's position cannot be reduced to a perceptual effect but it incorporates motor elements. They replicated the experiment by Tucker and Ellis (1998) with patients with visual extinction using cups with handles and cups in which the handles were replaced by visual cues (oval patches of size and luminosity equal to the handles) in the same position. The contralesional extinction was reduced when cups had handles affording a left hand grasp, even if no manual response was required, while there was no effect when handles were replaced by visual patches. It may be objected that there is evidence in the Simon effect literature that some compatibility effects are due to perceptual rather than to action linked factors - for example, compatibility effects have been found with arrows. Consider, however, that arrows can be conceived of as a powerful means to direct attention while preparing an action, and according to the premotor theory of attention shifts of attention and goal-directed action mechanisms are closely linked, because they are controlled by shared sensorimotor mechanism. For instance, preparation of motor programs related to eye movements plays a central role in orienting spatial attention. (Rizzolatti, Riggio, Dascola, & Umiltà, 1987)**.**

Second, Ellis and Tucker found a compatibility effect between the handle location and the hand compatible with it, whereas we found a compatibility effect between the handle location and the direction of the movement to be performed. Our organisms have only one effector and they have to move it either to the left or to right to provide an answer. Consider that in our simulations we do not distinguish between reaction time (RT) and movement time (MT), as is done in some recent studies on the Simon effect (Rubichi & al., 2000; Hietanen & Rämä, 1995). However, in the literature a Simon effect was found in both RT and MT. Thus we do not address the question of whether the effect occurs at the response selection or at the response execution stage.

3. CONCLUSIONS

We replicated with embodied neural network simulations the experimental results obtained by Tucker and Ellis, which show that the visual representation of an object incorporates motor information. The results can have two explanations, which are not necessarily conflicting. One explanation is that our results are simply due to a spatial effect, i.e. to the partitioning of the visual space into a left and a right side. In both Simulation 1 and 2 the partitioning of the space into a left and a right side cannot be determined with reference to the anatomical location of the two hands, as our organism has just one effector. Consider that experimental evidence on the Simon effect is controversial as to the role played by crossing hands while performing the task. As described before, much evidence shows that the key-pressing actions are not coded in terms of the acting effector but in terms of response location. In our study the partitioning of space into a left and a right side is entirely due to the kind of movement that the organism performs. In fact, the compatibility effect apparently depends, rather than on the distance between the appropriate response button and the handle, on the fact that the organism performs movements on the same or on the opposite side of space, i.e. on response location. This explanation is compatible with the Theory of Event Coding (Hommel, Müsseler, Aschersleben, & Prinz, 2001), according to which actions are coded in terms of their distal features, not of their proximal ones. Our results are perfectly compatible with the idea that actions are represented in terms of their goals, not in terms of a sensory code representing a specific spatial distance or of specific muscle innervation patterns. In any case, if we want to clarify the role of anatomic factors such as crossed vs. uncrossed hands in the results obtained in experiments, it will be necessary to simulate an organism with two arms and to use both tasks with uncrossed hand and tasks with crossed hands.

Another explanation of our results could invoke object affordances. The results of Simulation 2 suggest that seeing an object implies potentiating its affordances and re-activating previous motor experiences with the object. It remains an open question whether the activation of affordances is automatic or not, and whether the affordances linked to orientation are more variable

and might differ, both in behavioural terms and in terms of their neural underpinnings, from other more stable kinds of affordances, such as those related to size (e.g., Borghi & Riggio, 2009; Young, 2006; Buxbaum & Kalénine, 2010). In addition, it remains to determine whether the Stimulus-Response compatibility effect that we found is action specific or not action specific, i.e., whether visual affordances elicit a specific motor program or whether affordances activate a more abstract spatial code, which may potentiate a wide variety of responses to the afforded side of space.

Overall, our study suggests that Artificial Life simulations can be a powerful tool to model experimental results and can be helpful in solving problems left open by experimental research. In this study we replicated Tucker & Ellis (1998)'s result in a way that makes sure that the compatibility effect found is not necessarily due to a perceptual asymmetry of the object (see Symes, Ellis & Tucker, 2007, for a similar issue) and that the partitioning of the space into a left and right side is due entirely to the kind of movement performed by the organism. This finding may have important implications for experimental research on attentional effects and on affordances.

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Figure Captions

Figure 1. The organism's neural network.

Figure 2. The organism and one of the objects.

