The autopoietic nature of the “inner world”
A study with evolved “blind” robots

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Abstract. In this paper we propose a model of anticipatory behavior in robots which lack any sort of external stimulation. It would seem that in order to foresee an event and produce an anticipatory action an organism should receive some input from the external environment as a basis to predict what comes next. We ask if, even in absence of external stimulation, the organism can derive this knowledge from an “inner” world which “resonates” with the external world and is built up by an autopoietic process.

We describe a number of computer simulations that show how the behavior of living organisms can reflect the particular characteristics of the environment in which they live and can be adaptive with respect to that environment even if the organism obtains extremely little information from the environment through its sensors, or no information at all. We use the Evorobot simulator to evolve a population of artificial organisms (software robots) with the ability to explore a square arena. Results indicate that sensor-less robots are able to accomplish this exploration task by exploiting three mechanisms: (1) they rely on the internal dynamics produced by recurrent connections; (2) they diversify their behavior by employing a larger number of micro-behaviors; (3) they self-generate an internal rhythm which is coupled to the external environment constraints. These mechanisms are all mediated by the robot’s actions.

1 Introduction

From a psychological point of view past events and future events are essentially the same: they do not actually exist in the environment experienced by the organism but, this notwithstanding, they influence the organism’s behavior. Past and future become real exclusively in the organism’s mind or brain, as the organism recalls a past experience or foresees something which is going to happen. Recalling and foreseeing are two functions of memory, the neuro-cognitive function that allows organisms to keep trace of what has happened in order to decide what to do next (von Foerster, 1969). In recent years some psychologists have proposed to add to the classical memory typologies (short-term memory, long-term memory, episodic memory, etc.) another kind of memory defined as...
prospective memory (Brandimonte et al., 1996) which is at work in forecasting and planning behavior. An organism’s mind/brain contains a structure/function which encodes, at the same time, what the organism has experienced previously (past), what the organism will potentially experience (future), and what the organism is currently experiencing (present). The present, under the form of every sensation, thought, expectation, movement which the organism is now experiencing, must be “digested” (elaborated) in the framework of this neuro-cognitive structure/function. In this sense, cognition may be the result of an autopoietic process as defined by Maturana and Varela (1980). According to these authors, a genotype becomes an organism through an active interaction with the external environment: it extracts primary resources from the external environment (water, food, etc.) and it transforms them into tissues, organs, systems, etc. The organism is the factory of itself. This view of the organism can be extended to the genesis of cognitive structures. Cognition is an internal world that is linked with the external environment but is not a direct copy of it. Living systems are self-reproducing systems and cognition is one of the processes that characterize their self-reproduction. These systems are self-referential, operationally closed, and they compensate for the perturbations arriving from the external world to save their organization. However they also transform as a consequence of environmental stimulation.

This view can be related to Piaget’s (1971) conception of cognitive development as an interaction between assimilation and accommodation. Assimilation and accommodation are two complementary processes of adaptation. Assimilation changes the external world to adapt it to the internal world. Accommodation changes the internal world to adapt it to the external world. Cognition is the result of both processes.

In the context of robotics research Tom Ziemke (Ziemke, 2005; 2007; 2008; Jirrenbied, 2001) has studied intensively this “nonphysical space” that holds past, present, and future together in an “inner world”, a notion which has been first introduced by Hesslow (2002) and developed by Grush (2004). The metaphor is powerful and useful because it makes clear the crucial split between the external, physical world the organism is immersed in and its “internal”, private world which is hidden to other organisms but is fundamental in determining the organism’s behavior.

