# Input from the External Environment and Input from within the Body

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**Abstract.** Behaviour responds to both input from the external environment and input from within the organism's body. Input from the external environment has mainly the function to regulate the execution of the organism's activities while input from the body is used to decide which activity to execute. We evolve artificial organisms which to survive and reproduce have to both eat food and drink water in equivalent quantities and therefore at any given time they have to decide whether to look for food or water. We show that in some environments the appropriate behaviour can evolve with no need for the organism's brain to know the current level of energy and water in the body while in other environments the brain needs this information from the body in the form of hunger and thirst. We discuss how the body and the body's interactions with the brain are part of the overall adaptive pattern of an organism and must co-evolve with brain and behaviour.

## 1 Introduction

To survive and reproduce minimally complex organisms must be able to both execute effectively a number of diverse activities and to decide which activity to execute at any given time. These are two distinct abilities. Consider an organism that to survive has to both eat and drink. The organism's body includes a store of energy and a store of water and at each time step a fixed quantity of energy and water is consumed to keep the organism alive - if any of the two stores reaches zero level the organism dies. To remain alive the organism must be able to find food (energy) and water in the environment. The organism must also look for food or water when the level of either is low. Clearly, the individuals that survive must possess both abilities.

We call these two components of the adaptive pattern of organisms the *cognitive* (or tactical) component and the *motivational* (or strategic) component. Most research aimed at constructing artificial organisms that resemble real organisms is dedicated to studying the cognitive component of behaviour, that is, to endowing artificial organisms with the ability to execute a single activity aimed at some specific goal, although this single activity may be a complex one with a hierarchical structure of sub-abilities. The cognitive component of behaviour can be interpreted as the ability to respond to stimuli from the environment with the appropriate movements; but the behaviour of organisms is also caused by the internal states of the organism's body or brain. In fact, the sight of food should induce a behaviour of approaching and eating the food only if the organism is hungry. Otherwise, the food should be ignored. This simple example indicates the importance of the organism's internal states in determining the organism's behaviour.

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Recently research sought to capture the motivational and emotional aspects of behaviour with artificial organisms [1,2,3,4,5,6,7]. Studying behaviour by constructing embodied artificial organisms (robots) should facilitate an examination of the motivational and emotional aspects of behaviour since motivation and emotion appear intrinsically linked to the body beyond the brain and to the interactions between the body and the brain [4,8,9,10,11]. Robots have an "external body" (size, shape, sensory and motor organs) but not an "internal body" with its organs and systems. The study of motivation and emotion requires the development of both an external and an internal robotics [12].

We might say that organisms live in, and have to adapt to, two environments: the environment which is outside their body and the "internal environment" constituted by their own body. However, the two environments have a critical difference. While the external environment is what it is mainly independent from the organism (except for human technology), the internal environment clearly is part of the overall adaptive pattern of the organism and it evolves with the organism's behavior [13].

In this paper we will describe a number of simple simulations showing that the existence of a communication channel between the energy and water stores inside the organism's body and the organism's brain can be adaptive in some stereotypical environments but not in all environments. In some environments organisms may need to feel hungry and thirsty to survive but hunger and thirst are adaptations and they may not be particularly useful in other environments.

## 2 The Simulation Scenario

Our organisms are a simulated version of the Khepera robot [14] and we use the Evorobot* simulation tool (developed by Stefano Nolfi; cf. http://laral.istc.cnr.it/evorobotstar/). They have a cylindrical body, sensors with which they can detect food and water tokens, and two wheels that can be moved independently at different velocities. The organisms have energy and water stores with a level that can go from 1 (full store) to 0 (empty store). When they are born both stores are completely filled up but a fixed amount of energy and water is consumed at each time step.

The simulated organism lives in a walled environment of 1000x1000 pixels and its body occupies a circle of 75 pixels of diameter. When the organism's body reaches the wall, its orientation is changed randomly. The environment contains food and water tokens each of witch occupies a circle of 30 pixels. When the center of the organism's body enters in a token circle, the token disappears (and is replaced by a new token in another randomly chosen location) and the organism's relative body level is increased.

