Do it with rhythm - how internal clocks can simplify life for artificial and biological organisms

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Abstract

In this paper we use techniques from "artificial life" to investigate the role of "internal clocks" in certain simple forms of cognition. In two seperate sets of experiments we have evolved populations of "artificial organisms" exhibiting "efficient wandering" and "detour behavior". We show that in novel environments "organisms" with "internal" clocks achieve better performance than organisms with no ability to sense time. The architecture of these organisms is significantly simpler than alternative models of the same behavior. We therefore suggest that the use of "internal sensors" can significantly simplify cognitive tasks for biological as well as artificial organisms.

1 Introduction

The theme of this workshop is time. In this paper we will examine the role of time, and the ability to measure time, in certain very simple forms of animal cognition and behavior.

It is well known that virtually all animals possess "internal clocks" operating on a variety of scales - from milliseconds to months or even years (Farner 1985). These clocks - some of whose molecular and genetic mechanisms have been identified by recent research - regulate a broad variety of behaviors and body rhythms, from sleep and wakefulness to reproduction and migration (Aschoff 1981). Time and rhythm are, in short, a basic component of animal biology.

Internal clocks modulate the dynamics of neurotransmitter availability in the brain (Moore et al., 1993, Wagner et al, 1997). It is reasonable, therefore, to assume that cognition can make use of clock data. Here we use techniques from "Artificial Life" (Langton 1997) to show that "artificial organisms" with "internal clocks" are able to generate apparently complex behaviors using extremely simple neural mechanisms which did not require the complex "internal representations" posited by alternative models of the same behavior. This suggests that ability to measure the passage of time is strongly advantagous to animals, greatly simplifying the cognitive and behavioral tasks they are asked to perform.

2 Two simple behaviors

In our experiments we "evolve" "artificial organisms" exhibiting two well-known animal behaviors: the ability to "wander efficiently" (Walker & Miglino 1999, Miglino et al., 1995) and to "detour" (Walker & Miglino 1999b, Miglino et al. 1998).

The first behavior we examine is efficient wandering. When a mouse is released into an unfamiliar environment it "wanders" in what seems to be a random fashion. "Optimal foraging theory" predicts, however, that wandering will be "efficient": on release the mouse will rapidly visit a large proportion of the available territory (Stephens et al. 1986). The mouses's behavior is, in other words, less random than it seems. A number of experimental studies have supported this hypothesis (Gallistel 1990).

The second behavior we examine is the classical "detour problem". When an animal seeks to reach food or a mate it will often find an obstacle in the way. In these circumstances the only way it can reach its goal is to take an indirect route, involving the loss of visual contact with the target. This is "a detour". Detours have been demonstrated in many animals including chimpanzees (Koelher 1925) and rats (Tolman 1930, Tolman 1948). In the experiment reported here we replicate the detour behavior of two day old chicks, as observed by Regolin et al.(Regolin et al. 1994).

3 The experiments

It is well-known that manual modeling of complex behaviors can be extremely difficult and often leads to proposals which are "un-biological" in flavor. In our experiments we avoided these difficulty by using a so-called Genetic Algorithm (GA) (Holland 1975, Mitchell 1996) to "evolve" populations of "artificial organisms" (see methods section) controlled by Artificial Neural Networks (ANNs) and displaying the ability to perform a set task: in our first set of experiments "efficient wandering", in the second set: a detour.

Both sets of experiments involved the evolution the evolution of a population of 100 such "organisms". At the beginning of the experiment we generated random genomes for each organism. At the end of each generation we measured organisms' ability to perform the set task. Each was assessed in a number of different settings. In the case of wandering we used a "fitness function" which rewarded completeness and speed of exploration (see methods section). In the case of detour the fitness formula rewarded robots which successfully searched for the target and moved towards it. At the end of the testing process the 20% of fittest organisms were "selected" for reproduction. Each of the selected organisms was made to produce five clones. During this process we introduced random "mutations": bits in the genome were flipped from 0 to 1 or vice versa with a probability of 0.04 per bit/generation (wandering) and 0.02/bit/generation (detour). The cycle of test, reproduction and mutation was iterated respectively for 600 generations (wandering) and 350 generations (detour).

Finally we observed the behavior of organisms in a "novel environment" (see methods section) which they had not met during the evolutionary process. This test made it possible to measure the robustness of evolved network configurations with respect to minor changes in task definition.

4 Results

In both sets of experiments we successfully evolved organisms capable of achieving high levels of performance in novel environments as well as in the specific settings where they had evolved.