What is emerging in the new field of artificial adaptive systems is an issue which has played a fundamental role in the philosophical reflection and psychological investigation concerning the behavior of organisms: the delicate balance that exists in organisms between “external” (physical, concrete, public) reality and “internal” (psychological, immaterial, private) reality. Consider two pioneers of psychological research, Wundt (1874) and Watson (1913; 1914). Wundt investigated what happens inside a person’s mind by interrogating well-trained subjects whereas Watson used animal models to study observable behavior, each choosing one side of the split between “external” and “internal”. If in order to understand the behavior of organisms it is necessary to consider both their inner world and their external environment, constructing artificial organisms might make this
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possible.
The simultaneous consideration of both the internal and external side of behavior is particularly relevant if we wish to study anticipatory behavior. In order to produce an anticipatory action, organisms should possess some knowledge concerning the environment in which they live. It is usually assumed that this knowledge is founded upon integrating innate schemes with sensory experience, where sensory experience is provided by environmental stimuli (light, sound, smell, etc.) and is received by the organism’s sensory apparatus, including eyes, ears, nose. However, in addition to the external environment the organism’s body itself is a precious source of stimuli (Parisi, 2004). Examples are internal clocks, proprioception, signals from the gastroenteric apparatus, the hormonal system, etc. This stimulation is considered relevant to regulate the organism’s behavior but not to build up a “knowledge” of the external environment. For example, hunger can motivate an organism to choose a certain action to satisfy this need but it is not useful to construct a representation of the environment in which the organism lives.

Some authors have underlined that knowledge is not a registration of what happens in the external world. For example Maturana and Varela (1992) have stressed the fundamental importance of the “inner world” to build neuro-cognitive functions such as memory that allow organisms to survive in an unpredictable world. Human experience is fallacious, as it is shown by the blind spot of the optic nerve in the retina. If one looks at a fixed point and then he or she moves the gaze, the point disappears from the visual field, showing a blind spot in the retina in the area of departure of the optic nerve. Beyond the physiological relevance of this phenomenon, it is interesting that humans do not see that they do not see: human beings are tempted by an illusion of certitude, by the inclination to think that they live in a world in which things are what they seem to be, without considering alternatives. On the contrary, neuronal activations which are primed by external stimulation are determined by what is inside the person and not only by the perturbing agent, and are therefore different from person to person. For this reason we do not “see the world” but we “live our visual field”. We do not see the colors of the world but we live our chromatic space: every experience involves the experiencer and it is deeply rooted in his/her individual biological structure. An organism’s knowledge of the world is not a representation of the world “out there” but is the production of “sense for action”.

These challenging issues raise numerous and important questions and we have tried to answer some of them using an Artificial Life approach. We aim at investigating the possible role of internal stimulation in building a knowledge of the environment in which an organism lives and from which it receives no stimulation at all. We will explain in detail our approach with a concrete example. Let’s imagine an organism with a motor apparatus and an internal sensory apparatus, but totally without sensory organs that directly inform the organism concerning the current state of the external environment. The organism is completely closed inside itself at the sensory level. It can interact with the external
environment but it cannot get any direct information from the external environment. The organism is forced to create its own inner world on the basis of purely self-generated stimuli. But the organism cannot be said to be isolated from the external environment in that its actions have effects that modify the physical relation of the organism to the external environment and that the organism can exploit to behave adaptively in the environment. In nature there may exist no such organisms but the tools of Artificial Life can be used to explore this type of questions because Artificial Life is the study of both real and possible organisms (Langton, 1989; Nolfi and Floreano, 2000). In the next paragraph we will describe our approach, summarize some similar studied that have been already done, and make our research hypothesis explicit.

1.1 The Agent/Environment dynamic in the Animat approach

In the last 15 years a research methodology that uses simulation of artificial organisms to understand cognition in real organisms has carved out a space for itself inside Cognitive Science. Using this methodology, often called the Animat approach (Todd, 1992; Guillot and Meyer, 1994), it is possible to study how cognition emerges in the interaction between the agent, that is to say the artificial animal, and the environment, as represented in Figure 1.

![Fig. 1. Environment/Agent dynamic in the Animat approach](image)

The agent receives stimulation from the environment and reacts consequently. The environment, in turn, reinforces the agent, as stressed by Wilson (1991). The reinforcement can be given at different timescales. In embedded systems that use the back-propagation learning algorithm, for any input from the environment the experimenter provides the correct motor output to the artificial neural network controlling the organism’s behavior. In this case the reinforcement is immediate
and provided step by step. In the framework of artificial evolution (Nolfi and Floreano, 2000; Harvey et al., 1996), the reinforcement is given at the end of an individual’s lifetime as a fitness score which decides whether the individual will or will not reproduce. The two systems can be combined together with both artificial evolution at the population level and back-propagation learning at the individual level (Parisi et al., 1990).

What happens if the agent doesn’t receive any stimulation from the environment? This is interesting because natural organisms receive information from the external as well from the internal world whereas Animat models usually focus on environmental stimulation.

