Affordance Generation Enables Behavioral Plasticity and Cognitive Offloading in Evolving Robots

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Abstract—**In this paper we discuss the importance of the ability to perceive and generate affordances, i.e. opportunities for behaviour execution. More specifically we show how robots evolved for the ability to solve a given problem use the ability to generate affordances for displaying differentiated behaviour and/or to regulate how their behaviour vary over time.**

I. INTRODUCTION

Mobile robots are, by definition, physical system situated in an external environment displaying behaviors. An important aspect to consider is the fact that the behavior that these systems display is not only the result of the characteristics of the robot but is also the result of the ones of the environment. More precisely is the result of the bi-directional interaction between the robot and the environment.

The bi-directional nature of the interaction originates as a consequence of the fact that: (i) the perceptual environment, i.e. the sensory state that the robot perceives which depends on the external environment and on the relationship between the robot and the environment, influence the actions produced by the robot, and (ii) the actions produced by the robot influences the robot/environmental relation or the external environment which in turn influence the robots perceptual environment.

This fact has two important implications. The first implication is the fact that the possibility to display a certain behavior depends on the perceptual environment of the robot, i.e. on the characteristics of the physical environment, and on the characteristics of the robots perceptual system. The second implication is that the possibility to display a certain behavior depends on the ability of the robot to alter its perceptual environment through its actions.

We use the term affordance [1], [2] to indicate the perceptual states that support the exhibition of a certain behavior and the term affordance generation to indicate perceptual states that support the exhibition of a certain behavior which are generated by the robot through the execution of certain appropriate actions.

In this paper we demonstrate how the capability to generate affordances represent a prerequisite for the possibility to displaying multiple behaviors and for the possibility to display articulated behavior. This will be realized by analyzing the strategies developed by robots that are evolved for the ability to solve a certain task in a given environment. This paper is divided as follow, the next section we will present a series of experiment that address a task/problem that require the exhibition of multiple differentiated behaviors. In the third section we present a task/problem that require the exhibition of structured sequential behaviors.

II. BEHAVIORAL PLASTICITY

Behavioural plasticity is a special case of plasticity - the ability of an organism to react to internal or external environmental inputs with a change in form, state, movement, or rate of activity [3, p. 33]. It involves the capability to display multiple behavioral responses, which might differ in a continuous or discontinuous way, in a condition-sensitive manner [4].

Behavioural plasticity constitutes a key aspect of animal behavior. Indeed, behaviors are often organised in functionally specialised subunits governed by switch and decision points [5]. Examples of elaborate behaviors including several different phases regulated through a rich set of context-dependent rules include the courtship behavior of the grasshopper [6], the reproduction behavior of female canaries [7], web construction and predation behaviors in spiders [3], [8].

Behavioural plasticity is essential for enabling organisms to adapt to variations of their external and/or internal environment. In that respect, it is important to consider that what matters, from the point of view of the adapting individuals, is the organisms perceptual environment (i.e., the characteristics of the environment that the organism perceives given its sensory system and its relative location in the environment). This means that all environments are variable, from the perspective of an organism that is situated and performs actions in an environment, independently of whether they appear variable or not from the perspective of an external observer.

The term behavioral plasticity refers to agents displaying behaviors characterised by a functional modular organisation and displaying the capability to regulate the exhibition of the different sub-behaviors on the basis of their internal and external environment. For example in the case of a tennis player, behavioral plasticity refers to the capability of displaying multiple behaviors such as serve and volley (in which the player serves and then charges forward to the net), lob (a shot in which the ball is lifted high above the net) etc. and to the capability to select the appropriate behavior depending on the game context, for example the ability to execute a drop shot behavior, that consists in hitting the ball just over the net, when the opponent is far from it. The term behavioral plasticity should not be confused with neural plasticity, e.g., fine-grained modifications of the connection weights of the agents nervous system [9].

In [10] we studied experimentally how evolving robots can acquire and display behavioral plasticity, i.e., a series of behaviors that are exhibited in a context-dependent manner. In particular, we studied whether behavioral plasticity evolves during the course of the evolutionary process, and mainly which are the prerequisites for its evolution, and which are the mechanisms through which it is realized. The comparison of the results obtained in different experimental conditions indicates that the most important prerequisite for the evolution of behavioral plasticity is the capability to perceive and generate affordances, i.e., opportunities for behaviors [1], [2]. This capability depends on the richness of the robots perceptual environment that, in turn, depends on the richness of the robots internal and external environments, on the richness of the robots sensorymotor system, and on the ability to exploit sensorymotor coordination. In this section, we will present the results showing how the affordance generation mechanism enables the existance of behavioral plastic solutions.