Figure 3. Baseline simulation. Correct answers. Average of 10 replications. *Results obtained with genetic algorithm and with back propagation.*
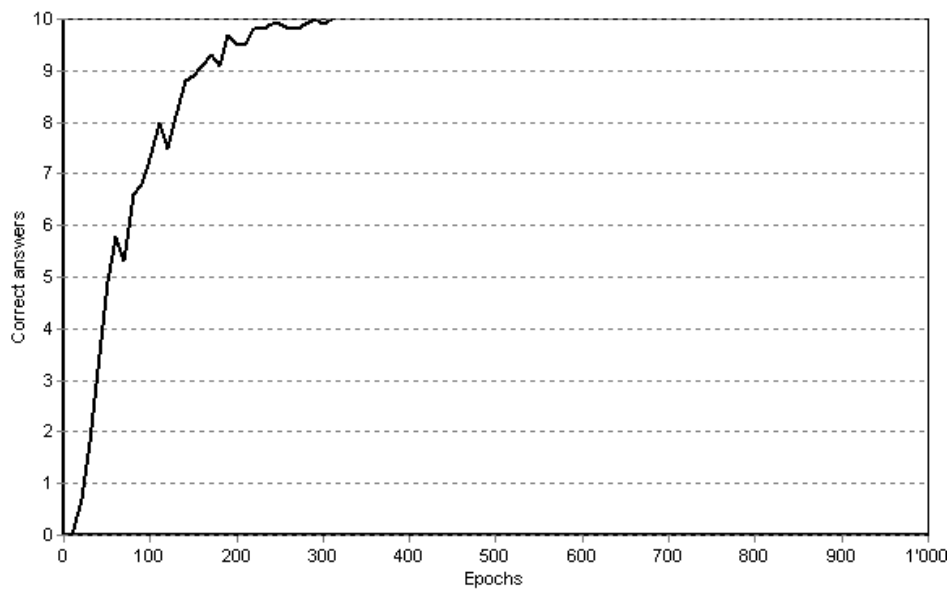
Figure 4. Simulation 1. Comparison between the correct answers in the compatible and the incompatible conditions. Average of 10 replications. *Results obtained with genetic algorithm and with back propagation.*

Figure 5. Analysis of the hidden units. Explanation.