The entire lifetime of an organism is made up of 10 epochs each lasting 1500 time steps. However, most of the time, the actual lifetime is shorter than that because an epoch is terminated if either the energy or water store of the organism goes to zero. At the beginning of each epoch the organism is placed at the center of the environment with a randomly chosen orientation.

The behaviour of the organisms is controlled by a neural network with 4 input (sensory) units, 2 output (motor) units and 4 hidden units. Each of the 4 input units sends its connections to all hidden units, and each hidden unit sends its connections to each output unit. In the simulations in which the organism's nervous system is informed of the levels of energy and water in its body, the organism's neural network has 2 additional sensory units that send connections to all 4 hidden units. We will call these units "motivational units" (hunger and thirst units). 2 of the 4 sensory units detect the food tokens and the other 2 detect the water tokens; in each pair one unit gets activated by tokens seen on the right ($RU$ for right unit), and the other one by tokens seen on the left ($LU$ for left unit), according to the following expressions:

$$RU(d,\phi) = K\left[A{+}B\,Log\left(\frac{1}{d^2}\right)e^{-\frac{(\phi+60^o)^2}{2\sigma^2}}\right],\ LU(d,\phi) = K\left[A{+}B\,Log\left(\frac{1}{d^2}\right)e^{-\frac{(\phi-60^o)^2}{2\sigma^2}}\right].$$

When a food/water token appears in the visual field of the organism, the activation levels of the corresponding sensory units vary with the logarithm of the inverse square distance, $d$, of the token from the organism; the activation depends also on the angular position of the token in the organism's visual field, $\phi$ - the left and right half-fields are set to be oriented, respectively, $60^o$ to the left and $60^o$ to the right with respect to the frontal direction; $\sigma$ determines the eye angular view spread and its value is $45^o$. $K$, $A$ and $B$ are constant values set up to ensure activation spans the interval $[0,1]$ ($A = 1.596$, $B = 0.110$, $K = 0.75/Log(N)$ in environments (1), (2), (3), and $K = 0.5/Log(N)$ in Env. (4), where $N$ is the total number of tokens in the environment (see below for environment descriptions)). Each of the activation values of the two output unit determines (linearly) the separate speed of the corresponding wheel and therefore the trajectory followed by the organism. The 2 *motivational* units, when present, are internal sensory units informing the neural controller of the level of energy (*hunger* unit) and water (*thirst* unit), in the organism's body. The activation value of each of these units maps linearly the level of the corresponding resource (1 for full store, 0 for empty store).

Each simulation starts with a population of 100 randomly generated organisms. At the end of the 10 epochs comprising their life, each organism is assigned a fitness which is simply the total duration (number of time steps) of its life. The individuals which eat food and drink water in sufficient and comparable quantities live longer in each epoch and therefore are more likely to have offspring - the 20 robots with highest fitness are selected for reproduction. Each robot generates 5 offspring inheriting the same genome of their (single) parent, with the addition of random mutations (each one of the bits of the genome has a $4\%$ probability of being mutated). Each simulation lasts for 1000 generations and is repeated 10 times starting from randomly generated organisms.

We have run four different simulations in four different stereotypical environments (for other details see Tab. 1). Env. (1) contains 5 food tokens and 5 water tokens. Env. (2) contains 5 food tokens and only 1 water token. Env. (3) is "seasonal": it contains 5 food tokens and only 1 water token in 5 of the 10 epochs of an individual's lifetime, and 5 water tokens and only 1 food token in the other 5 epochs. In all these 3 environments the tokens are randomly distributed. Env. (4) contains 3 food tokens and 3 water tokens but the tokens are distributed in patches, with all the food tokens located inside a square of 60 pixels of side and the same for the water tokens, while the centers of the two patches are at a distance of 600 pixels.

We have evolved two different populations in each of the four environments. The organisms of one population (Sim for "simple") do not have the motivational circuit while the organisms of the other population (Mot) do have this circuit.

