Chapter 10
The strategic level and the tactical level of behaviour

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Abstract

We introduce the distinction between a strategic (or motivational) level of behaviour, where different motivations compete with each other for the control of the behaviour of the organism, and a tactical (or cognitive) level, where the organism executes the activities aimed at reaching the goal decided at the strategic level. To illustrate and operationalise this distinction we describe three sets of simulations with artificial organisms that evolve in an environment in which in order to survive they need either to eat and drink or to eat and avoid being killed by a predator. The simulations address some simple aspects linked to the strategic level of behaviour, i.e. the role played by the environment in determining what are the motivations driving an organism and what is the strength of each of these motivations. Other phenomena investigated are the usefulness for the organism's brain to receive information from its own body (e.g., in the form of hunger or thirst), how inter-individual differences among individual organisms may concern both the strategic and the tactical level of behaviour, and how the unsolved competition between very strong motivations can lead to pathological states such as depression. AQ1

10.1 Introduction

The behaviour of organisms has both a strategic level and a tactical level. The first is the level at which an organism decides the particular activity in which it will be engaged at any particular time. The tactical level is the level at which the organism executes the specific behaviours that implement the activity decided at the strategic level, allowing in this way the organism to reach the goal of the activity. The tactical level is obviously important because it is the actual level of behaviour. Unless the organism is able to generate the appropriate behaviours that will allow it to reach the goal of the activity decided at the strategic level, the organism's survival will likely be compromised. But the strategic level is even more critical because, in order to survive and reproduce, the organism has to accomplish many different activities and generally it cannot be involved in more than one single activity at any given time. Therefore, there must exist some mechanism within the organism for deciding to which specific activity to dedicate. Examples of different activities are eating, drinking, avoiding predators and other dangers, finding a partner for reproduction, insuring the survival of one's offspring, sleeping, reacting appropriately to physical pain, etc.. Every time an organism faces such a dilemma, it must decide, for example, to eat rather than drink or sleep, and then execute the specific behaviours leading to the desired goal. The strategic and tactical level of behaviour may be labelled 'motivational' and 'cognitive' respectively. An organism's chances to survive and reproduce depend on both its capacity to appropriately manage the competition between different motivations (choosing the specific one that must govern its behaviour at any given time; strategic or motivational level), and its ability to generate the appropriate sensory-motor mappings (tactical or cognitive level) that constitute the activity aimed at satisfying the current motivation.

One must note that the words 'strategic' and 'tactical' tend to be used in a different sense. If the activity chosen at the motivational level is complex and it involves a hierarchical structure of sub-goals and sub-activities, one may call 'strategic' the higher levels of this hierarchical structure and 'tactical' the lower levels. For example, if I decide to dedicate myself to eating, this activity may involve going out to buy some food, cooking it, and then ingesting the cooked food. This is a complex hierarchy of sub-activities and sub-sub-activities. In terms of our distinction between a strategic and a tactical level of behaviour all the sub-activities and sub-sub-activities that implement the activity of eating belong to the tactical (cognitive) level of behaviour. On top of the tactical or cognitive level there is the strategic (motivational) level where I must decide whether to dedicate myself to the activity of eating or to some different activity instead. This decision arises from an internal competition between motivations that have different strengths. If I am actually eating, this means that the motivation of eating has won the competition against other motivations for the control of my behaviour at this particular time. The study of the hierarchical structure of activities is a classical topic of research in both psychology and artificial intelligence (Miller, Galanter, & Pribram, 1986; Fikes & Nilsson, 1971). Motivation, of course, is another classical topic of psychology. However, little work has been done so far on constructing artificial systems that have different motivations and know how to decide which motivation must control their behaviour at any given time. Attempting to understand how these artificial systems could work may help us to reach a better understanding of real organisms' behaviour.

In this chapter we will illustrate our distinction between the strategic and the tactical levels of behaviour by describing a series of computer simulations in which populations of artificial organisms evolve in various types of environments. The goal of these simulations is to operationalise and articulate the notions of a strategic and a tactic level of behaviour, as well as to address some simple questions concerning the motivational level (for a general discussion on motivation in artificial organisms see Parisi, 1996).

One important question is how motivations win the competition against other motivations for controlling the organism's behaviour at any given time. One common interpretation consists in seeing each motivation as associated with a specific strength. The motivation that wins competition is simply the strongest one. The strength associated to different motivations can be operationally defined by observing the behaviour of an organism in its natural (ecological) or in a controlled (experimental) environment. For example, if an organism is exposed to food and water at the same time and it reacts by approaching food rather than water, we can conclude that its motivation to eat is stronger than its motivation to drink. The strength of any particular motivation may vary among different individuals and may also be different at different times for the same individual. Various factors can explain the current strength of a motivation. Examples are the age of the individual, or the current inputs received by the individual's brain from within the body, or from the external environment, or self-generated by the organism's brain itself (Parisi, 2007).

A second important question concerns the role played by the environment in which an individual lives in determining both the motivations of the organism and their relative strength. The behaviour of an organism is aimed at allowing its survival, in that only if it is able to survive the organism can hope to have offspring and, in this way, to insure the presence of one or more copies of its genes in future generations. But the behaviour exhibited by a particular organism depends on the particular characteristics of the environment in which the organism lives or, more precisely, the environment where the population to which the organism belongs has lived in the past. Behavioural ecology is the discipline that investigates how behaviour reflects the particular environment in which organisms live (Krebs & Davies, 1997; Stephens & Krebs, 1986). But, of course, it is more generally evolutionary biology that studies how organisms become adapted to their environment through the selective reproduction of the best individuals and the constant addition of new variants to the population, mainly resulting from random mutations affecting the inherited genes. Using a simulation framework very similar to that of our simulations, Seth (2002; 2007) has simulated the evolution of the motivational system of artificial organisms living either in a social or a non-social environment. His research has shown how the nature of the environment shapes the motivational system of the organisms.

Evolution can shape both the motivational and the cognitive level of an organism's behaviour in that the inherited genes contain information specifying both what the different motivations and their basic strength are, as well as which behaviours the organism must exhibit in order to satisfy the different motivations. Inherited genes only specify the basic motivations and the basic behaviours or behavioural dispositions of the organism. Especially in humans the particular experiences acquired during the life of the individual and the ability to learn from these experiences are responsible for the appearance of different motivations and behaviours.

A third question is how the motivational and the cognitive level are actually implemented in the organism. Very often the strategic level involves the arrival of information from the organism's body to the organism's brain. For example, if the organism must decide whether to look for food or water it may be useful for the organism's brain to receive information concerning the quantity of energy (hunger) and liquids (thirst) currently present in the body. The brain of an organism may be viewed as made up of two interacting parts or circuits, one sub-serving the motivational level and the other sub-serving the cognitive level. The motivational circuit processes information from the body, while the cognitive circuit processes information gathered from the external environment. Information from the body arrives to the motivational circuit, which acts together with the cognitive circuit to determine the organism's behaviour. However, since the body constitutes an internal environment which, unlike the external environment, co-evolves with the brain in order to insure the organisms' reproductive chances, a system for informing the brain about the current level of energy and liquids may be more useful in certain types of environments. In other cases, however, it is the sensory input from the external environment that may trigger the motivational circuit and cause the organism to decide the activity to be executed. For example, to survive in an environment that contains both food and a predator an organism should look for food when the predator is absent but it should cease looking for food and react appropriately to the predator instead, for example by flying away when the latter appears. In these circumstances it may be important for an organism's brain to include a motivational circuit that, like the cognitive circuit, is activated by sensory inputs coming from the external environment. However, the two circuits still have different roles and they may process different aspects of the sensory input gathered from the environment. At any particular time the environment usually sends many different inputs to the organism's brain, and one crucial role of the motivational circuit is to cause the cognitive circuit to 'pay attention' to one of these inputs while ignoring the others. To say that the organism 'pays attention' to one input while ignoring the others is the same as saying that the organism responds to that input and not to the others. For example, if the organism's body informs the organism's brain that there is little energy but sufficient liquids in the body, i.e., if the organism feels hungry but not thirsty, it will ignore sensory input from water and respond to sensory input from food by approaching and eating it. In a different environment, if sensory input coming from outside the body informs the organism's brain that a predator has appeared in the environment, the motivational circuit will cause the cognitive circuit to ignore sensory input from food and to respond exclusively to the information related to the predator.