Figure 6. Simulation 1. Comparison of the hidden units' activation after the Baseline Simulation and after the compatible and the incompatible conditions of Simulation 1.
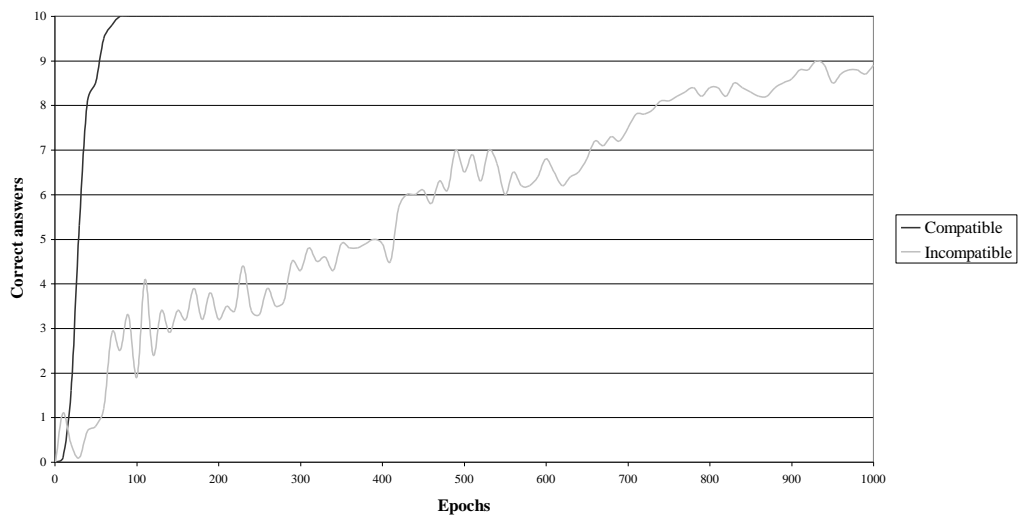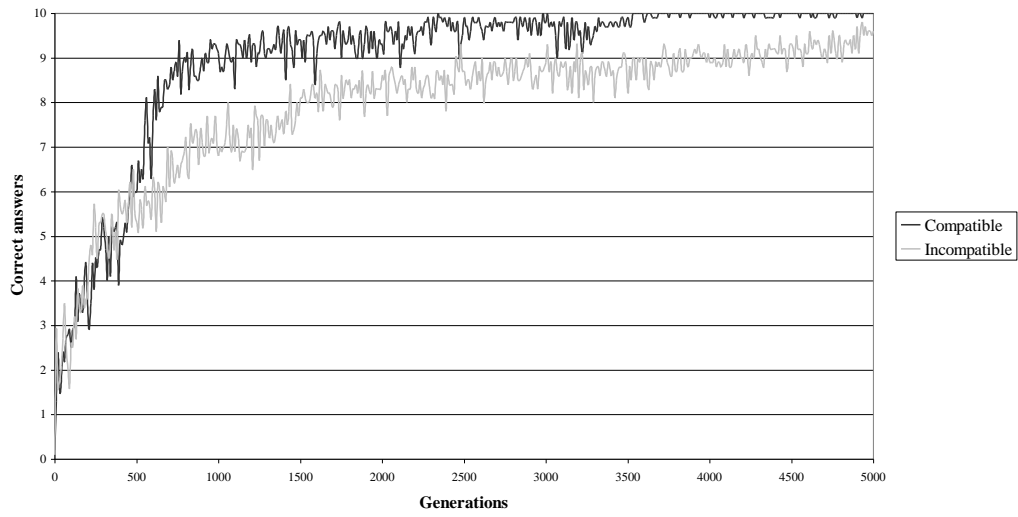
Figure 7. Simulation 2. Comparison between the correct answers in the compatible and the incompatible conditions. Average of 10 replications. *Results obtained with genetic algorithm and with back propagation.*
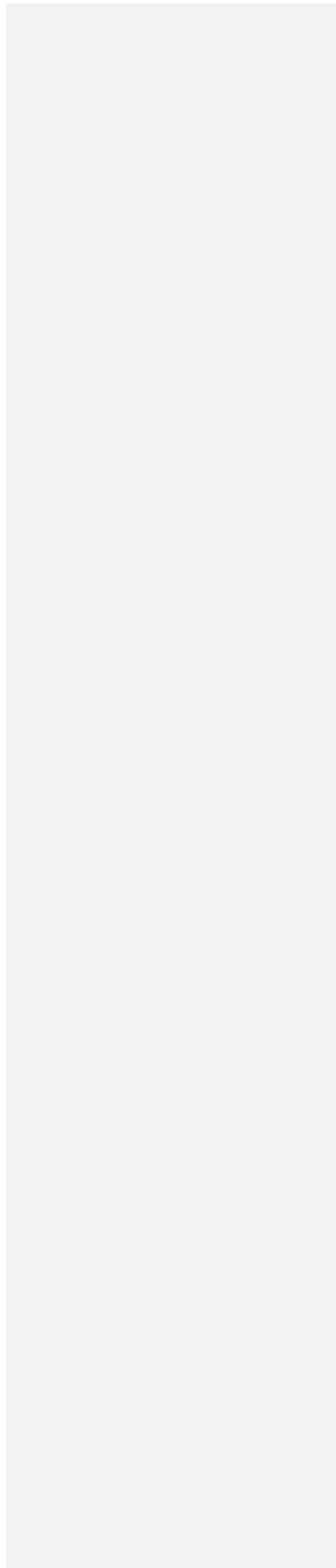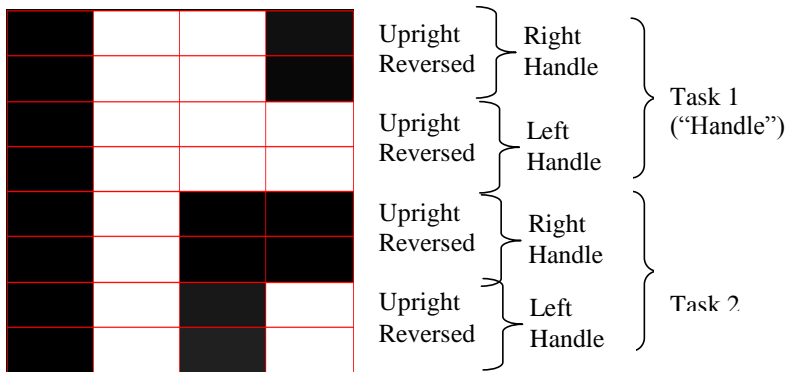
Figure 8. Simulation 2. Comparison of the hidden units' activation after the Baseline Simulation and after Simulation 2.