# 3 Results

## 3.1 Fitness

Figure 1 and Table 2 show the fitness distributions of the 1000 individuals of the final generation of the 10 replications of the evolution in all four environments and their mean and standard deviations, separately for the Sim and the Mot organisms (the Mem organisms will be discussed later in the section "Motivation as memory").

We see that in environments (1) and (2) the two populations reach comparable levels of fitness, whereas in environments (3) and (4) the Mot populations perform better: the presence of the information coming from the body stores correlates with higher adaptive skills in the environments (3) and (4), but not in environments (1) and (2).

*Balanced* environment (same quantity of food and water tokens): the organisms can adapt to this environment by developing a simple behaviour which consists in approaching whatever token is closest, regardless of it is a food or a water token. This behaviour ensures both foraging efficiency and diet balancing and does not require the knowledge of the current bodily levels of energy and water.

*Unbalanced* environment (food is five times scarcer than water): in this environment too it is possible for the organisms to develop an effective and balanced behaviour with no need for their nervous system to be informed about the current bodily levels of energy and water: they can simply evolve a tuned *preference* for food.

*Seasonal* environment (food tokens are five times scarcer than water tokens in half of the seasons and the opposite is true in the other half of the seasons): in a seasonal environment the behavioural strategies of the organisms living in a "static" environment like (1) and (2) are suboptimal, because they are not capable of coupling with the ever

**Table 1.** Environment features (*seasonal* environment: outside the brackets one season, inside brackets the opposite season)

| | Env. (1): *balanced* | Env. (2): *unbalanced* | Env. (3): *seasonal* | Env. (4): *patched* |
|---|---|---|---|---|
| Living cost per cycle | 0.040 | 0.040 | 0.025 | 0.025 |
| Minimum lifetime | 250 | 250 | 400 | 400 |
| Energy per token | 0.2 | 0.4 | 0.4 | 0.03 |
| # of food tokens | 5 | 1 | 1(5) | 3 |
| # of water tokens | 5 | 5 | 5(1) | 3 |

**Table 2.** Fitness data in all the four environments at last generation of evolution. "Ave" is the population's mean fitness, "Best" is the best individual's fitness.

| | | *balanced* | *unbalanced* | *seasonal* | *patched* |
|---|---|---|---|---|---|
| Ave | Sim | 302 ±2 | 330 ±5 | 574 ±60 | 480 ±3 |
| | Mot | 299 ±2 | 329 ±5 | 685 ±16 | 485 ±9 |
| | Mem | 311 ±2 | 366 ±5 | 672 ±26 | 489 ±9 |
| Best | Sim | 353 ±2 | 435 ±8 | 801 ±118 | 561 ±3 |
| | Mot | 350 ±2 | 443 ±10 | 1064±32 | 614 ±32 |
| | Mem | 370 ±3 | 504 ±9 | 987 ±71 | 581 ±8 |

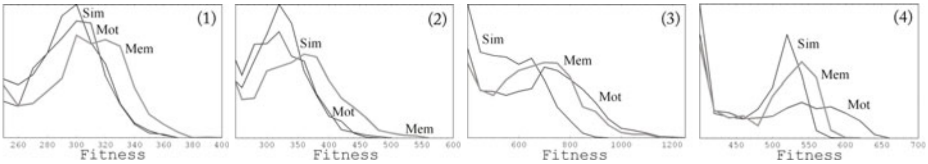

**Fig. 1.** Fitness distributions of the populations of the last generation of evolution in all the four environments (from left to right): (1) *balanced*, (2) *unbalanced*, (3) *seasonal*, (4) *patched*. Comparison between Sim, Mot and Mem populations.

changing environmental conditions (remember that our organisms haven't got any type of "season sensor"). In Env. (3) the communication channel between the body stores and the brain results a strong adaptive tool (see Fig. 1, and Tab. 2, third column), consenting our organisms to *counterbalance* the environmental biases of seasons by going after food when energy in their body is low and going after water when water is low.