Finally, artificial organisms with motivational circuits can be useful to explore inter-individual differences in behaviour and pathologic conditions of the psychiatric (e.g., depression) rather than neurological (e.g., aphasia) type.

Inter-individual differences may be not only differences in ability levels (cognitive) but they may also be differences in character or personality (motivational). Pathological conditions such as depression can be interpreted as due to competition between different but equally strong motivations so that no motivation is able to prevail, leading to maladaptive or pathological behaviours. Individual organisms that are unable to survive and reproduce may belong to two different typologies: individuals that are not very good in properly executing an activity such as approaching food or water or flying away from a predator (cognitive deficit) and individuals which become 'paralyzed' or behave in other maladaptive ways when they are exposed to two competing motivations that are both very strong (motivational deficit).

10.2 Simulations

The simulations we are going to describe have been developed using the Evorobot[1]simulator (Nolfi & Floreano, 2000). Evorobot is a simulation tool which permits to carry out experiments using a simulated replica of the Khepera robot (Mondada, Franzi & Guignard, 1999). The robot has a cylindrical body of 55 mm of diameter and 30 mm of height, eight proximity and light sensors, and two DC motors with incremental encoders respectively connected to two independent wheels that make it possible for the Khepera robot to move and rotate its body.

10.2.1 Eating and drinking

In this experimental setup (Saglimbeni & Parisi, 2009) a population of organisms has both to eat and drink in order to survive and reproduce. The body of each organism contains a store of energy and one of water. At each time-step they consume a certain amount of both energy and water just to stay alive. If either one of the two stores become empty, the organism dies. In order for the organism to survive, the two stores have to be regularly replenished with new energy and water supplies. The environment used for this setup is a square of 1,000 $\times$ 1,000 pixels (px), surrounded by walls. The organism occupies a round space with a diameter of 75 px. The environment contains food (providing energy) and water (providing liquids) tokens, each of them represented by a circle with a diameter of 30 px.

To eat a food token or drink a water token, all an organism needs to do is to move over one of these tokens with the centre of its body. The token then disappears, and it is immediately replaced by a new one of the same type located in a random position. Each organism lives alone in its individual copy of the environment, for ten epochs of 1,500 time-steps each. At the beginning

[1] http://laral.istc.cnr.it/evorobot/simulator.html

of each epoch, the environment is cleared and a new random distribution of food and water tokens replaces the preceding one.

The organisms can live in one of four possible scenarios. Scenario 1 contains five food tokens and five water tokens, randomly distributed, capable to refill the corresponding store in the organism's body with 0.2 units of either energy or water. Scenario 2 contains more food than water tokens or, in other simulations, more water than food tokens (the ratio is always five-to-one). The different abundance of food and water is kept constant during the ten epochs. Since to survive in the new environment is more difficult than in the previous one, each token refills the corresponding store in the organism's body by an amount equal to 0.4 instead than 0.2 units. Scenario 3 is the same as Scenario 2, but now the distribution of food and water changes seasonally. In one season (epoch) food is more abundant than water but in the next season water is more abundant than food, cyclically. Scenario 4 includes two distinct zones or patches, one containing three food tokens and the other one containing three water tokens. The patches are squares areas of 60 px of side and their centres are located at a distance of 600 px from each other. In this case the quantity of energy or water contained in a single token is **0.03** units. The four different environments are also associated to different energy and water consumption rates for the organisms. All of the organisms start each epoch with the maximum amount of energy and water in their bodily stores, i.e. 1.0 unit, and at no time during the simulation this value can exceed the starting level. At each time-step they consume 0.0040 water and energy units in Scenarios 1 and 2; 0.0025 in Scenarios 3 and 4. A minimum lifetime is therefore guaranteed even without eating any food or drinking any water: 250 time-steps per epoch in Scenarios 1 and 2, and 400 time-steps in Scenarios 3 and 4. AQ2

The organism's behaviour is governed by a feed-forward neural network made of three layers of units (see Figure 10.1(a)). The input layer includes two units encoding the distribution of food tokens currently contained in the organism's visual field, and two units encoding the location of water tokens. The reason for having two units for each type of tokens is that the visual field of the organism is divided into two half-fields, respectively left and right. One unit in each pair encodes the presence of food (or water) tokens in the left half of the visual field, while the other unit does the same for the right half. Assuming 0° as the organism's current facing direction, the left visual half-field is centred at $+60^\circ$ and covers an area ranging from $+105^\circ$ to $+15^\circ$; the right visual half-field is centred at -60° and focuses from -15° to -105° degrees. The vision range of the organisms is unlimited in terms of extension. The activation values of the input units are calculated according to eqs. (10.1) and (10.2).

$$\text{left\_unit} = \sum_{i=1}^{n} K\left[A + B^{*}\log\left(\frac{1}{d_i^2}\right)e^{-((\phi_i-60)^2/(2\sigma^2))}\right] \qquad (10.1)$$

$$\text{right\_unit} = \sum_{i=1}^{n} K \left[A + B^* \log\left(\frac{1}{d_i^2}\right) e^{-((\phi_i - 60)^2/2\sigma^2)} \right] \tag{10.2}$$

where: n is the number of food or water tokens within the current half-field, d_i and ϕ_i respectively identify the distance and the angle (based on the current heading direction) between the organism and the i-th token detected, K is a factor that accounts for the number of tokens present in the scenario ($K = 0.75/\text{Log(N)}$ for Scenario 1, 2, and 3; $K = 0.5/\text{Log(N)}$ for Scenario 4, with N equal to 10 for Scenario 1, 6 for Scenarios 2, 3, and 4); A and B are parameters, arbitrarily set to 1.596 and 0.11 respectively, used in order to prevent a sensory unit from being activated with a value greater than one or lesser than zero;σcorresponds to half of the angular view capability for each 'eye', which is 45. Linking the input to the output units are four hidden neurons sharing the following sigmoidal activation formula (where y_i is the activation value of the i-th neuron and x is the weighted sum of the all inputs received):

$$y_i(x) = \frac{1}{1 + \exp(-x)} \tag{10.3}$$

These four hidden units are fully connected to both the input and output layers. The two output units are respectively linked to the two motors controlling

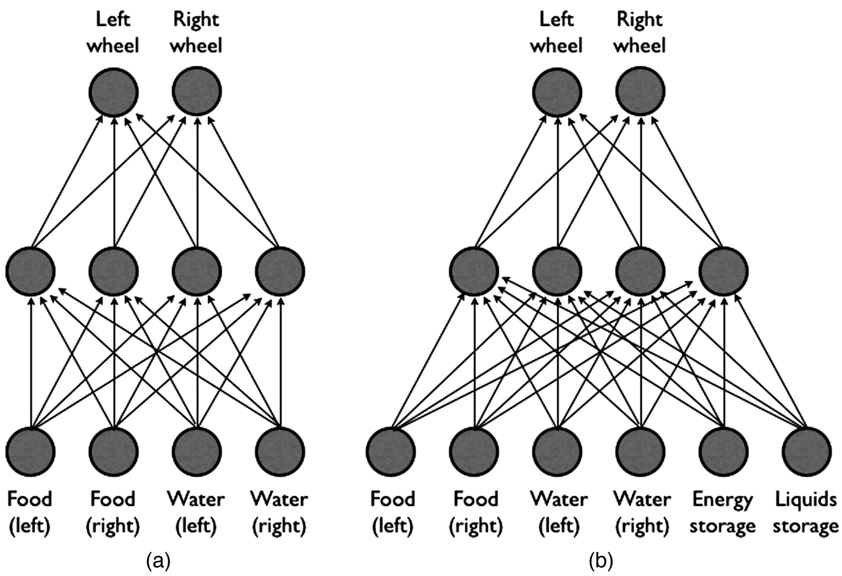

Figure 10.1 The neural network architectures used for the simulations described in section 10.1. (left: Figure 1(a), right: Figure 1(b))

the wheels and therefore the movements of the organism (0: maximum backward speed, 0.5: do not move, 1: maximum forward speed). The organisms' maximum speed corresponds to 8.6 px per time-step. Bias is applied to the units of both the hidden and output layers. The input units do not have any bias instead and they rely on a simple identity transfer function.