4.1 Wandering

In our work on wandering behavior we compared the performance of organisms with and without "internal clocks". The results showed that so long as organisms were tested in the same environment where they had evolved they achieved similar levels of fitness - whether or not they possessed an internal clock. In novel environments, on the other hand, organisms with internal clocks outperformed organisms without clocks (see Figure 1).

An examination of the trajectories followed by these two classes of organism helps to explain these results. Figure 2 shows a typical trajectory for an organism with no internal clock. This strategy is highly adapted to the specific environment where the organism has evolved. The diameter of the semi-circles and the length of the line segments in the trajectory are perfectly adapted to to the cell-size used for evaluation purposes. The easy to describe, environment-dependent strategies evolved by organisms with no internal clock may be compared with the more complex behavior produced by organisms which are able to take account of time input.(see Figure 3). In experiments with these organisms we observe, as in the previous case, that the organism turns on meeting an obstacle. It appears however that it also turns (at an oblique angle) on receiving input from its internal clock. In many cases the robot will then traverse the field box following a curved trajectory which maximizes the number of cells

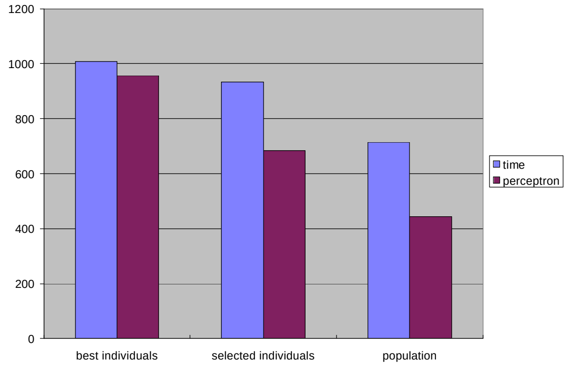

Figure 1: Wandering behavior in a rectangular ”open field box”. Trajectory of a robot with ”internal clocks”

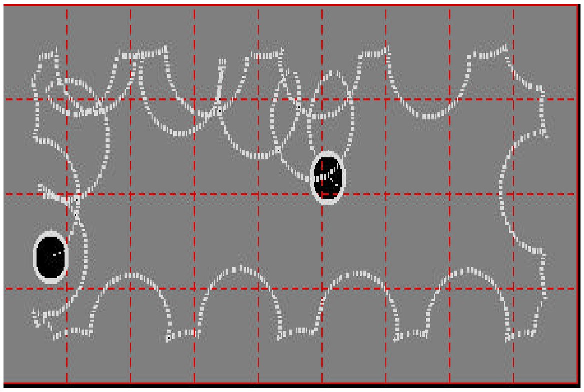

Figure 2: Wandering in a rectangular “open field box”: trajectories followed by robots with no “internal clocks”

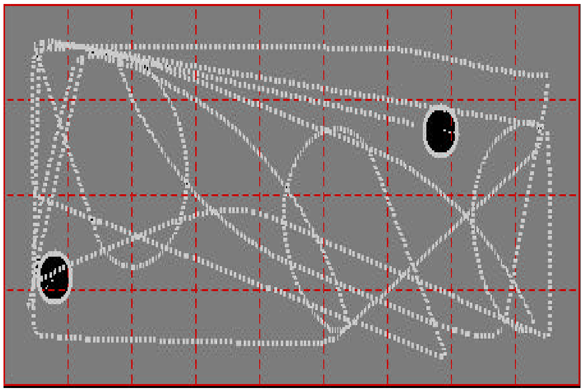

Figure 3: Efficiency of wandering in robots, with and without "internal clocks"

visited en route. The ability to periodically change direction is independent of the external environment where the robot has evolved.

Comparing organisms with and without "internal clocks" it may be observed that in the absence of any other source of input the former have necessarily adapted to the specific environments where they evolved. The latter, on the other hand, have access to a source of input (the "internal clocks") whose characteristics are independent of the external environment. This explains the superior performance of "clocked" organisms in unfamiliar environments.

4.2 Detour

In the case of detour behavior systems without internal clocks completely failed to generate effective detours; with internal clocks they behaved in ways which were statistically indistinguishable from the behavior of the two day old chicks used by Regolin et al. (Regolin et al. 1994) in their experiments (Walker & Miglino 1999). Here again an examination of trajectories (see Figure 4) casts light on the way in which a "sense of time" can assist behavior.

In different simulations robots evolved different strategies. We have not as yet performed a detailed analysis of these strategies or of the underlying computational mechanisms. In general however they appear to be based on simple rules, for example (see Figure 4):

1) Main: Move forward turning first clockwise (slowly) and then anti-clockwise (more rapidly).