In the present paper we use a modified version of the environment/agent dynamic in the Animat approach. We eliminate any stimulation that the agent may receive from the environment in order to address explicitly the issue of how our artificial organisms can produce their own world by just relying on its their “inner world”, as shown in Figure 2.

Fig. 2. Environment/Agent dynamic in the Animat approach: the inner world

As shown in the above Figure we modify the agent/environment interaction by removing the sensory link between the agent and the environment. The agent cannot rely on its sensory apparatus to decide which action to take but it can still use its motor apparatus to produce actions that are not rewarded step by step but at the end of the evolutionary process.

1.2 Some seminal studies

The research presented here draws inspiration from some seminal studies that we quickly review here in order to underlie what is different in our study.

In 1994 Todd and colleagues published an experiment in which an adaptive,
survival-enhancing behavior emerged in simple simulated creatures which had no direct sensory contact with their environment. They described the evolution of the behavioral repertoires of these sensor-less creatures in response to environments with different spatial and temporal distributions of food. The main difference with our study lies in the theoretical goals. They explored the level of adaptiveness in these blind creatures to establish a baseline with which the adaptive behavior of Animats with sensors and internal states could be compared, whereas we wish to understand how the internal world can come in resonance with the external world to produce adaptation.

In this respect it is appropriate to report Ziemke and colleagues' work (cfr. Ziemke et al., 2005; Hesslow and Jirenhed, 2007, Jirenhed et al., 2001) who explored the possibility of providing robots with an “inner world” based on internal simulation of perception rather than an explicit representation world model. Starting from a neuroscientific hypothesis they studied how internal simulation of perception can be used by mobile robots to respond appropriately to their environment, presenting various experiments with a simulated robot controlled by a recurrent neural network shaped by an evolutionary algorithm. Their work suggests that internal simulation of perception may be sufficient to adapt. We start from a very similar research hypothesis and we use a very similar setup but our agents do not have to explicitly simulate their perception.

The most recent paper we cite here is by Lungarella and Sporns (2006). In their work they start from the idea that organisms continuously “select and sample information used by their neural structures for perception and action, and for creating coherent cognitive states guiding their autonomous behavior” (ibidem). They stress that information processing is not solely an internal function of the nervous system, but instead sensorimotor interaction and body morphology can act as constraints that create statistical regularities in sensory input which allow the emergence of adaptive behavior. Their paper is important for interpreting our results since we also wish to understand how internal and external worlds can coordinate and generate regularities that can result in adaptive behaviors.

In the next section we will formulate more explicitly our research questions.

**Our research hypothesis** In the present paper we continue to explore the issues that have been raised by the studies reviewed above, trying to answer the following questions: Can internal stimulation be sufficient to solve a spatial task? Is there any difference with respects to Animats that rely on stimulation? Which mechanism do our organisms use to adapt?

We have simulated a spatial behavior with two questions in mind:

1. Can robots exhibit adaptive spatial behaviors that rely only on internal stimulation?
2. If yes, how is that possible?

Asking these questions may be important because the possible answers may clarify how at an evolutionary scale anticipation can lead to adaptation even in the extreme case of an organism with no direct sensory feedback from the external
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Our agents, even if they lack stimuli, can rely on two channels to get in touch with the environment: action and “evolutionary” reinforcement, that is, the selective reproduction of the best individuals in a succession of generations. In the simulations that we will describe the robots are able to move adaptively in their environment by implicitly predicting the sensory input and by just relying on their predictions to generate their behavior, and not on actual sensory input coming from the outside environment.

2 Method

In our experiments we use the Evorobot simulator (Nolfi, 2000) to evolve populations of artificial organisms (software robots) with the ability to solve a spatial task: exploring a square arena by visiting as many portions of the arena as possible. The simulator, developed by Stefano Nolfi at ISTC-Cnr, makes it possible to run Evolutionary Robotics simulations that can then be transferred on real robots.

2.1 Artificial Organisms

Each artificial organism consists of a physically accurate simulation of a robot with a circular body of 5.5 cm of diameter, which is a model of the E-puck robot developed at EPFL, Switzerland (www.e-puck.org)(Fig. 3).