The organisms must respond to sensory input from food and water tokens by approaching and consuming them efficiently and in such a way that they can avoid dying because of lack of energy or water in their body. The simulation starts with a population of 100 organisms whose neural networks have randomly assigned synaptic weights and biases within the range [+5.0; -5.0]. Those values are encoded as binary digits sequences in the individuals' genomes. Starting with random genomes implies that at the beginning of the simulation the organisms' behaviour is not very efficient. They are unable to approach food and water tokens efficiently and they may eat and not to drink, or vice versa, so that their average life length is rather short. However, the individuals that succeed in eating and drinking sufficiently and in a balanced way, and therefore live longer, have more offspring than other individuals. The evolution towards a population of organisms able to correctly cope with the desired task takes place through a genetic algorithm. At the end of the ten epochs spent inside the simulated environment, all individuals are assigned a fitness value corresponding to the total number of time-steps of their life. The 20 individuals with the highest fitness values are selected for reproduction. Each of them then generates five offspring that inherit the same connections weights and biases of their (single) parent. The 100 new individuals constitute the next generation. Random mutations are applied to all offspring: each bit of the genome's binary representation has a 0.04 probability of being mutated, thus modifying the corresponding real value. Since offspring inherit the same synaptic weights of their parents with the addition of random mutations, the result is a progressive increase in the effectiveness of the behaviour of the organisms and a progressive lengthening of their average life. The organisms of later generations tend to approach food and water tokens efficiently and in a balanced way so that the energy and water stores in their body are unlikely to become empty at any given time. The evolutionary process is iterated for 1,000 generations and then repeated ten times, each time re-assigning new random connection weights and biases to the members of the starting population. The results coming from the ten experimental replicas are averaged together in order to identify a stable evolutionary trend. For each type of scenario we contrast two different populations of organisms. In one population the neural network controlling the organisms' behaviour has the architecture described above. Therefore in this condition the organisms' behaviour is determined exclusively by the sensory inputs coming from the external environment. In the second population we add two more units to the organisms' neural network (see Figure 10.1(b)). The activation level of these additional units co-varies (linearly within 0 and 1) respectively with the current level of energy and water in the two stores inside the organism's body. The two new units are fully connected to the hidden layer of the network. In this second condition, therefore, the organisms' behaviour is controlled both by the sensory input from the external environment (perceiving food and water tokens) and by the internal input from their own body (level of hunger and thirst). The neural pathway from the sensory input units to the hidden layer simulate the cognitive circuit discussed in the Introduction, while the neural pathway from the two additional units to the hidden units simulates the motivational circuit. The 'brain' of the organisms that possess only the cognitive circuit has no information from within the body but only information from the external environment. These organisms ignore what hunger and thirst are. The 'brain' of the organism endowed with both a cognitive and a motivational circuit receives information both from the external environment and from within the body, which means that the organisms may feel hungry and thirsty. (For simulations in which artificial organisms can be either hungry or thirsty but not both hungry and thirsty at the same time, see Cecconi and Parisi, 1993).

The results of the simulations show that there are no differences in terms of fitness (as measured by length of life) between the populations with and without the motivational circuit in Scenarios 1 and 2, whereas the population with the motivational circuit has more fitness than the population without the motivational circuit in Scenarios 3 and 4. Why? To answer this question one has to consider that the behaviour of the organisms has to be effective at both the strategic and tactical levels. At the strategic level an organism's behaviour is effective if it makes the organism able to approach food when its body needs energy, and water when its body needs liquids. At the tactical level the organism's behaviour is effective if the organism is able to approach both food and water tokens efficiently, by going straight and fast towards the desired token. The conditions that make the behaviour of our organisms effective at the tactical level are identical in all four scenarios, whether or not their 'brain' contains a motivational circuit. In contrast, the conditions that make their behaviour effective at the strategic level vary with the different scenarios, with the motivational circuit playing a crucial role in Scenarios 3 and 4 and no role in Scenarios 1 and 2. (Figures 10.2 and 10.3) AQ3

In Scenario 1 food and water are equally abundant. They are randomly distributed within the environment and therefore the organisms can be effective at the strategic level by simply approaching the nearest token, whether it is food or water. Given the nature of the environment this behaviour will insure a balanced diet of food and water, with no need for a motivational circuit. A motivational circuit is also not necessary in Scenario 2 where food is always more abundant than water (or vice versa). In this scenario the organisms evolve a tendency to go towards the type of token which is less abundant, unless the more abundant token is very close. This is an extremely simple behaviour, nonetheless capable of insuring a balanced diet of food and water even if the organisms' neural network lacks a motivational circuit. Therefore in Scenarios 1 and 2 there are no difference in terms of fitness between the organisms with and those without a motivational circuit. This implies that it makes no sense,

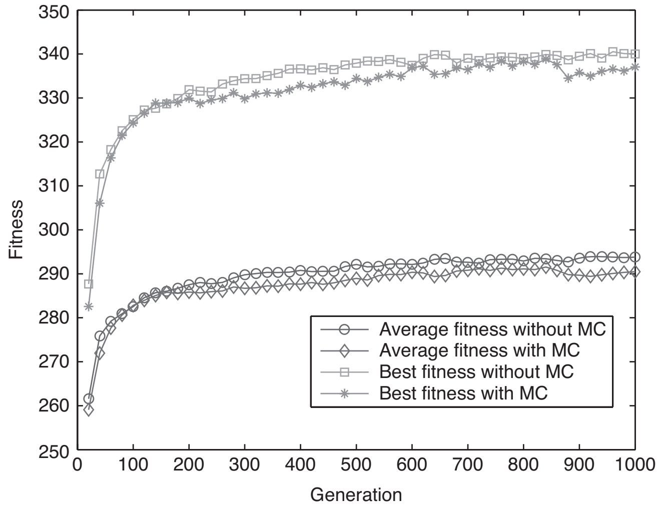

Figure 10.2 Average and maximum fitness for organisms living into Scenario 1, respectively with and without receiving information about their energy and liquids reserves

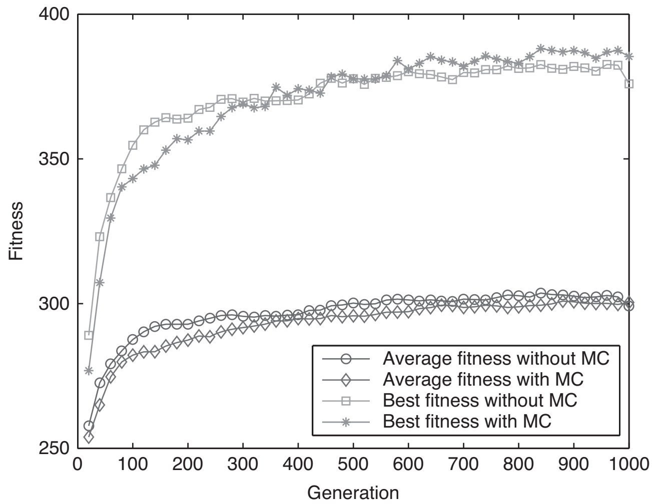

Figure 10.3 Average and maximum fitness for organisms living into Scenario 2, respectively with and without receiving information about their energy and liquids reserves

from an evolutionary perspective, to invest in the development of a motivational circuit.