A. The method, the task and the robot

For studying this issue, we used a cleaning task in which a robot has to clean an indoor environment, i.e., visit at least once each portion of 20x20cm, with a central and a peripheral area and which the dimensions vary along the different trials (the shape of the environment can be seen in Fig. 1, the exact dimensions can be seen in [10]). Each robot was evaluated in 3 trials, during 6m15s, with different initial positions and orientations and environmental dimensions. The robot used was a MarXbot [11], a differential drive wheeled robot with a diameter of 17cm. The robot is equipped with 24 infrared sensors evenly distributed along the robots body and capable of detecting objects in a range of 10cm. Moreover, it is equipped with a rotating laser sensor capable of detecting obstacles at longer distance. Experiments were run in simulation using the FARSA open-software tool [12], [13] that includes an accurate simulator of the robot and of the environment.

The robots are provided with a feed-forward neural network controller. In all experiments, the robots are equipped with eight sensory neurons that encode the average activation state of eight groups of three adjacent infrared sensors each and two motor neurons that encode the desired speed of the two robots wheels. The sensory neurons are fully connected with the motor neurons and motor neurons are provided with biases. The state of the motor neurons is computed on the basis of the logistic function. The state of the sensory neurons and the desired speed of the robots wheels are updated every 50 ms. Experiments have been replicated in the following two experimental conditions:

(T) Time: The robots are provided with an additional sensory neuron that encodes the time passed since the beginning of the current cleaning session (trial), i.e., whose activation state linearly varies between 1.0 and 0.0 during the course of the trial. This sensor has been added to enable the robot to vary the behavior during the course of cleaning sessions. Notice that this sensor enables the robot to access information extracted from the robots internal environment (e.g., a robot clock situated inside the robot body), while the other sensors enable the robot to access information extracted from the external environment

(R) Range sensor: The robots are provided with an additional sensory neuron that encodes the average distance of obstacles located within 1 m detected through the rotating laser range sensor. This sensor has been added to enable the robot to vary its behavior in narrow versus open areas

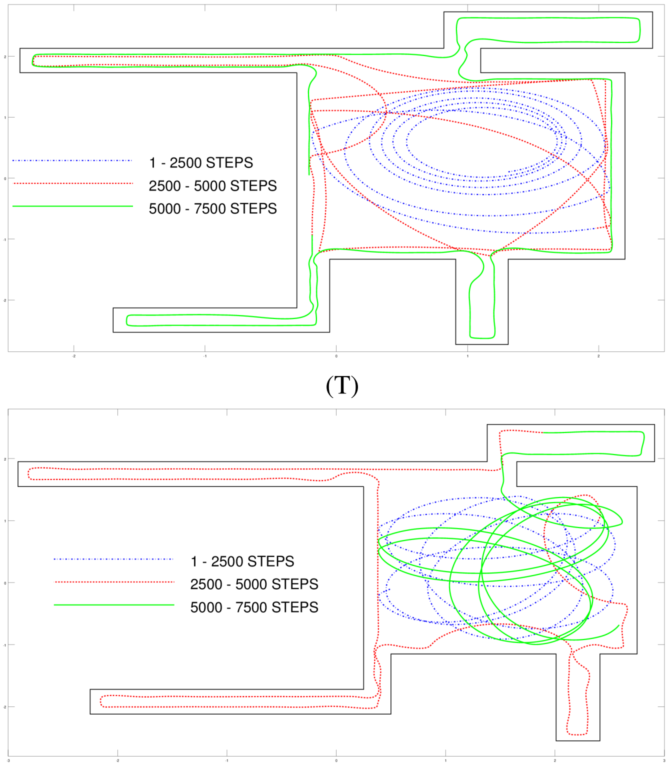
The evolutionary algorithm used consisted in a initial population of 20 randomly generated genotypes, which encoded the connection weights and biases of 20 corresponding individual robots (each parameter was encoded by 8 bits and normalized in the range [5.0, +5.0]). The fitness of each trial was calculated by counting the percentage of 2020cm portions of the environment that were visited from the robot at least once during the trial. The total fitness was calculated by averaging the fitness obtained during the three trials. All individuals were allowed to generate an offspring that was also evaluated for three trials. The 20 offspring were generated by creating a copy of the parent genotype and by mutating each bit with a 2% probability. The genotype of offspring was used to replace the genotype of the worst parents or discarded depending on whether or not offspring outperformed the parents. The genotypes of the initial population were generated randomly. Each evolutionary experiment was replicated 20 times starting from different randomly generated initial populations.

B. Results

In [10] we demonstrated how behavioral plasticity, i.e., the ability to display and regulate multiple behaviors, can enable the adaptive robots to achieve better performance and that the emergence of behavioral plastic solutions depends on the characteristics of robots neural controllers. In the present work, we are interested in the qualitative behavior of behavioral plastic controllers in order to show how the affordance generation mechanism is an important underlying mechanism that allow the evolution of behavioral plastic controllers.

In the fig. 1 we can see that the best evolved robots from (T) and (R) are able to display at least two well-differentiated behaviors assuming different functions. A first behavior for cleaning the central area, exploratory behavior, and a second one for cleaning the peripheral areas, wall-following behavior.