Motor output

2 Units

4 Units

15
Units

2 Units

2 Units

Visual input   TASK   Proprioceptive
                      DEMAND   input

Handle

Upright
Reversed } Right Handle }

Upright
Reversed } Left Handle   } Task 1 ("Handle")

Upright
Reversed } Right Handle }
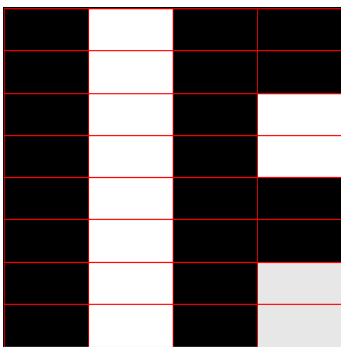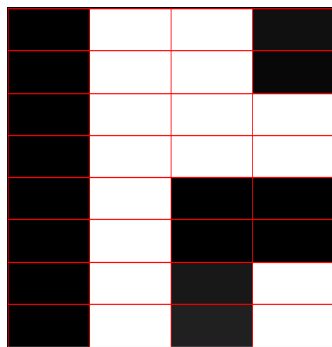
Upright
Reversed } Left Handle   } Task 2
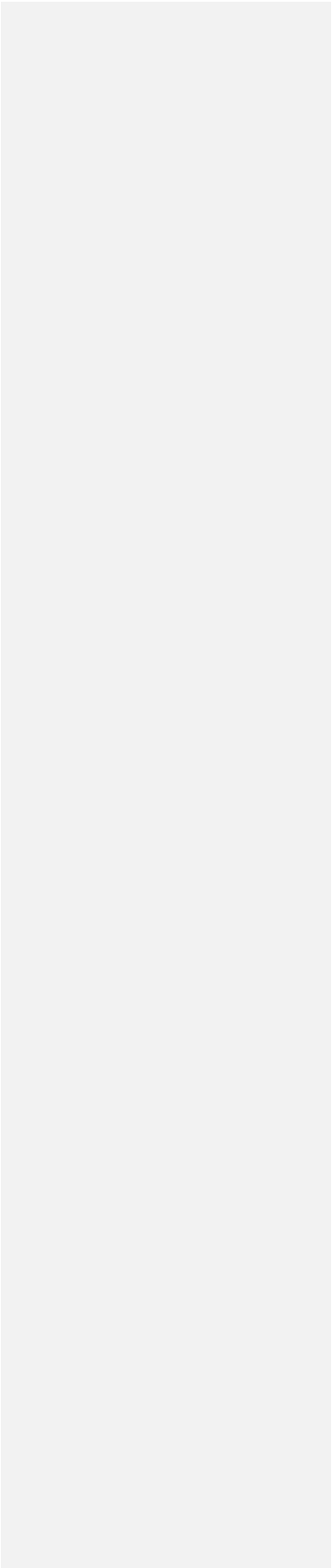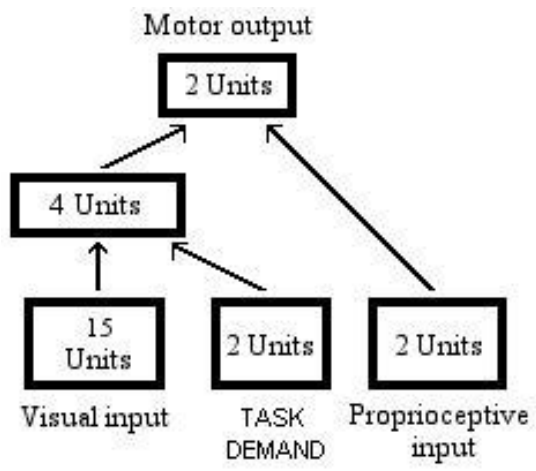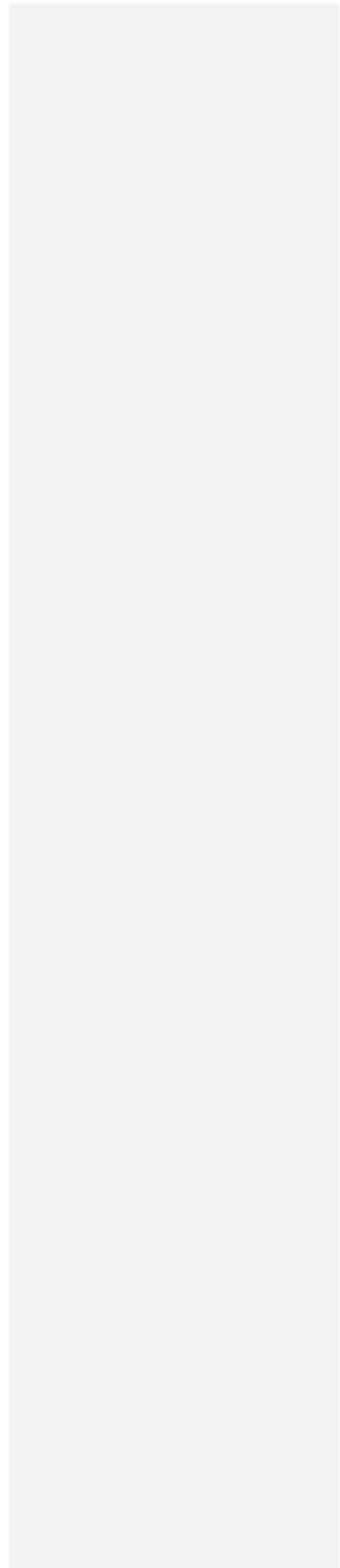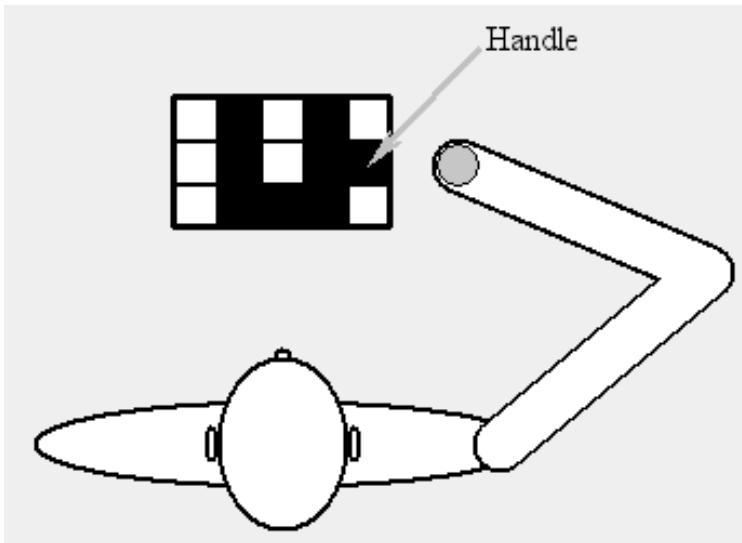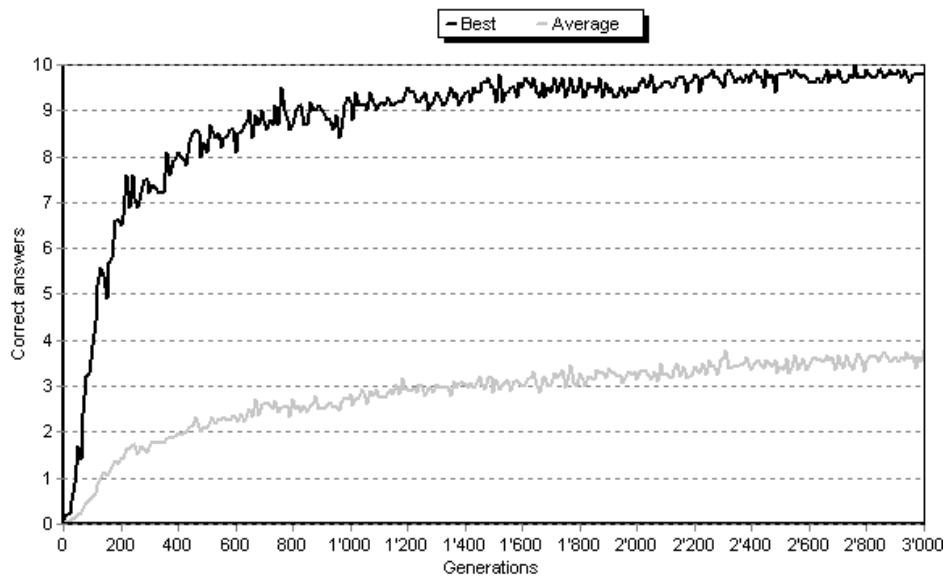
Baseline   Compatible   Incompatible

Baseline

Simulation 2