*Patched* environment (food and water are equally abundant but the tokens are distributed in two separate patches, one with food tokens and the other one with water tokens): in this environment too the organisms cannot simply go after the token which is closest to them like the organisms living in Env. (1) because if an organism happens to be in a food patch this behavioural strategy would imply eating a lot of food but possibly running out of water and dying, and vice versa if the organism finds itself in a water patch. For the organisms living in Env. (4) it is advantageous to feel hunger and thirst in order to be able to *abandon* a food patch if they are thirsty and a water patch if they are hungry (see next section for more details).

## 3.2 Experimental Tests

To test this interpretation of the fitness results we have tested the individuals of the last generation in each of the four simulations with and without motivational units in controlled, "experimental", conditions, identical for all individuals. We examined the behaviour of each individual in a situation in which the individual is exposed to a single food and water token at the same time, with the two tokens located one at $45^o$ to the left and the other at $45^o$ to the right with respect to the organism facing orientation (in all conditions we exchanged the position of the food and water tokens). In different conditions the food and water tokens are located at 5 different distances from the organisms, where the ratio of the distances from the organism of the two tokens is varied between 1 (equal distances) to 5 (one token five times closer to the organism than the other token). Furthermore, for the organisms which receive information from the body (hunger and thirst), in each condition energy and water can have the following pairs of levels: 0.25/1, 0.33/1, 0.5/1, 0.5/0.5, 1/0.5, 1/0.33, 1/0.25, i.e., the organisms can have the same level of hunger and thirst (0.5/0.5) or they can be much more hungry than thirsty, or vice versa.

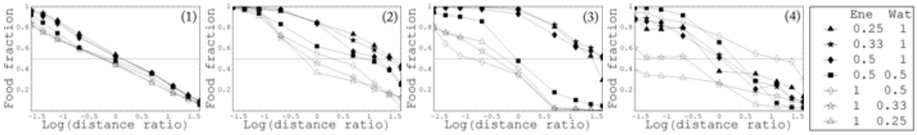

**Fig. 2.** Average *food choice fraction* as a function of the logarithm of the ratio between the distance of the food token and the distance of the water token from the organism in all the four environments (from left to right): (1) *balanced*, (2) *unbalanced*, (3) *seasonal*, (4) *patched*. The test is performed on the Mot individuals of the last generation of evolution for several (see legend) values of energy and water in the body.

The quantitative results of our analysis of the behaviour of the Mot organisms living in different environments are shown in Fig. 2, and can be summarized as follows:

*Balanced* environment: the organisms tend to go to the nearest token, regardless of it is food or water (negative slope of the curves) - this is not much affected by the levels of the two body stores (the curves are all close to each other).

*Unbalanced* environment: the organisms tend to prefer the food tokens, less abundant in their environment (the curves are shifted upwards). The organisms have learnt to use the information coming from the body: they increase their preference for food when they are more hungry than thirsty, and they decrease it when the opposite is true (the filled dots curves are above the empty dots ones); at full stores (1/1) the organisms show no preference for any of the two types of tokens when food is roughly 3 times more distant than water.

*Seasonal* environment: the organisms choose to go to the nearest token if they are equally hungry and thirsty (black filled squares) but the bodily state strongly biases their preference towards the more needed resource.

*Patched* environment: in this environment too, the levels of the two body stores influence the choice behaviour of the organisms in the adaptive way (filled dots curves mostly above the empty dots ones) even though the data are more noisy.

These results allow us to say that Mot individuals have learnt how to use the information arriving from within the body as this is a useful adaptation in environments (2), (3) and (4). This ability leads to an adaptive advantage in the *seasonal* and the *patched* environments, but not in the *unbalanced* environment (space precludes an in depth discussion of this point here). It is worth noting that, even if the difference in the average population's fitness between Sim and Mot organisms in the *patched* environment is not very great, the strategies they have evolved to survive are different. The Sim organisms developed a - not very efficient - "back and forth" strategy: they go straight towards the patch they see, and they spin when they don't see anything. In contrast, the Mot organisms show a sort of "restricted area search" (ARS) behaviour [15]: they remain in the patch they are in (eating or drinking) and they abandon it to reach the other one only when the relative body store is almost empty.