Before doing the qualitative analysis of the behaviors, it is important to point out that the behavior displayed by an embodied and situated agent is a dynamical process unfolding in time that results from the robot/environmental interactions. This implies that the organization of behavior/s varies at different timescales. Moreover, this implies that the sensory states experienced by the robot at a given time step are co-determined by the actions produced by the robot during



(T)

(R)

Fig. 1. Typical trajectory displayed by the best robots of the two experimental conditions. The portions of the trajectory produced during the first, second, and third part of the trial (i.e. from step 1 to 2500, from step 2501 to 5000, and from step 5001 to 7500, respectively) are shown with different colors and line style.

previous robot/environmental interactions. If we use the term affordance introduced by [1] to indicate sensory states that elicit the production of specific behaviors, this implies that the affordances are not only extracted through sensors from the internal and/or the external environment but are also generated by the robot itself through actions.

This means that even robots using a simple navigation strategy, for instance going straight when no sensor is active, and turning when the front sensors become activated, at a short timescale (i.e., at a timescale of seconds) tend to exhibit at least two different low-level behaviors: (1) an obstacle-avoidance behavior that consists in turning while the robot detects an obstacle on its frontal side, and (2) a move-forward behavior that consists in moving straight or almost straight while the robot does not detect obstacles in its frontal side. This implies that there exist behavioral plasticity also at this short timescale. These solutions arise often on evolutionary robotics navigation experiments since they play a functional role (i.e., it enables the robot to avoid being stuck and to keep exploring the environments) and also because it is supported by the availability of always-available and easy-to-use affordances. This also implies that plasticity is not a binary but rather a continuous property. The greater the number of behaviors/complexity of the sub-behaviors exhibited by a robot is and the greater is the range of timescales at which the robot exhibits differentiated behaviors, the greater the behavioral plasticity of the robot is.

This ideal situation, however, in which the robot can rely on robust and ready-to-use affordance states only characterises few lucky cases (incidentally, this probably explains why the combination of obstacle-avoidance and navigation behaviors represents a widely used experimental scenario in robotics). In other cases, the affordance states supporting behavior differentiation and arbitration should be extracted through internal elaboration and/or generated through the exhibition of appropriate behaviors. In the rest of this section, we focus exclusively on the longer timescale.

As we have seen in the Fig. 1, both the best robots displayed behavioral diversification at the longer timescale, e.g., it requires the exhibition of an exploration and a wall-following behavior lasting for minutes. In this case, however, the robot cannot rely on ready-to-use affordances that indicate when the robot should display the first or the second behavior and when the robot should switch from one to the other behavior. To achieve this kind of behavioral plasticity, the evolving robots should find a way to: (1) keep producing the same behavior for a prolonged period of time, (2) switch behavior at the right moment, and (3) realize a suitable transition during behavior switch. We will illustrate in details how the evolved robots manage to master these requirements in the different experimental conditions in the next three sub-sections.

1) Producing behaviors for prolonged periods of time:

All evolved robots solve the problem of producing a given behavior for a prolonged period of time by realizing each behavior in a way that ensures that they keep experiencing stimuli of the right type during the execution of that behavior. In cases in which the robots should exhibit two differentiated behaviors, i.e., an exploration and a wall-following behavior, this implies that they should realize the former and the latter behaviors in a way that ensures that they keep experiencing stimuli of type 1 and 2 while they exhibit the former or the latter behavior, respectively, and should react to the stimuli of the two types by producing actions that enable them to keep producing the former or the latter behaviors, respectively. The two classes of stimuli, thus, assume the role of affordances for the first and for the second behaviors, respectively. These affordances are not directly available from the environment, as in the case of the states affording the obstacle-avoidance and move-forward behavior discussed above, but are generated by the robots themselves through their actions (i.e., through the ability to realize each behavior in a way that ensures that the robot keeps experiencing the corresponding affordances). This form of dynamical stability presents some similarities with the one that can be obtained in situated agents through homeokinesis [14], a task-independent learning process that can enable situated robot to synthesize temporarily stable behaviors, though the mechanism and the processes through which this is realized are completely different.

All robots displaying multiple behaviors (i.e., (T) and (R) robots) exploit this affordance generation mechanism. However, the (T) robots also exploit other additional mechanisms that enable the robots to keep producing each behavior for a prolonged period of time. Thus, let us start by describing the strategy used by the best (R) robot that only relies on this affordance generation mechanism.