2) Taxis: On visual contact with target turn sharply towards the target. Return to Main

3) Wall following: If left proximity sensors active turn right. If right sensors active turn left. Move forwards until obstacle out of view. Return to Main

(1) - an essential component in the overall strategy - requires a sense of

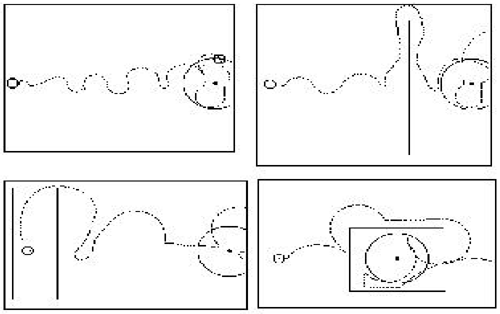

Figure4: Detour behavior: trajectories followed by a typical robot in the four training environments. Legend: Small circles: terminal points for trajectories (if within field box). Large circle: target area rewarded by fitness function

"time". When the robot is a long way from any obstacle it receives no external stimuli. It is only the input from its "internal clocks" which allows it to modify its behavior, actively exploring the environment for new stimuli. The combination of exploration and taxis, which these sensors make possible, represents an efficient strategy for moving towards the target even when it is often outside the camera's field of vision.

5 Discussion and conclusions

Classical models of animal behavior make no explicit reference to time. For the behaviorist animal behavior is a simple function of the stimuli the animal receives from the outside world (Watson 1925). Schematically:

(1) $B = f(S)$

where B is the behavior and S a set of external stimuli.

This is the behavior we observe in "artificial organisms" with no internal clock. If the environment is stable "artificial evolution" can achieve impressive results, as in our experiments with wandering in a familiar environment. Optimal behavior in one environment may however be severely suboptimal in a another. Our experiments show that an organism may evolve a highly effective strategy for wandering in an open field box of one particular shape; a small change in the measurements of the box is enough however to completely invalidate the strategy. For anyone who has observed the elasticity of real-world animal behavior such a rapid degradation of performance seems biologically unrealistic.

Modern cognitive science recognizes that in reality animal behavior is more than a simple response to external stimuli. Many behaviors are best explained by positing the existence of "internal representations". Schematizing again:

(2) $B_t = f(S_t; R_t)$
$R_t = g(S_{t-1}; R_{t-1})$

where $B_t; S_t$ and R_t stand for Behavior, Stimuli and Internal representations at time t. These are the equations for a "finite state automaton".

Many cognitive scientists argue that navigational skills (such as those needed for efficient wandering or detours) require the presence of "topographical maps" (Tolman 1930, Tolman 1948, Gallistel 1990), perhaps implemented via "place cells" within the animal's brain (O'Keefe & Nadel 1978). In our own experiments, on the other hand, "topographical maps" or "place cells" are excluded by design; the network architecture has no "hidden neurons"; there is no location where place information could be represented; the only inputs received by the output neurons are those from the sensors and the internal clocks. In short:

(3) $B = f(S; T)$

where T is the output from an "internal clock" - a counter which counts up to a certain number and cycles back to zero.

We prove, in other words, that very simple "artificial organisms" with internal clocks can perform efficient wandering and simple detours without resort to internal representations. This does not demonstrate that biological organisms do not possess or use such representations; this is a highly controversial issue (Benett 1996, Burgess 1997, Gallistel 1990, O'Keefe and Nadel 1978, Tolman 1930, Tolman 1948). What it does show is that the use of time data can significantly simplify a number of cognitive tasks. There are many circumstances in which it is useful to change behavior once a certain time has passed - even in the absence of external stimuli. Given that all animals possess internal clocks it would be surprising if evolution had failed to exploit them for cognitive purposes. It seems very likely that "doing it with rhythm" makes life simpler for biological as well as artificial organisms.

6 Methods

6.1 Artificial organisms

The artificial organisms used in our experiments were software simulations (Miglino et al. 1996) of the well-known Khepera robot (Mondada et al., 1993). Input to the robot came from 8 infrared proximity sensors, 4 sensors linked to a linear video-camera and 3 "time sensors". Proximity sensors have a sensory field of 20° and are sensitive to obstacles within 3 cm of the sensor. Output (between 0 and 1) is a continuous, decreasing function of distance to the obstacle. The video-camera has a field of vision of 36°. Each sensors produces an output of 1 if the center of the target lies within its own 9° field of vision. The output values of the three time sensors were initially set to zero, increasing respectively by 0.01, 0.02 and 0.03 on each cycle of computation. When a sensor value reached 1 it was reset to zero. The motor apparatus consisted of a left and a right wheel driven by stepping motors which can move both forwards and backwards. The motor apparatus was controlled by an Artificial Neural Network (ANN) with input neurons representing the state of the sensors and output neurons controlling the stepping motors. A number of different architectures were tested. The architecture finally chosen was based on a simple Perceptron (Minsky & Pappert 1988) in which all sensors have a direct connection to the two output units. Evolution involved "mutations" in connection strengths. The genome of the organism consisted of a sequence of binary coded numbers (8 bits per number) representing the strengths of individual connections.