The situation is different for Scenarios 3 and 4. Scenario 3 is seasonal, with more food than water during one season and the opposite during the following one. Since the organisms ignore what the current season is, to survive they must necessarily rely on information coming from their body. If they feel hungry they have to approach the nearest food token, while if they feel thirsty they have to go toward the closest water token. For these organisms, therefore, it is necessary to possess a motivational circuit that informs their 'brain' of the current level of energy and water in their body. The same is true for Scenario 4, where food and water tokens are located in separate zones. The organisms without a motivational circuit that happens to end up in the zone with food and without water will eat a lot but it is likely that they will die due to a lack of water. The opposite will happen if they end up in the zone abundant in water but with rare food tokens. These organisms too need a motivational circuit capable of informing their 'brain' about the current level of energy and water in their body in order to leave the food zone to go to the water zone when they feel thirsty and to do the opposite when they feel hungry. This explains why for the organisms living in Scenarios 3 and 4 the existence of a motivational circuit results in higher fitness. (Figures 10.4 and 10.5)

The different adaptive patterns of the distinct populations can be clearly demonstrated if we test an individual organism in a standardized (laboratory) situation in which the organism perceives both a single food token and a single

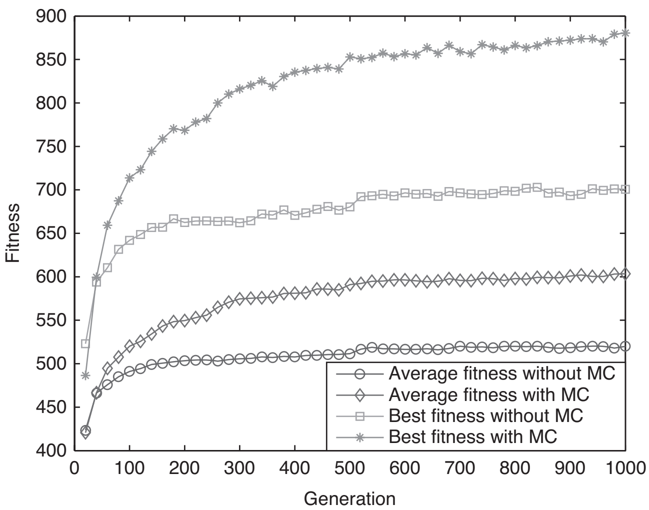

Figure 10.4 Average and maximum fitness for organisms living into Scenario 3, respectively with and without receiving information about their energy and liquids reserves

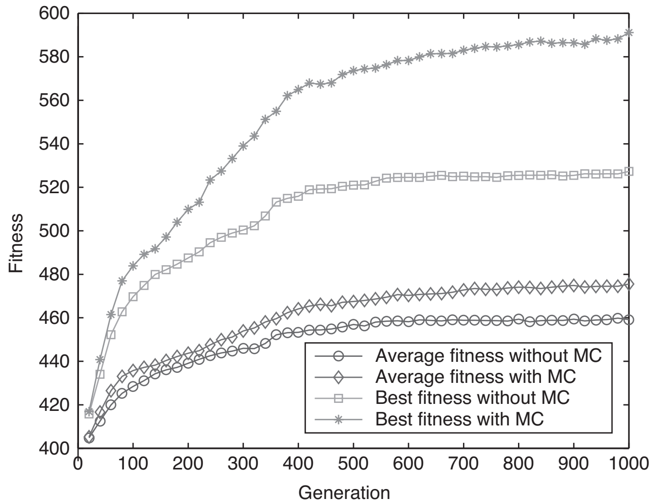

Figure 10.5 Average and maximum fitness for organisms living into Scenario 4, respectively with and without receiving information about their energy and liquids reserves

water token. Manipulating the distance between the organism and the two tokens, as well as its levels of hunger and thirst (for the organisms with a motivational circuit), we can measure the organism's preferences by examining if it approaches the food or the water token. The organisms evolved in Scenario 1 tend not to have any systematic preference for either the food or the water token when the two tokens are located at the same distance from the organism. They simply tend to approach the closest token, regardless of whether it is food or water. As the distance between the organism and the farthest token increases, this tendency to go toward the closest token strengthens. For these organisms, however, it does not make much of a difference whether they have a motivational circuit or not. This is because their adaptive pattern does not rely on the presence of a motivational circuit and on their ability of respond appropriately to hunger and thirst. The organisms that have adapted to Scenario 2, for example to a scenario with food stably more abundant than water, tend to consistently approach the less abundant water token if the two tokens are at the same distance. They approach the food token only if the water token is much more distant than the first one. For these organisms, too, the presence of a motivational circuit has no noticeable influence on their behaviour in the experimental situation. In contrast, for the organisms that have adapted to Scenarios 3 and 4, where the possession of the motivational circuit is critical for evolving an effective behavioural pattern, the behaviour in the experimental situation is clearly influenced by their level of hunger and thirst. If food and water tokens are at the same distance they clearly approach food if they are hungry and water if they are thirsty.

If we define as 'environment' the origin of all the inputs arriving to an organism's brain, we can distinguish between an external environment, which consists in what lies outside the organism's body, and an internal environment, which consists in what lies inside its body. On the basis of the simulations described in this Section we can conclude that organisms having two distinct needs to satisfy (but the results can probably be generalised to numbers higher than two) have to evolve a behaviour which in some evolutionary scenarios depends only on the external environment, and in other scenarios depends on both the external and the internal environments. In Scenario 1 the internal environment is not important because the equal abundance of food and water and their random distribution allow the organisms to behave effectively without having to choose to approach food or water or, as we may also say, without deciding whether to pay attention to food and ignore water or vice versa. In Scenario 2 the internal environment is also irrelevant because of the greater abundance of food with respect to water (or the opposite in different simulations), which allow the organisms to always prefer the less abundant type of tokens, thus developing a tendency to ignore the more abundant one. In Scenarios 3 and 4, on the contrary, the internal environment becomes critical. The organisms can survive much better if they respond to the internal environment (to their hunger and thirst) when deciding to approach food and ignore water or to approach water and ignore food.

10.2.2 Eating and escaping from predators

In the simulations described in the preceding Section, the motivational circuit has its origins within the internal environment, reflecting the level of energy and water currently present in the organism's body. But a motivational circuit can support the strategic level of behaviour even if the event that triggers the circuit lies outside the body. In this Section we describe simulations that illustrate how the strategic level of behaviour can rely on information gathered from the external environment (Petrosino & Parisi, in preparation). The following description will only highlight the elements of novelty contained in the new simulations compared to the preceding one. All the non-specified details should be considered the same as in the simulation described in Section 10.2.1. AQ4

A population of organisms lives in an environment containing 24 randomly distributed food tokens. In order to survive and reproduce the individuals have to approach and eat these food tokens. The environment is bigger compared to the one described in the previous paragraph and its size is now 1,500 $\times$ 1,500 px. The organisms have a store of energy in their body, part of which they consume at each time-step to stay alive. The starting level of energy for all the organisms is 1.0 unit (and this level cannot be exceeded) and the organisms consume 0.0028 energy units at each time-step. Therefore they have to eat regularly in order to replenish their store of energy and avoid dying. The food tokens have a circular shape with a diameter of 68 px. Each of them contains 12 energy units. When the centre of the body of an organism move on a token, the diameter of the latter is reduced by 4 px, while the energy contained in the individual's body is increased by 0.014. The token disappears when its diameters becomes less than 20 px. The organisms also have to face a second problem however. At random intervals a predator (represented by a circle with 70 px diameter) appears and approaches the organism. Each organism lives for five epochs made of 2,000 time-steps each, while the predator can appear during any step between zero and *PredatorAppearance*.[2] If the predator reaches the organism, the latter is killed and no further epochs are evaluated. Therefore, to stay alive the organisms have to both approach and eat the food tokens when the predator is absent and to ignore food and fly away from the predator when it appears. The predator remains into the environment for 150 time-steps before disappearing (and reappearing again during the next epoch). Therefore, in order to remain alive the organism must be able to avoid being reached by the predator until it disappears. Unlike the organisms' behaviour, the predator is hardwired rather than evolved. When it appears, at each time-step the predator approaches the organism in the best possible way, by minimizing the Manhattan distance from the two agents.