The best (R) robot realizes the exploration behavior by moving forward far from obstacles and by turning left near obstacles located in its frontal and frontal-right side and realizes the wall-following behavior by moving forward along walls when it perceives an obstacle on its left side and by turning left when the activations of its left-side sensors decrease (see Fig. 1, bottom). By behaving in this way, the robot ensures that it keeps experiencing sensory states of type 1 during the exploration behavior and sensory states of type 2 during the wall-following behavior (where type 1 includes states in which the infrared sensors are not activated or in which the frontal or right infrared sensors are activated and type 2 includes states in which the left infrared sensors are activated). In other words, as we said above, the problem of keep producing the two behaviors for prolonged period of time is solved by producing each behavior in a way that ensures that the robot keeps experiencing stimuli affording the same behavior (i.e., stimuli that elicit actions which lead to the production of the same behavior).

In (T) robots, the cue provided by the temporal neuron co-determines the behavior produced by the robot and, consequently, is used to keep producing the current behavior for a prolonged period of time. Indeed, whether the robot keeps producing the exploration behavior or switches to the wall-following behavior also depends on the state of the temporal neuron. On the other hand, the state of the time neuron influences the duration of the exploration behavior only during a critical phase, i.e., when the state of the time neuron is smaller than 0.6 and greater than 0.4 (see Fig. 1, top). During the rest of the trial, the ability of the robot to keep producing the exploration behavior or the wall-following behavior relies on an affordance generation mechanism analogous to that described above for the best (R) robot. Interestingly, in the case of the best (T) robot, the temporal neuron is also used to progressively vary over time the way in which the exploration behavior is realized so as to regulate the probability that the robot keeps experiencing sensory state affording the execution of this behavior. Indeed, by initially moving forward and turning left of several degrees, the robot eliminates, completely, the possibility to encounter a wall on its left side (i.e., the possibility to experience stimuli affording the alternative wall-following behavior). Then, by moving forward and progressively reducing the angle of turn over time, the robot becomes progressively kinder with respect to the possibility of experiencing stimuli affording the wall-following behavior. This brings us to the question of how robots manage to switch behavior.

2) Switching between alternative behaviors: The problem of switching between different behaviors is also solved through affordance generation. To understand how robots can act in a way that enables them to both experience stimuli affording the current behavior and stimuli affording the alternative behavior, we should reformulate the definition of affordance generation in probabilistic terms. Evolved robots solve the problem of producing a given behavior for a prolonged period of time and the problem of switching behavior by realizing behaviors in a way that ensures that they keep experiencing stimuli affording the current behavior with a given high probability and stimuli affording the alternative behavior with a given low probability, respectively.

All evolved robots solve the problem of keep producing the same behavior for a prolonged period of time and the problem of switching behavior in this way. However, the (T) robots also rely on additional complementary mechanisms, as we illustrate below.

In the case of the best (R) robot, the switches from the exploration behavior to the wall-following behavior occur when the robot encounters a wall on its frontal-left side during the execution of the exploration behavior (see Fig. 2, top), a situation that occurs with a low probability for the reason described in the previous section. Overall, this means that the exploration behavior is realized in a way that the robot keeps experiencing stimuli affording the exploration behavior most of the time, while occasionally experiencing stimuli affording the alternative behavior. Clearly, this is an example of how the simultaneous evolution of form and regulation can be solved. The same mechanism is responsible for behavior production (i.e., the prolonged production of the same behavior) and for behavior switch. This affordance generation strategy enables the best (R) robot to switch from the exploration to the wall-following behavior at the optimal moment on the average but with a high variability among trials (the robot switches at 2.99±1.02min, 500 trials). The high variability negatively impacts on performance since it often leads to situations in which the time dedicated to the two behaviors is unbalanced. The problem is particularly serious when the switch from the exploration behavior to the wall-following behavior occurs too early, since circling along the periphery of the environment for more than one lap is useless. This probably explains why the best robot of the (R) experimental condition also developed an ability to switch back from the wall-following behavior to the exploration behavior when the robot encounters a wall frontally after exiting from a peripheral corridor (see Fig. 2, bottom). This latter ability is lacking in the best robots of the other (R) replications that consequently achieved lower performance. In other words, the best (R) robot is capable of displaying reversible behavioral switch.

In the case of the robot evolved in the (T) experimental condition, the switch is regulated by both the stimuli experienced by the robot (i.e., by affordance generation) and by the cue provided by the robots internal clock. This double regulation enables the best (T) robot to carefully balance the time allocated to the two types of behavior and to reduce the variability among trials (i.e., the transition occurs 3.17±0.11min, 500 trials). The double regulation process was observed in the analysis of the trajectories produced by the robot during a series of trials in which the robot always starts