![Fig. 3. The E-puck robot model in the 3D simulated environment](image)

Each robot is equipped with 8 infrared proximity sensors (that can detect objects within 3 cm of the sensor) and a black/white linear camera with a receptive field of 100 degrees whose content is encoded in 8 input units. The robot
displaces itself by using 2 wheels (one on each side of the robot) powered by separate, independently controlled motors. The control system is an Artificial Neural Network. We use neural architectures with two properties: the existence of recursive connections and the nature of the sensory input. All neural networks have an output layer with two units that control the robot’s two wheels. In all neural networks, furthermore, there are five internal units which are all connected to both output units. However, in different simulations the robots have neural architectures that can be different with respect to sensory input and internal structure. There are four conditions of sensory input: no sensory input, infrared sensory input, visual (camera) input, both infrared and visual input. There are also two internal architectures: no recursive connections and recursive connections (from the output units to the internal units and Elman "memories" for the internal units), for eight conditions in total which are shown in Figure 4. At time t0, neural networks with no sensory input have an input pattern of 1 for each hidden unit that has a different, evolvable threshold.

Fig. 4. The neural architectures. In the graph are shown the eight different internal architectures. In four of these architectures there are no recursive connections while the recursive connections are present in the remaining four architectures. Each of these internal architectures is associated with one of four possible sensory input conditions: no sensory input, infrared sensory input, visual (camera) input, both infrared and visual input. Therefore we have a total of eight different experimental conditions.
2.2 The task and training procedure

A Genetic Algorithm is used to train the connection weights of all network architectures. At the beginning of each simulation, we create 100 neural networks with random connection weights that are assigned to 100 robots. We then test each robot’s ability to solve the exploration task. Each robot is positioned at the centre of a square arena with peripheral walls and four lights placed at the four corners of the arena. If the robot happens to hit the walls, the robot dies. At the beginning of each trial the robot is positioned in the arena with a randomly chosen face-direction and is allowed to move around for 500 computation cycles (1 ms per cycle). For analysis’s sake we consider the square arena, which is actually continuous, as made up of cells that cover the entire square area (40x40 cells). Each time a robot visits a cell it has not visited before its fitness is increased by one unit. At the end of life the 80 robots with the lowest fitness are eliminated (truncation selection) while the remaining 20 robots are cloned (asexual reproduction). Each parent generates five offspring, and a value randomly chosen from the uniform distribution [-1, +1] is added to 2 per cent of the offspring’s connection weights. We run eight different experiments with “recursive” vs. “non recursive” conditions and four “sensory” conditions (see Figure 4). Each experiment is repeated 10 times with different initial conditions (different randomly generated connection weights for the neural networks of the individuals of the first generation).

3 Results

3.1 Fitness values

The next graph (Fig. 5) shows the fitness values, that is, the number of cells that are visited for the first time by the simulated robot, for each of our eight experiments. Data refer to the fitness values calculated on the last 10 generations (on 100 total generations) for 10 repetitions (these are therefore aggregated data calculated on 100 values). Each bar in the histogram represents the average for a single simulation. Grey bars refer to average values while black bars refer to best values. To identify each simulation we use this code: r means recursive condition while nr means non recursive condition. Neural architectures without recursive condition are shown on the left columns in Figure 4 while neural architectures with recursive condition are shown on the right columns. Letters indicate sensory input conditions where no letter means no external stimuli, A means 8 infrared sensors, B means 8 units for the camera, and AB means 8 infrared sensors plus 8 units for the camera.

As can be seen from the graph, the fitness values of the best subjects of the last 10 generations suggest that recursive connections are beneficial for robots with no sensory information. In the graph, in fact, considering the best values for each simulation we can see that in the experimental conditions without sensory input and with recurrent connections as many cells are visited by the organisms as in the conditions with sensory input, while in absence of recurrent connections
the performance of the organisms without sensory input is very bad. Considering the best robots for r (no sensory input and recurrent connections) and related condition rA, rB, and rAB and applying a one-way ANOVA, we see that there are no significant differences in the number of visited cells with sensory condition as factor: $F(3,36)= 2.667; p= 0.062$.

The important role played by recursive connections depends on the fact that they allow to overcome stereotypical behavior in favor of more variable behaviors, as we will see in the next section. Therefore we have an interesting answer to our first question: yes, it is possible to observe adaptive behaviors in robots with only internal stimulation under certain conditions, namely the presence of recursive connections that allow the robot to build an internal dynamic, an “inner world” in Ziemke and colleagues’ words, which is coupled with the environment. They succeed in coordinating endogenous stimuli with the constraints of the external environment and to use this coordination to generate a motor behavior which is adaptive.