The neural network that controls the organisms' behaviour includes two input units providing information about the location of the nearest food token as well as two neurons encoding the location of the predator (when it is present into the environment the two units encoding). In order for the organism to see a food token or the predator, these need to be within a distance of 260 px from the centre of the organism's body. The input units are fully connected to a layer of internal units, which is in turn fully connected to the output units controlling the displacements of the organism in the environment (Figure 10.6(a)). The initial population of organisms has randomly assigned connection weights and biases. The organisms evolve their behaviour in a succession of generations, with the individuals able to live longer having more offspring than the individuals with a shorter life. Living longer depends on both the ability to eat food when the predator is absent and the ability to escape from the predator when the predator is present. The fitness of an individual is measured as the total number of food units collected during its entire lifespan. At the end of each generation, a genetic algorithm selects the 20 fittest individuals for reproduction. Elitism is applied so these 20 individuals are copied to the next generation without any modification. Each parent generates four offspring inheriting its connection weights and biases. Their genomes are randomly mutated by switching the value of each of the binary digits with probability 0.02.

Two different versions of the simulation have been run. In the first version the organisms' neural network is as we have described it: the input units encode the perceptions of food and predator, the output units control the organism's movements, and the internal units provide a link between the input and the

[2] Various simulations have been run, using different values for PredatorAppearance (150, 200, 250, and 300 respectively).

output units. In the second version a new internal unit is added to the organisms' neural network. This unit receives connections only from the input units encoding the presence and location of the predator and it sends its connections to the output units (see Figures 10.6(b)), bypassing the hidden layer. This additional unit is like all other internal units, except for just one difference. While an ordinary internal unit has an intrinsic and constant bias, which always activates the unit together with the values arriving from the input units, the bias of the additional (motivational) unit is only present when the predator is present and perceived by the organism. This implies that when the predator is absent or not perceived by the organism the motivational unit has an activation value equal to zero, thus not having any role in determining the organism's behaviour. The neural pathway which goes from the input units encoding the predator to the motivational unit and then to the output layer is what we define as the 'motivational circuit'. In contrast, the 'cognitive circuit' is the neural pathway linking all the input units to the ordinary internal units and then to the output units.

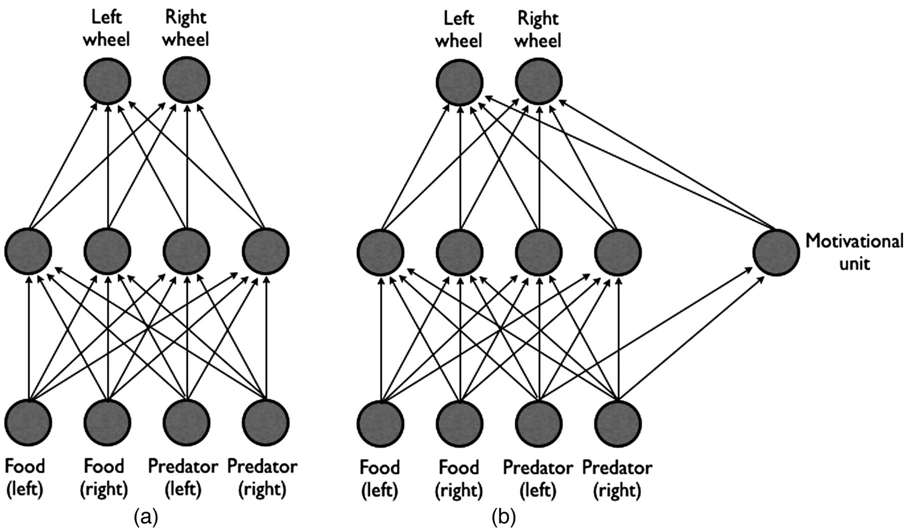

Figure 10.6 The neural network architectures used for the simulations described in Section 10.2.2 (left: a, right: b)

The results of these simulations (Figures 10.7 and 10.8) show that the addition of the motivational circuit to the organisms' neural network allows the individuals to reach higher levels of fitness compared to the organisms lacking this circuit. How can we explain this difference in fitness? To understand these result it is important to look at the organisms' behaviour when the predator is absent and when it is present. When the predator is absent, both the organisms with and those without the motivational circuit appear to be only interested in food. They approach the nearest food token, eat it, and then move to the next one. However, if we test the organisms in a controlled environment

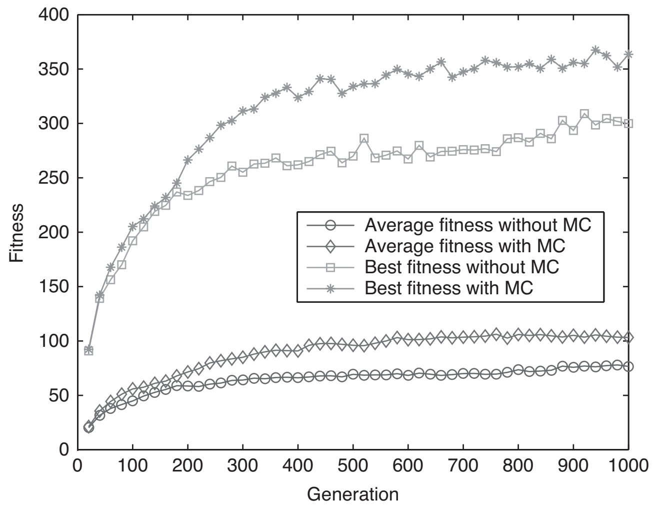

Figure 10.7 Average and maximum fitness for the organisms provided or not with the motivational circuit, using PredatorAppearance = 250

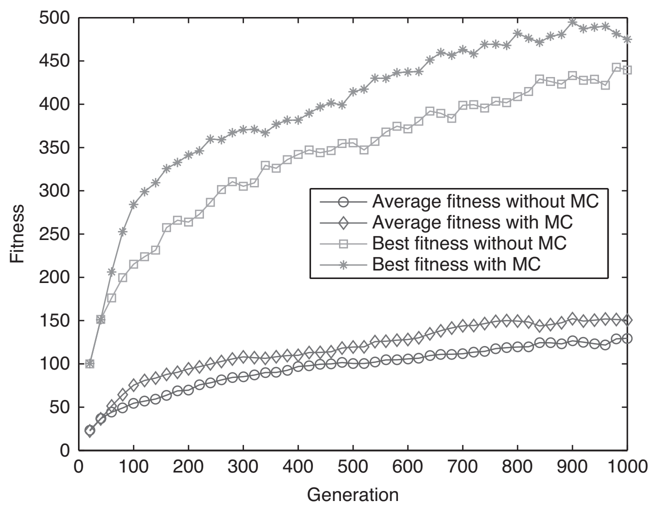

Figure 10.8 Average and maximum fitness for the organisms provided or not with the motivational circuit, using PredatorAppearance = 300

containing only food and no predator, we see that the organisms with the motivational circuit are better in approaching the food tokens than the organisms lacking the motivational circuit. This therefore appears to be one of the reasons why the organisms endowed with the motivational pathway obtain a higher fitness than the organisms without this circuit.