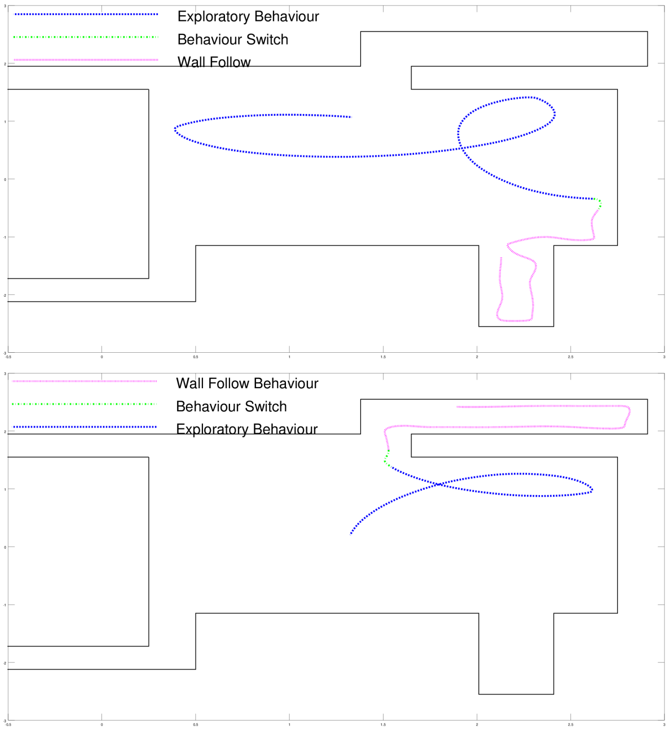


Fig. 2. Illustration of how the best (R) robot switches from the exploration to the wall-following behavior and vice versa (left and right, respectively)

from the same position and in which the orientation of the robot and the state of the time neuron are systematically varied (data not shown, see [10]). Whether the robot switches or not to the wall-following behavior depends both on the state of the internal clock and on the state of the infrared sensor that the robot experiences when it approaches the wall. Overall, this shows that whether the switch between the two behaviors occurs or not depends both on the state of the internal clock and on the way in which the exploration behavior is realized which, in turn, influences the type of stimuli that the robot experiences. As mentioned above, in the case of the best (T) robot, the state of the time neuron is not only used to regulate the probability that the robot switches behavior directly (the probability that the robot initiates a wall-following behavior in a given relative position in the environment) but is also used to regulate the way in which the exploration behavior is realized which, in turn, influences the probability that the robot will later experience stimuli affording the wall-following behavior.

3) Realizing suitable and effective behavior transitions: The large variability in the transitions presented by the best (R) robot is strongly reduced by the (T) robot granting them a performance advantage over (R). This timely transition is possible through the use of preparatory actions based on the internal clock. As presented above, the (T) robot progressively changes its behavior which not only makes the exploratory behavior more effective, but also changes the probability of generating the affordance for the wall-following behavior as time goes by. Actually, this affordance generation complemented through the specific preparatory action of getting closer to the wall in the critic period,i.e., at intermediary values of the internal clock (as can be seen in the middle part trajectory in Fig. 1, top).

III. COGNITIVE OFFLOADING

Developments in psychology, neuroscience, linguistics, robotics and philosophy have clarified that cognition cannot be studied properly without taking into sufficient account the role of the body, action and the external world [15], [16], [17], [18], [19], [20], [21]. The agents body and the environment in which it is situated provide a great deal of structure that is used to operate appropriately. Consequently, in many cases the internal capabilities required are much simpler than those previously hypothesized within disembodied accounts. For example, moving around in a city does not necessarily require an elaborate representation of the citys layout. The ability to recognize a limited number of turning decision points combined with the ability to just follow the street between decision points might suffice [22]. Similarly, baseball players do not need to estimate the trajectory of the flying ball to be intercepted through complex calculations. They can simply adjust their running speed so as to maintain the relative angle between their eyes and the ball constant [23].

Exploitation of the information that can be extracted directly from the environment and of the effects of situated actions do not only affect the agents low-level capabilities. Embodied and embedded strategies (like those described above) co-exist and interact with different strategies that are less dependent on agent/environmental interactions and more dependent on internal processes at all levels of organization [19]. However, the relation and the interaction between strategies and capabilities that differ in that respect have not yet been investigated. Consequently, the question of how these different types of strategies can be integrated from an operational and developmental perspective is still open. In particular, one important question that needs to be answered is the following: Is cognition truly seamless implying a gentle, incremental trajectory linking fully embodied responsiveness to abstract thought and off-line reason? Or is it a patchwork quilt, with jumps and discontinuities and with very different kinds of processing and representations serving different needs ? [19].

In [24] we investigated the relation between the development of reactive and cognitive capabilities. In particular we demonstrated how the development of reactive capabilities promotes the development of cognitive capabilities. For this purpose, we defined cognition as the ability to integrate sensory-motor information over time into internal states and to use these internal states to regulate the way the agent reacts to perceived stimuli. The term cognition is often used in a more restricted way. In the above definition, we focus on a fundamental capacity that is at the basis of all cognitive capabilities (e.g. perception, memory, attention, decision-making, reasoning, language, etc.).