## 4 Motivation as Memory

There might be an alternative interpretation for our results, based on *memory* rather than *motivation*. The present state of the body might function, if it is communicated to the brain, as a sort of memory of what the organism has done recently. When the energy level is high and the water level is low, this means that the organism recently has eaten and not drunk and therefore it should drink rather than eat, and the opposite when the energy level is low and the water level is high. Since memory of recent behaviour is useful in environments (3) and (4) but not in environments (1) and (2), the existence of a motivational circuit results in higher fitness in environments (3) and (4) only.

To test this alternative interpretation we have added an explicit memory mechanism to the neural network of our organisms consisting of two parts. The network's hidden units are now *leaky* neurons and have fully *recurrent connections* [16]. A population of organisms endowed with this new neural network but without the motivational circuit has been evolved in all four environments.

The results show that in all four environments the organisms possessing the memory mechanism reach a higher fitness level compared to those without it (see Mem data in Fig. 1 and Tab. 2). In other words, while the motivational circuit leads to a higher performance only in environments (3) and (4), the memory circuit leads to a higher performance in all four environments. This seems to indicate that memory and motivation are two distinct mechanisms, with separate effects on organism performance. The memory circuit has a positive influence on the cognitive component of organism behaviour, causing a more effective manner of approaching tokens in the environment and therefore being useful in all sorts of environments (data not shown). In contrast, the motivational circuit has a positive influence on the motivational component of the organisms' behaviour, leading to more effective "decisions" on whether to approach food or water and therefore being useful only in the particular environments in which such decisions are critical for survival, i.e., in our environments (3) and (4).

A further proof in favor of a distinction between memory and motivation is that evolved organisms endowed with both our memory circuit and our motivational circuit reach a higher level of performance in environments (3) and (4) with respect to both the organisms possessing only the memory circuit and the organisms possessing only the motivational circuit (data not shown). This clearly indicates that the two circuits have distinct functional roles and that in the appropriate environments these functional roles can have separate and additive beneficial influences on organism performance.

## 5 Discussion

Evolving a system that informs an organism's brain of the current state of the organism's body depends on the environment in which the organisms happen to live. All our organisms need to both eat and drink in more or less equal quantities in order to survive and have offspring. However, possession of a communication channel between body and brain that informs the brain of the current level of energy and water in the body is only advantageous in some environments. Examples of such environments are an environment in which food and water abundances change seasonally and an environment in which food and water are distributed in patches. In these environments it is critical for the organisms to evolve a motivational system that tells the brain how much energy and water is currently contained in the body so that behaviour can be determined by both input from the external environment and input from within the body.

It is interesting to note that while the external environment is given, the internal environment is not given but co-evolves with the brain. To adapt to the external environment means to develop the appropriate sensory organs and the appropriate neural processing system that allow the organisms to survive and reproduce in that environment. To survive in our *seasonal* and *patched* environments the organisms have to develop both a body that sends the appropriate input to the brain and a brain that responds appropriately to this input from their body.

We conclude by indicating two directions of future research. The role of an evolving body in the general process of adaptation can be studied in other ways. For example we could take into account the fact that the rate of consumption of energy and of water is not a given but is part of the entire adaptive pattern of the particular organism, and therefore can co-evolve with the rest of the organism, i.e., with its sensory organs, brain, and behaviour. A second direction of research concerns other aspects of competition between motivations (for a study of action selection in a social environment see [17]).

We are currently running simulations in which the organisms have two motivations: eating food and avoiding being captured by a predator. These simulations seem to indicate that there are two types of individuals which tend not to have offspring: individuals that are not very good at finding food (a tactical or cognitive problem) and individuals that are too afraid of the predator to look for food (a strategic or motivational problem).

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