6.2 Simulation environments

6.2.1 Wandering

Robots were tested four times in a rectangular 90 cm by 40 cm box and four times in a square 60 cm by 60 cm box. On each test the robot started with a randomly chosen position and orientation. For measurement purposes the terrain was divided into square 10 cm by 10 cm cells. Each test consisted of 1,000 cycles of computation.

6.2.2 Detour

Each environment consisted of an open field with no external fence. In the first environment there was no obstacle between the robot and the target. The second, third and fourth environments selected for actual detour behavior. In the second environment the target was placed behind a linear obstacle 80 cm long. In the third environment Khepera was placed inside an 10*80 cm corridor. The fourth environment used a 40*70 cm U-shaped obstacle (see Figure 4). Obstacles were 3 cm high and of negligible thickness; the target was 12 cm high. It follows that in the "evaluation sessions" the robot was always able to "see" the target even when the path to the target was obstructed by an obstacle. The evaluation test was repeated five times for each environment. At the beginning of each cycle the robot was placed in a randomly chosen position 90 cm from the target. The heading was chosen randomly from a uniform distribution.

6.3 Fitness functions

6.3.1 Wandering

$fit = ncells + (nCycles - cyclesToCompletion)$

Where:

fit is the fitness attributed to the robot

$nCells$ is the number of different cells touched by the robot during exploraiton

$nCycles$ is the duration of the exploration (in cycles)

and

$cyclesToCompletion$ is the number of cycles traversed before the robot has touched every cell in the box. (If the robot never touches all the cells $cyclesToCompletion$ is assigned the same value as $nCycles$.)

6.3.2 Detour

On each cycle of computation, for each organism the system computes the following function

```
IF ("some infrared sensor" > 0 && old_position >< new_position) fitness++
IF ("some infrared sensor" > 0 && old_position = new_posion) fitness--
IF (distanceToTarget < 15 cm.) fitness += 10
```

The first two components in the fitness formula are designed to encourage obstacle avoidance; the last component rewards the robot when it approached the target.

6.4 Novel environments

6.4.1 Wandering

The novel environment consisted of a 120 cm by 90 cm box which the organisms had not encountered during the evolutionary process. As in the tests of fitness during the evolutionary process each robot was tested from 4 different starting positions. Given the larger size of the new environment the number of computation cycles was increased to 3,000.

6.4.2 Detour

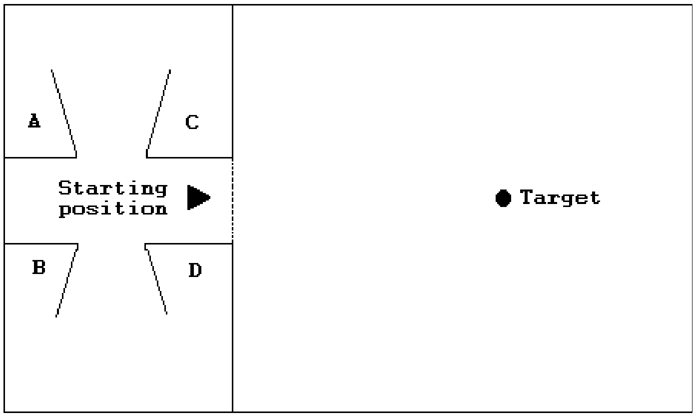

Figure 5:

The organisms were tested in a computer replica of an experimental setting used by Regolin et al. to demonstrate detour behavior in two day old chicks. (see Figure 5)

The organisms are placed in a "cage" divided in two by a barrier. The part of the cage on the other side of the barrier contains a corridor. On the end of the corridor facing the target there is a window through which the organisms can "see" the target. On each side of the corridor there are apertures leading into two compartments, one facing the target, and one facing in the opposite direction. The two compartments facing the target are labeled C and D.; the two compartments facing in the other direction are labeled A and B. At the beginning of each test the organism is placed in the corridor close to the barrier and allowed to wander freely. The system records the first compartment the organism enters and the time it takes to reach it. The test is halted after 600 cycles of computation.

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