3.2 Behaviors

In Figures 6 and 7 behavioral strategies of the best robot of each simulation without and without sensory input are represented together with their neural
In absence of recurrent connections, robots can produce only stereotypical behaviors: they draw a circular trajectory because a circular trajectory of the appropriate radius allows them to avoid hitting the wall and die.

In fact it is worth noting that this circle has a radius that depends on the size of the square arena. This is an efficient strategy, considering that the robots has no access to external information and must avoid bumping into walls which they cannot perceive. However, when the robots have recurrent connections their performance increases dramatically: their recurrent connections generate an internal dynamic that, under evolutionary pressure, tends to be tuned with the constraints of the external environment. We observe more variable trajectories which are always curved but which lead the robots to visit many more cells of the arena.

This behavioral strategy is quite different from what we observe in robots with sensory input, because, in this case, the best thing to do is to go straight until they perceive a wall and to turn before bumping into it. In absence of stimulation walls become a constraint, because they must be avoided, and this leads to the emergence of behavioral strategies which explore the cells that are far enough from the walls.
3.3 Output patterns

In order to answer our second question and investigate the role of the inner world in producing appropriate behavioral sequences we examined the activation patterns of the output layer for the single best agent of the last generation in each replication of the simulations. The continuous activation value of the two output units is made discrete when it is transferred to the two wheels, with values going from -20 to 20 for each motor. Therefore we can count the number of different output patterns, which is a measure of the variability or variety of the robots’ micro-behaviors. We focus on the recursive condition, as in absence of recursion performance without external stimuli is very poor. The results indicate that a larger number of different micro-behaviors (number of different output patterns) are necessary to solve the task with self-generated stimulation. There are significant differences between the experimental Conditions, with a decreasing mean number of output patterns going from the condition with IR sensors + camera to the condition without stimulation, as shown in Figure 8.

Comparing for example the best robots of the last generation for condition r (no sensory input and recurrent connection) and related condition rA, rB and rAB and applying a one-way ANOVA, we see that there are significant differences in the number of output patterns with sensory condition as factor: $F(3,36)=$
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40.606; p= 0.00. In absence of variable external stimulation, the robots create their own internal variable stimulation. Robots without any external stimulation are able to accomplish the task to explore effectively the square arena if they are provided with recursive connections that create an internal dynamic which in turn produces a more varied behavior.

3.4 Hidden units activation

To further answer our questions, we have also analyzed what kind of internal dynamic emerges in robots with no access to external information. We have observed that, when robots display an efficient behavior, a kind of oscillator emerges in their hidden unit activation. Let us consider, for example, one of the most interesting behavioral strategy and the corresponding neural activation of motors and hidden units that was displayed by the best robot in the recursive condition r without stimulation. Both behavior and neural activation are shown in Figure 9.

As can be seen from the Figure, this very efficient sensor-less strategy results from the emergence of an internal oscillator that provides an internal temporal
Fig. 9. The behavior (up) and the corresponding neural activation (down) of one of the best performing sensor-less robot.

dynamic. It is important to underline that this temporal dynamic is strictly coupled with the spatial constraints so as to make it possible to avoid bumping on the wall while still visiting as many cells as possible. The spatial constraints that are present in the environment are translated into a time rhythm in the “inner world”.

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4 Conclusions

The results of our simulations suggest that, at least for the simple artificial organisms studied in our research, an adaptive behavior can indeed emerge even in absence of direct sensory information from the external environment. Even if they are closed in their own self-generated internal world, the simulated robots establish a useful relation with the external environment through their action. In fact, by realizing and exploiting a precise coordination between produced output and self-generated internal input, i.e., between the external and the internal worlds, the robots are able to successfully adapt to their environment. This is possible because action is accurately selected under evolutionary pressure, and the evolutionary pressure causes the emergence of a kind of resonance between inner world and external world. Through the physical interactions between the organism and the environment, after a demanding search the possibility emerges to utilize action to know the environment, even if there is no sensory input from the environment. In other words, the organism’s actions become the vehicle for developing a representation of the environment.