But the more interesting difference in behaviour between the two sorts of organisms can be seen if we look at what happens when the predator appears. In this situation, what is expected from the organisms is that they ignore the food tokens and exclusively focus on trying to escape from the predator. Both the organisms with the motivational circuit and those without it are able to do so but, again, the organisms with the motivational circuit are better than the organisms lacking it. This therefore is another reason why they have a higher fitness. The greater ability of the organisms with the motivational pathway to escape from the predator is observable both in a controlled (experimental) condition and in an ecological condition. In the controlled condition the organisms are tested inside an environment containing only the predator and no food. In the ecological condition the predator appears at regular intervals into an environment containing a certain number of food tokens. In the controlled condition the organisms with the motivational pathway appear to be better able to escape from the predator. But the more interesting results concern how the two types of organisms react when the predator appears in their natural environment containing food, forcing them to suddenly starting to ignore food in order to dedicate themselves solely to flying away from the predator. If we observe the behaviour of the organisms when they first perceive the predator we see that an organism endowed with the motivational circuit tends to react 'impulsively' by running at the maximum speed along its current direction of movement, whatever that direction is. Only when the predator gets very close to the organism, the latter reacts in a more reasoned way by moving in a direction opposite to the one from which the predator is approaching it. This type of complex behaviour is typically observed in the organisms endowed with the motivational circuit while it is rarely present in the organisms lacking it. The organisms without a motivational circuit tend instead to adjust their speed according to the distance between themselves and the predator. Instead than reacting impulsively, running at the maximum speed possible when the predator appears, they progressively increase their speed the more the predator gets close to them.

If we examine what happens in the neural networks of the two types of organisms we may find an explanation for why they react differently at the first appearance of the predator. We first measure the activation level of the two output units determining the organism's motor behaviour when the predator is at different distances from the organism, from very distant to very close. Then we compare the activation level of the same two units both when food is normally present in the environment and when food is experimentally removed from it. Notice that, from a neural point of view, the degree to which the organisms ignore (i.e., do not pay attention to) the food sensory input when the predator is present is indicated by how similar the activation level of the two motor output units is when food is present but is not attended to by the organism (ecological condition) and when food is actually absent (experimental condition). The organisms whose neural networks include a motivational circuit are better able to ignore food and react to a suddenly appearing predator than the organisms lacking the motivational pathway. This is indicated by the fact that the activation level of their two output units, and therefore their motor behaviour, tends to be very similar both when the predator has just appeared but is very distant and there is no other sensory input because there is no food present (experimental condition) and when the predator has just appeared and there is input from food (ecological condition) also. In fact, the similarity between the activation level of the two output units in the two conditions can be considered as the neural basis for ignoring food when the predator appears in the ecological condition. However, as the predator approaches the organism and it is perceived as nearer by the organism, the difference between the activation level of the two motor output units in presence and in absence of food first increases and then it decreases until it reaches almost zero. This indicates that, when the predator is very close to the organism, food is completely ignored by the organism although the sensory input from food continues to arrive to the organism's sensors. (A further analysis of this phenomenon, which appears not to depend on the 'cognitive capability' of the organism, but on the presence of the motivational circuit, can be found in Ruini & Parisi, 2008).

Returning to the organisms' behaviour we can describe the behaviour of the organisms with the motivational circuit in response to the predator as made up of two successive stages. When the predator is first perceived and it is still distant from the organism, the organism responds with an 'impulsive' or 'emotional' and not well reasoned behaviour: the organism runs very quickly in any possible direction, which is not necessarily the one maximizing its distance from the predator. However, this emotional response allows the organism to better ignore food and to pay attention only to the predator. And in fact, among the organisms endowed with a motivational circuit, the individuals that display this type of emotional response to the first appearance of the predator tend to have more fitness than the organisms that do not exhibit this emotional reaction (see Figure 10.9).

One can better understand the respective role played by the motivational and the cognitive pathways if we examine the activation level of the internal unit of the motivational pathway when the predator is at different distances from the organism and if we alternatively lesion the motivational and the cognitive pathways of the organism's neural network. As we have already said, when the predator is absent or it is not perceived by the organism because of the distance, the internal unit of the motivational pathway has zero level of activation and therefore the motivational pathway itself has no influence on the organism's behaviour. However, as soon as the predator is perceived by the organism, this internal unit is activated and cooperates with the cognitive

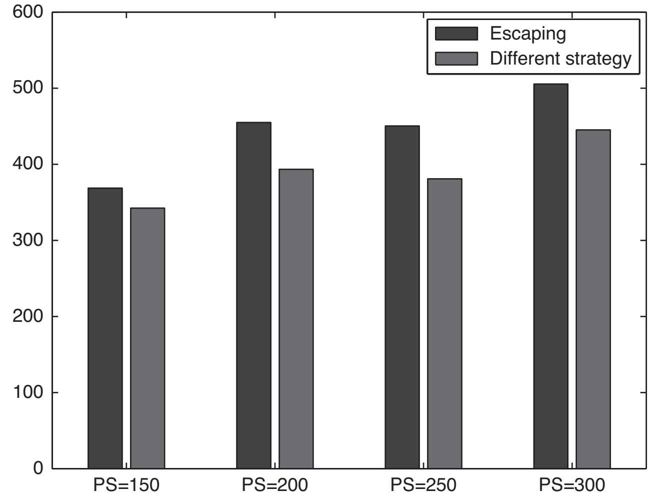

Figure 10.9 Fitness values for organisms endowing the motivational circuit but showing different behaviours when the predator appears (left: moving at a maximum speed along a random direction; right: following a different strategy). On the X axis different values of Predator Appearance are represented: 150, 200, 250, and 300

pathway in determining the proper behaviour to adopt. If we measure the activity level of the of the internal unit of the motivational pathway when the predator is perceived by the organism, but is at various distances, we see that this value is very high when the predator is distant from the organism but it quickly lowers and almost reaches zero level when predator gets closer to the organism (see Figure 10.10). This appears to show that the motivational pathway plays a role in determining the organism's behaviour especially when the predator first appears but it rapidly becomes less important when the predator approaches the organism. When the predator first appears the motivational circuit is activated and it has two types of influences on the organism's behaviour: it cancels the role of the sensory input from food in determining the organism's behaviour so that the behaviour turns out to be determined only by the sensory input from the predator and it causes in the organism an emotional reaction which, as we have already said, consists in moving very fast but not necessarily away from the predator. On the other hand, when the predator gets closer to the organism, the internal unit of the motivational circuit quickly reduces its activation level, which implies that it is the cognitive pathway which takes control of the organism's behaviour, inducing a more reasoned behaviour of moving away from the predator. This analysis is confirmed by the fact that if we lesion the motivational pathway, the organism is less able to avoid the predator in the experimental condition in which only the predator is

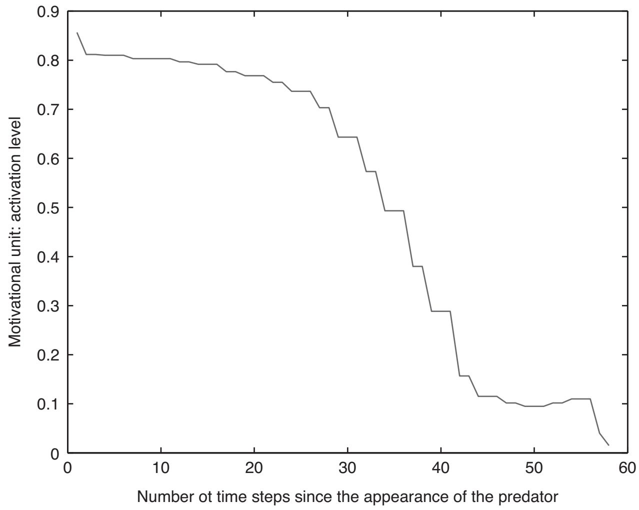

Figure 10.10 This graph has been obtained by deploying six individuals (exhibiting the behaviour of moving at the maximum speed possible when the predator appears), one by one, at the centre of an empty environment. Cutting their connections to the output layer they have been made unable to move. Then a predator has been put into the environment, letting it hunt the organism for 60 steps. For each organism, the test is repeated five times with the predator appearing in different positions and the measures averaged. What this plot shows is the average activation value of the motivational unit with the passing of the time-steps

present and there is no food. In contrast, if we lesion the cognitive pathway, what is observed is that, when the predator approaches the organism, the latter tends to be unable to avoid being killed.