Specifically, the reactive capabilities studied are related to one aspect that is particularly relevant from the viewpoint of the relation between reactive and cognitive strategies which is called cognitive offloading. In other words, the possibility of offloading cognitive work onto the environment [25], [26], [27]. In particular, the possibility of acting so as to encode the states that can be used to regulate the agents behavior onto the external environment and/or onto the relation between the agent and the environment. In fact, the possibility of encoding the required states internally or externally suggests that cognitive strategies and reactive strategies (that rely on cognitive offloading) represent two alternative but functionally equivalent modalities. A simple example of cognitive offloading related to everyday human life is crossing two fingers so to avoid forgetting to perform a certain action [27], [28], [29]. An example of cognitive offloading realized in a robotic scenario consists of dropping markers in the environment that are used to find the way back to the home location [30].

In this section we present an analysis of the qualitative behavior of the evolved agents in order to show how the affordance generation mechanism allowed the use of cognitive offloading as preparatory actions for making a decision in a delayed-response task. As demonstrated in [24] the cognitive offloading mechanisms evolved promoted the posterior development of solutions relying also on the use of internal information.

A. The method, the task and the robot

The robot and the evolutionary method were the same presented in the previous section, the main changes are the task and the neural controller. The task consisted of a delayed-response task, more specifically a double T-Maze (see fig. 3) that included four different destinations and two types of stimuli that could be experienced in four different corresponding patterns (left-left, left-right, right-left, right-right). The robot starts at the bottom of the central corridor and based on the stimuli perceived at the beginning of this corridor, it has to properly turn at the junctions in order to arrive to the target area.

Evolving robots are provided with a continuous recurrent neural network controllers (see [31], [32]). The sensory layer includes eight sensory neurons that encode the average activation state of eight groups of three adjacent infrared sensors, six neurons that encode the average activation of the rotating scanner over sixty degrees, and eight neurons that encode the percentage of green and blue pixels detected in four ninety degrees sectors of the visual field of the camera. These input neurons are fully connect both to a continuous recurrent hidden layer with 6 neurons, and to 2 motor output neurons. The activation function used for each neuron was a standard sigmoid. For more detailed information about the method, the task and the robot see [24].

B. Results

The trajectories produced by the best evolved robot can be seen in Fig. 3, this robot achieved a performance of 96.3% in a post-evaluation test of 600 trials. In fact, the behavioral analysis of this robot indicates that the experienced signals are used to systematically alter the positions assumed by the robot at the end of the central corridor (Fig. 3). These positions influence the type of stimuli the robot experiences at the first junction which, in turn, determine whether the robot will turn left or right at the junction. The position of the robot at the end of the first corridor also influences how the turning is realized, i.e., whether the robot produces a tight turn or a wider one, and consequently the position assumed by the robot in the second corridor. Indeed, after experiencing the right-right signals the robot assumes the right most position at the end of the first corridor and then a right position in the second corridor. By contrast, after experiencing the right-left signals the robot assumes the central position at the end of the first corridor and then a left position in the second corridor. This ability to differentiate the relative position assumed in the second corridor on the basis of the position assumed at the end of the first corridor enables the robots to turn in the appropriate direction also at the second junction. The same things happens when the robots travel towards the other two left destinations.

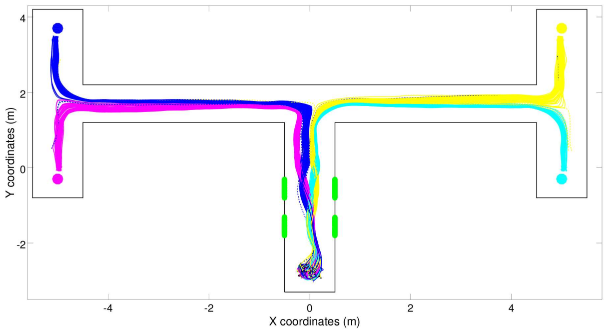


Fig. 3. Trajectories produced by the best robot over 300 trials. Full and dashed lines indicate successful and unsuccessful trials, respectively. The color indicates the corresponding target destination (magenta: left-bottom, blue: left-top, cyan: right-bottom, and yellow: right-top).

The four behaviors displayed by this robot (indicated by the trajectories shown in magenta, blue, cyan and yellow in Figure 3) are dynamical processes that arise from the robot/environmental interactions and that converge toward four fixed-point attractors. These basins of attraction enable the robot to reach four different destinations without varying the way it responds to perceived stimuli (i.e. by using a reactive strategy that always responds in the same way to the same stimuli independently from the stimuli experienced before). This can be explained by considering that the way in which the robot reacts to perceptual stimuli and the way in which perceptual stimuli change (as a function of the action performed by the robot and of the characteristics of the local portion of the environment) ensure that the robot keeps moving towards the correct destination while remaining in the current basin of attraction. To solve the problem, therefore, the robot only needs to enter into the appropriate basin of attraction in the first corridor while it perceives the green stimuli.