Our sensor-less organisms, which cannot sense directly the external environment, are in fact not isolated from the external environment because action is able to establish a link with the external world. This is an “operationally closed system” in Maturana and Varela’s sense. Our organisms, in fact, are provided with a motor apparatus and an internal dynamic but they completely lack sensors that can collect information on what is “out there”. They can interact with the external world but they cannot receive direct information from the external world. A system like this, since it cannot react to external stimulation, is forced to build an internal model of the world on the basis of self-generated, internal, private stimulation. The system is not actually isolated from the external world because it has an opportunity to act on the environment in such a way that it becomes possible to develop a relation between the system and the environment, a relation which is not sensory but is behavior-based. In other words, the organism cannot receive external stimuli but it can collect clues about the external environment through action and these clues give the organism the possibility to establish an useful system/environment interaction.

This interaction allows the simulated robot to anticipate what is going to happen. Even in absence of sensory stimulation the robot is able to avoid bumping into the walls, anticipating the inauspicious event that would put an end to its life. This anticipation ability emerges in the neural network in that the network’s hidden units autonomously develop an oscillator that provides an internal temporal dynamic. This primordial form of anticipation resides in the neural network’s rhythm which is strictly coupled with the spatial properties of the environment and the robot’s current location and orientation in the environment.

Under evolutionary pressures the agents’ neural control architecture extracts and incorporates the statistical regularities and information structure underlying their interactions with the environment, and in this way the external constraints and the internal dynamic come in resonance. The flow of information between the hidden units and the robot’s effectors is actively shaped by the robot’s in-
interactions with the environment on an evolutionary scale. These results confirm the fundamental importance of embodiment and situatedness in the behavior of organisms.

Our computer simulations demonstrate how the behavior of artificial organisms can reflect the particular characteristics of the environment in which the organisms live. The behavior that emerges can be adaptive with respect to the environment even if the organisms obtain extremely little information from the environment through their sensors, or no information at all. Of course we observe very peculiar behavioral strategies in our cognitively challenged, sensor-less creatures, including the use of looping movements as time-keepers. Our simulations show how the ability to explore the environment can emerge from the interaction, made possible by action, between two coupled processes: the agent’s internal dynamic and the agent/environment dynamic.

From the point of view of autopoiesis the results of our simulations suggest that at least for our simple artificial organisms internal stimulation can by itself generate adaptive behaviours and can be the building block of an internal world that produces adaptation to the external world.

One possible objection to our conclusion might be that real organisms hugely rely on external stimulation to adapt to their environment. This is undoubtedly true but we think that our simulations demonstrate that external stimulation is only one of the information sources that make it possible to build a representation of the world. In principle, and in extreme cases, internal self-generated stimulation may be sufficient. The “in” is as important as the “out”; they work together in the process of “producing of world”.

This implies that real organisms, endowed with cognitive systems with very complex dynamics, may exploit their internal dynamics to anticipate the future and on the basis of these anticipations generate useful behaviors. These results also confirm that the brain is a self-referential recursive machine whose organization is maintained in spite of environmental perturbations, even if it is triggered by them.

Our simulated agent “knows” the external world in that its control system is able to map the spatial structure of the environment (obstacle position, reinforcement area, etc.) in self-produced temporal structures (internal rhythms). Spatial regularities in the outside world and temporal regularities in the “inner” world come into resonance and this happens thanks to the agent’s actions in the environment.

As already discussed in the introduction our work is inspired by previous studies and it tries to extend some of their results. With respect to Todd’s simulations (1994) our work proposes a mechanism to explain how the internal world can come into resonance with the external world to produce adaptation. What we have found is that one type of spatial regularity (the square walled arena) is translated into an internal representation based on time. In relation to Ziemke and colleagues’ work (cfr. Ziemke et al., 2005; Hesslow and Jirenhed, 2007, Jirenhed et al., 2001) we start from a very similar research hypothesis and use a very similar set-up with a minimal animal model, but our agents do not have to
explicitly simulate their perception. Rather than simulating the percepts that they cannot obtain from the external world, our agents are forced to build an independent internal dynamic that is coupled with the external constraints. In our future research our goal is to extend the types of tasks that our organisms have to accomplish and to use other neural architectures with and without recurrence in order to understand what are the best architectures, and why.

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