Our conclusion is that, for the organisms endowed with a motivational circuit, evolution has created a sort of division of labour between the motivational and the cognitive circuit. This division of labour may explain why the organisms with a motivational circuit are better than organisms lacking this circuit not only at avoiding being killed by the predator but also at eating food when the predator is absent. In fact, since the motivational circuit responds to the presence of the predator and to the distance of the predator from the organism while the cognitive circuit responds only (or mainly) to the direction from which the predator is approaching the organism, by having a less heavy information load the cognitive circuit can better process information from food (when the predator is absent) and can respond more effectively to food. In the organisms lacking the motivational pathway this division of labour is impossible and this may explain why they are both less able to avoid being killed by the predator and to eat food efficiently.

10.2.3 Entering or not entering the predator's zone

In this Section we describe a third set of simulations similar to the ones described in Section 10.2.2. The main difference is the fact that the predator can now only appear in a particular zone of the environment and cannot exit from that zone. The environment is a bit smaller than the previous one, given its size of 1,200 × 1,200 px. The zone where the predator can live is a circular sub-area of 300 px of diameter. 18 food tokens, each having a diameter of 35 px, are randomly distributed in the environment. Food is present both outside and inside the predator's zone (11 food tokens are outside the predator's zone and seven inside) but the food contained in the predator's zone is more energetic than the food situated outside. Therefore, the organism is caught in a conflict between remaining outside the predator's zone but not eating the more energetic food present there and penetrating the predator's zone to eat the more energetic food that can be found there but risking being killed by the predator. The organisms do not have any motivational pathway in their neural network. Two different simulations have been run: one in which the neural network controlling the organisms' behaviour includes an additional sensory input unit encoding the information that the organism has penetrated the predator's zone (say, a sensory unit encoding an odour associated with the predator) and another version in which the neural network lacks this additional sensory unit (see Figure 10.11). The sensory unit is connected to the neural network's internal layer in the same way as all the other inputs. The other input units respectively encode the location of the nearest food token and the location of the predator. The latter units only get activated when both the organism has penetrated the predator's zone and the predator is present there.

Furthermore, in both versions of the simulation we have varied two parameters: the dangerousness of the predator (as measured by its speed of movement) and the energetic value of the food present inside the predator's zone, which is always more energetic than the food outside the predator's zone but can, in different simulations, be twice or five times richer. The results obtained (summarised in Table 10.1) show that the organisms' behaviour is sensitive to these experimental manipulations.

The organisms are more likely to enter the predator's zone when the predator is less dangerous than when it is more dangerous, as well as when the food present availabel inside the predator's zone is more energetic than the food outside. These results apply to both the organisms endowed with the additional sensory unit telling them that they have entered the predator's zone and the organisms lacking this additional sensory unit. Another result is that the organisms with the odour sensory unit reach higher level of fitness than the organisms without. This is particularly true when the predator is very

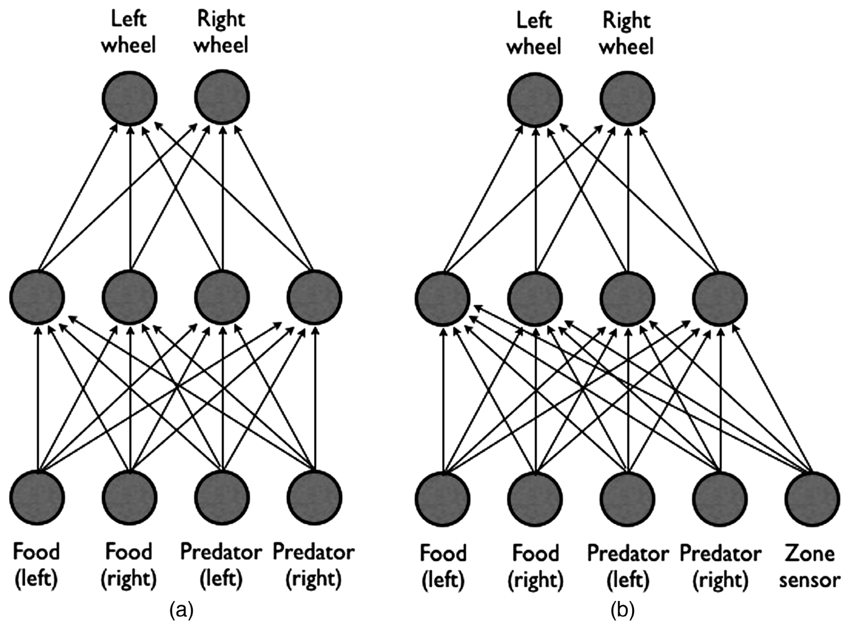

Figure 11 The neural network architectures used for the simulations described in Section 10.2.3 (left: a, right: b)

Table 10.1 Fitness values (calculated on the entire populations as average of the last 20 generations) in the different experimental conditions

	S5/E2		S5/E5		S9/E2		S9/E5	
	BF	**AF**	**BF**	**AF**	**BF**	**AF**	**BF**	**AF**
Without zone sensor	483	200	557	228	270	110	316	123
With zone sensor	530	217	596	238	329	133	318	127

Note: S, predator's speed; E, energetic value of the food; BF, best fitness; AF, average fitness.

dangerous and when the food in the predator's zone is highly more energetic than the food outside the zone. When the predator is more dangerous or the food in the predator's zone is only slightly more energetic than the food outside, it is not very useful or sensible for the organisms to enter the 'hazard zone'. Therefore the organisms endowed with the odour sensory unit tend to exit the predator's zone as soon as this unit tells them they have entered it. This possibility is not availabel to the organisms without the odour sensory unit, and this explains why these organisms have less fitness than the organisms possessing the additional unit. On the other hand, when the predator is not very dangerous or the food in the predator's zone is much more energetic than the one outside, it makes more sense to enter the predator's zone, even at risk of being killed. In all cases the organisms endowed with the odour sensory unit can rely on an entirely reliable clear-cut (yes or no) information that they are inside the predator's zone, which they can adaptively exploit. In contrast, the organisms lacking the odour sensory units do not know if they have entered the predator's zone and they can only rely on the appearance of the predator and respond to this volatile information. This is another possible explanation for why the organisms with a motivational circuit score higher fitness values than the organisms lacking the circuit.

10.3 Inter-individual differences in behaviour and the appearance of pathological behaviour

Inter-individual differences in behaviour are an important aspect of living organisms. Of course, all kinds of inter-individual differences play a crucial role in biology since evolution is based on inter-individual variability, i.e., on the reproduction of some individuals against other individuals and the constant addition of new variability through genetic mutations. But the study of inter-individual differences may be specifically useful to better understand the complex mechanisms underlying behaviour. Inter-individual differences may in fact result from the different functioning of the various components of the neural and, more generally, bodily systems underling behaviour, therefore allowing us to identify what these components are and how they exactly work. Artificial organisms endowed with both a motivational and a cognitive system are located in a larger space of possible inter-individual variability than organisms only relying on a cognitive system. Our simulation experiments make possible to start the exploration of this larger space of inter-individual variability.

The simulations described in this chapter use a genetic algorithm to evolve the organisms in their environments. The use of an evolutionary algorithm implies that in each generation some individuals do reproduce while other individuals do not (or some individuals have more offspring than others). Since evolutionary algorithms tend to be used in order to obtain some desired behaviour, the researcher is typically interested in the individuals that reproduce and therefore approximate the desired behaviour rather than in the individuals that do not reproduce. But if one is interested in inter-individual differences in behaviour, the individuals that do not reproduce may be more interesting than the ones that do reproduce. In our simulations the individuals that do reproduce tend to be organisms functioning effectively at both the motivational and cognitive levels. On the other hand, the individuals that do not reproduce can be individuals that function well at the motivational level but not at the cognitive level, or vice versa. In fact, if in our simulations we look at the individuals that do not reproduce, we see that the reason behind their inability to reproduce may reside in their motivational or in their cognitive system, but not necessarily in both. If in our simulations with both food and predator we test in controlled conditions (with either food or the predator present but not both) various individuals that do not reproduce, we may find that some of them are good at approaching food in absence of the predator and at flying away from the predator in the absence of food, but they have trouble in avoiding being killed by the predator in their natural environment (in which the predator appears when food also is present). These individuals tend to be distracted by food and, for this reason, they may easily be killed by the predator. These are individuals good at the cognitive level but not at the motivational level. On the other hand, other individuals that do not reproduce may present the opposite pattern. They may be good at ignoring food when the predator appears, but not very effective at approaching food in absence of the predator. These individuals are good at the motivational level but not very good at the cognitive level. The existence of these two types of individual confirms the usefulness of our distinction between the strategic and the tactical level of behaviour.