So the selection of the appropriate behavior (i.e. the convergence toward the appropriate basin of attraction) is the result of the bifurcation process that occurs in the first corridor and that is regulated by perception of the green stimuli. In other words, it is the result of the fact that while the robot travels along the first corridor, it varies its position and orientation on the basis of the perceived green stimuli in a way that ensures that at the end of the first corridor the robot assumes a position and orientation that enable it to enter in the right basin of attraction.

At this point, the use of the affordance generation mechanism is clear also in this task. Following the same principle presented in the previous section, that the stimuli experienced by the robot in a given time step is co-determined by the actions produced by the robot during previous robot/environmental interactions. In this particular task, we see that the position of the robot at the junctions is determined by its actions at the time it encounters the green stimuli. This sort of preparatory action creates a stimulus differentiation at the time a turn has to be made, facilitating the decision making process.

This possibility of encoding information on external variables related to the agent/environment relation is crucial for developing cognitive capabilities. The demonstration of this fact is beyond the scope of this paper, for detailed results and analysis see [24]. The possibility to operate either relying on cognitive offloading through the affordance generation mechanism, or relying on internal information integrated over time guarantees the synthesis of a robust and effective solution for the studied task.

IV. CONCLUSION

In this paper we described two sets of experiments that require the exhibition of differentiated behavior. More specifically we described a series of experiments in which a robot was evolved for the ability to vacuum clean variable environments and for the ability to navigate to the appropriate destination by alternating turning/left or turning/right behavior with move straight behaviors. The analysis of the results indicates that in both cases the evolved robots rely on an affordance generation mechanism.

More specifically, the results described in section II indicate that the mechanisms that support the evolution of behavioural plastic solutions characterized by multiple differentiated behaviours are the ability to perceive affordances (i.e. perceptual states encoding opportunities for behaviours) and the ability to realize smooth and effective transitions between different behaviours. The perception of affordance constitutes a prerequisite for the possibility to develop differentiated behaviour and for the possibility to effectively arbitrate them, i.e. selecting the behaviour that is appropriate for the current robot/environmental context and regulating the duration of each behaviour. The required affordances are generated by realizing each behaviour in a way that ensures that the robot keeps experiencing sensory state affording the current behaviour with a given high probability and sensory states affording alternative behaviours with a given low probability.

Moreover, the results described in section III indicates that the problem of generating an articulated behaviour that involve the production of a series of differentiated sub-behaviours over time is solved by offloading in the robot/environmental relationship the information that can be used to determine the behaviour that should be produced by the robot during the different navigation phases.

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REFERENCES

[1] J. J. Gibson, *The ecological approach to visual perception*. Houghton Mifflin, 1979.

[2] A. Chemero, *Radical embodied cognitive science*, ser. A Bradford Book. Cambridge, Mass.: MIT Press, 2011, oCLC: 698839160.

[3] M. J. West-Eberhard, *Developmental Plasticity and Evolution*. Oxford ; New York: OUP USA, Feb. 2003.

[4] P. E. Komers, "Behavioural plasticity in variable environments," *Canadian Journal of Zoology*, vol. 75, no. 2, pp. 161–169, Feb. 1997. [Online]. Available: http://www.nrcresearchpress.com/doi/abs/10.1139/z97-023

[5] C. R. Gallistel, *The Organization of Action: A New Synthesis*. L. Erlbaum Associates, 1980.

[6] D. Otte, "Simple Versus Elaborate Behavior in Grasshoppers an Analysis of Communication in the Genus Syrbula," *Behaviour*, vol. 42, no. 3, pp. 291–321, Jan. 1972.

[7] R. A. Hinde, *Animal behavior: a synthesis of ethology and comparative psychology*. New York, NY, US: McGraw-Hill, 1966.

[8] R. R. Jackson and R. S. Wilcox, "Spider Flexibly Chooses Aggressive Mimicry Signals for Different Prey By Trial and Error," *Behaviour*, vol. 127, no. 1, pp. 21–36, Jan. 1993.

[9] S. Nolfi and D. Floreano, "Learning and Evolution," *Autonomous Robots*, vol. 7, no. 1, pp. 89–113, 1999. [Online]. Available: http://link.springer.com/article/10.1023/A:1008973931182

[10] J. T. Carvalho and S. Nolfi, "Behavioural plasticity in evolving robots," *Theory in Biosciences*, pp. 1–16, Jul. 2016. [Online]. Available: http://link.springer.com/article/10.1007/s12064-016-0233-y

[11] M. Bonani, V. Longchamp, S. Magnenat, P. Retornaz, D. Burnier, G. Roulet, F. Vaussard, H. Bleuler, and F. Mondada, "The marXbot, a miniature mobile robot opening new perspectives for the collective-robotic research," in *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct. 2010, pp. 4187–4193.

[12] G. Massera, T. Ferrauto, O. Gigliotta, and S. Nolfi, "FARSA: An Open Software Tool for Embodied Cognitive Science," in *Advances in Artificial Life, ECAL 2013*. MIT Press, Sep. 2013, pp. 538–545. [Online]. Available: http://mitpress.mit.edu/sites/default/files/titles/content/ecal13/978-0-262-31709-2-ch078.pdf

[13] ——, "Designing Adaptive Humanoid Robots Through the FARSA Open-source Framework," *Adaptive Behavior - Animals, Animats, Software Agents, Robots, Adaptive Systems*, vol. 22, no. 4, pp. 255–265, Aug. 2014. [Online]. Available: http://dx.doi.org/10.1177/1059712314536909

[14] R. Der and G. Martius, *The Playful Machine: Theoretical Foundation and Practical Realization of Self-Organizing Robots*. Springer Science & Business Media, Jan. 2012.

[15] F. J. Varela, E. Rosch, and E. Thompson, *The Embodied Mind: Cognitive Science and Human Experience*. Cambridge, MA: Mit Press, Feb. 1993.

[16] E. Thelen and L. B. Smith, *A Dynamic Systems Approach to the Development of Cognition and Action*. Cambridge, MA: MIT Press, Jan. 1996.

[17] R. F. Port and T. V. Gelder, *Mind as Motion: Explorations in the Dynamics of Cognition*. Cambridge, MA: MIT Press, 1995.

[18] R. Pfeifer and J. Bongard, *How the Body Shapes the Way We Think: A New View of Intelligence*. MIT Press, Oct. 2006.

[19] A. Clark, "An embodied cognitive science?" *Trends in Cognitive Sciences*, vol. 3, no. 9, pp. 345–351, Sep. 1999. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1364661399013613

[20] J. R. Stewart, O. Gapenne, and E. A. D. Paolo, *Enaction: Toward a New Paradigm for Cognitive Science*. Cambridge, MA: MIT Press, 2010.

[21] A. Clark, *Being There: Putting Brain, Body, and World Together Again*. MIT Press, Jan. 1997.

[22] F. Keijzer, "Representation in dynamical and embodied cognition," *Cognitive Systems Research*, vol. 3, no. 3, pp. 275–288, Sep. 2002. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1389041702000438

[23] M. K. McBeath, D. M. Shaffer, and M. K. Kaiser, "How baseball outfielders determine where to run to catch fly balls," *Science (New York, N.Y.)*, vol. 268, no. 5210, pp. 569–573, Apr. 1995.

[24] J. T. Carvalho. and S. Nolfi, "Cognitive offloading does not prevent but rather promotes cognitive development," *PLoS ONE*, vol. 11, no. 8, pp. 1–25, 08 2016. [Online]. Available: http://dx.doi.org/10.1371%2Fjournal.pone.0160679

[25] M. Wilson, "Six views of embodied cognition," *Psychonomic Bulletin & Review*, vol. 9, no. 4, pp. 625–636, 2002. [Online]. Available: http://link.springer.com/article/10.3758/BF03196322

[26] N. Maeda, "External working memory and the amount of distributed cognition," in *Proceedings of the 34th Annual Meeting of the Cognitive Science Society*, 2012, pp. 1954–1959. [Online]. Available: http://mindmodeling.org/cogsci2012/papers/0342/paper0342.pdf

[27] E. F. Risko and T. L. Dunn, "Storing information in-the-world: Metacognition and cognitive offloading in a short-term memory task," *Consciousness and Cognition*, vol. 36, pp. 61–74, Nov. 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1053810015001221

[28] S. J. Gilbert, "Strategic offloading of delayed intentions into the external environment," *Quarterly Journal of Experimental Psychology (2006)*, vol. 68, no. 5, pp. 971–992, 2015.

[29] ——, "Strategic use of reminders: Influence of both domain-general and task-specific metacognitive confidence, independent of objective memory ability," *Consciousness and Cognition*, vol. 33, pp. 245–260, May 2015.

[30] J. R. Chung and Y. Choe, "Emergence of Memory in Reactive Agents Equipped With Environmental Markers," *IEEE Transactions on Autonomous Mental Development*, vol. 3, no. 3, pp. 257–271, Sep. 2011.

[31] R. D. Beer and J. C. Gallagher, "Evolving Dynamical Neural Networks for Adaptive Behavior," *Adaptive Behavior*, vol. 1, no. 1, pp. 91–122, Jun. 1992. [Online]. Available: http://adb.sagepub.com/content/1/1/91

[32] O. Gigliotta and S. Nolfi, "On the Coupling Between Agent Internal and Agent/ Environmental Dynamics: Development of Spatial Representations in Evolving Autonomous Robots," *Adaptive Behavior - Animals, Animats, Software Agents, Robots, Adaptive Systems*, vol. 16, no. 2-3, pp. 148–165, 2008. [Online]. Available: http://dx.doi.org/10.1177/1059712308089184