Similar results have been obtained in the simulations in which the predator can only appear in a particular zone of the environment. Among the individuals that do not reproduce some are very good at approaching food outside the predator's zone. But these same individuals behave inefficiently when they happen to enter the predator's zone. When they enter the predator's zone these individuals tend to remain at the border of the zone because they are attracted by the more energetic food present inside but at the same time they are 'afraid' of the predator. Therefore they are unable to eat both the food inside the predator's zone and the food outside. These individuals can be classified as good at the cognitive level, but not at the motivational level. On the other hand, there are other non-reproducing individuals that are good at the motivational but not at the cognitive level. When they happen to enter the predator's zone they either try to eat some of the more energetic food present in that region or they quickly exit the predator's zone becoming interested in the food present outside. However, these individuals are not very good at approaching food, either inside or outside the predator's zone, and this low level of functioning at the cognitive level is sufficient to prevent them from reproducing.

The behaviour of the first type of organisms (motivational deficit) can be considered as pathological and, more specifically, exemplifying (at a very basic level, of course) the clinical condition of depression. The individual is caught between two strong motivations and it is unable to decide which one to pursue. The consequence is that the individual does nothing, which of course implies that the individual will probably not reproduce. It is interesting to note that this type of pathological behaviour can be more easily observed when the two motivations are both strong. As we have observed, different motivations compete for the control of behaviour based on their strength. The strength of a motivation can be an intrinsic and therefore constant property of the motivation or it may vary with time and circumstances. For example, in the simulations with equal abundance of food and water in the environment we observe the pathological condition of doing nothing when the organism is exposed to both a food token and a water token put at the same distance if the organism is both very hungry and very thirsty.

10.4 Conclusions

In this Chapter we have described some simulations that illustrate our distinction between the strategic (motivational) level and the tactic (cognitive) level of the behaviour of organisms. This has allowed us to investigate some simple phenomena involving the strategic level and its interaction with the cognitive level. To survive and reproduce organisms must be able to satisfy many different motivations. Since they usually can pursue only one motivation at a time they need a mechanism that allows them to decide which motivation attempt to satisfy at any given time. This is the strategic level of behaviour. Once they have decided which motivation to pursue, they must be able to execute the activity which allows them to reach the goals of the winning motivation. This is the tactic level of behaviour. At the strategic level different motivations compete for the control of the organism's behaviour and the motivation that wins the competition is the one which currently has the highest strength. Using simple computer simulations of artificial organisms evolving within artificial environments, we have shown that the motivations (and its strenght) of an organism depend both on the particular environment in which the organism lives and on the current state of its own body. In some scenario, but not in all of them, it is useful that the body sends information about its current state to the organism's brain so that the organism can take into account this information together with information coming from the external environment in order to decide which motivation to pursue. Our simulations have shown that, in these scenarios, organisms endowed with an information channel going from the body to the brain and transmitting information about the level of energy and liquids currently contained into the body reach higher levels of fitness than organisms which do not have this information channel availabel. Like real organisms, artificial organisms can spontaneously evolve such information channels. For example, organisms that when their body is damaged should cease any type of activity in order to recover more quickly and safely will autonomously evolve a pain sensory unit in the neural network controlling their behaviour which tells their brain that some damage has occurred on the physical level (Acerbi & Parisi, 2007).

While the cognitive level of behaviour mainly uses information originated in the external environment, the motivational level tends to use inputs that originate within the organism's body. However, as we have seen in our simulations with predators, sensory input from the external environment can activate motivations and therefore it can indirectly control the behaviour of an organism by passing through the organism's motivational system. Another role of the external environment that we have not explored is that sensory input coming from outside the body can augment the current value of some motivations, leading in this way a particular motivation to win the fight against other competitors and take control of the organism's behaviour. In psychology this type of sensory inputs from the environment are called incentives. For example, passing in front of a restaurant can increase the current value of my motivation to eat, and as a result I can decide to dedicate myself to satisfy it by interrupting any other activity aimed at a different motivation. This shows that the play of different motivations in my brain can not only motivate me to engage in one activity rather than in a different one but it can also cause the interruption of the current activity.

10.5 Discussion

In this chapter we have distinguished two basic systems that determine the behaviour of organisms, the motivational system and the cognitive system. Although the two systems are distinct and are implemented by mostly different neural circuits, the motivational and the cognitive levels of behaviour influence each other in a number of ways. The motivational system influences the cognitive system in that it directs the attention of the organism to only one of the many inputs arriving to the organism's sensors from the environment. This is an important direction of research that can be pursued using our simulation framework. For example, some experiments with humans have shown that stressful conditions increase the selectivity of attention (Chajut & Algon, 2003), and one could replicate these results with artificial organisms in order to formulate explicit models of this effect. On the other hand, the activities that the organism executes to pursue its current motivation may generate inputs influencing the motivational system and thus causing the organism to shift to another motivation. This also is a very interesting direction of future research.

One aspect that has not been investigated throughout this chapter is how the strategic level of an organism's behaviour could be affected by the emotions he experiences. Emotions are clearly related to motivations, but the strategic level of behaviour concerns motivations, not emotions. Emotions can be defined as the arrival of inputs to an organism's brain that are generated inside the organism's body (or perhaps even within the brain itself). These inputs, of course, play a crucial role in deciding which motivation will control the organism's behaviour. However, we think that motivation is the most basic phenomenon, so the one that is interesting to investigate. Motivations control in fact the behaviour of an organism even when the organism does not feel any particular emotion. Emotion is part of the motivational system but it is a particular phenomenon which occurs in particular circumstances, that is, when one motivation wants to 'rise its voice' in order to be heard and to win the competition with other motivations. (For the influence of emotion on the behaviour of artificial organisms, see Canamero, 2005; Perez, Moffat & Ziemke, 2006; Ziemke, 2008).

We have also seen that constructing artificial organisms endowed with a motivational level of behaviour makes it possible to explore a larger space of inter-individual differences that are observed in real organisms. If an organism has just one single goal or motivation, an individual can only differ from another individual in that one is better than the other at reaching that particular goal. This is a quantitative difference in ability. But real organisms differ among them not only in a quantitative but also in a qualitative way, because they have many different motivations. Differences in personality or character are qualitative, not quantitative differences. If one constructs artificial organisms with many different motivations and a motivational level of behaviour it becomes possible to study organisms which differ from one another not only in level of ability but also in character or personality, where differences in character and personality are mainly differences in motivations and in their strength. One can even construct individual profiles of artificial organisms based on a number of different characteristics referring to both their abilities and their motivations.

In our artificial organisms the motivational level of behaviour is implemented as a special pathway in the neural network that controls an organism's behaviour. This pathway is extremely simple and this simplicity contrasts sharply with the richness and complexity of the neural systems that underlie the motivational level of behaviour in real organisms. Another important direction of research is to use what we know about the brain and the brain's interactions with the rest of the body to endow the neural network of our artificial organisms with more realistic neural pathways that capture how motivations control an organism's behaviour (French & Canamero, 2005). The motivational system may reside in different parts of the brain with respect to the cognitive system (e.g., sub-cortical vs. cortical) and may have different structural and functional properties (more rapid and more prolonged action). More generally, it may turn out that while the cognitive system of an organism can be simulated by remaining at the cellular level (a neural network's unit corresponding to a neural cell or neuron) and by considering only the organism's brain, the organism's motivational system can only be simulated if one goes one step down and reaches the molecular level, and if one considers not only the organism's brain but also the interactions of the brain with the rest of the organism's body (Parisi, 2004).

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