More from the Body: Embodied anticipation for swift re-adaptation in neurocomputational cognitive architectures for robotic agents

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Abstract. The coupling between a body (in an extended sense that encompasses both neural and non-neural dynamics) and its environment is here conceived as a critical substrate for cognition. We propose and discuss the plan for a neurocomputational cognitive architecture for robotic agents, so far implemented in its minimal form for supporting the behavior of a simple simulated robotic agent. A non-neural internal bodily mechanism (crucially characterized by a time scale much slower than the normal sensory-motor interactions of the robot with its environment) extends the cognitive potential of a system composed of purely reactive parts with a dynamic action selection mechanism and the capacity to integrate information over time. The same non-neural mechanism is the foundation for a novel, minimalist anticipatory architecture, implementing our bodily-anticipation hypothesis and capable of swift re-adaptation to related yet novel tasks.

Keywords: cognitive robotics; embodied cognition; dynamic systems; neuromodulation; anticipation; multiple time scales; bio-regulation.

1 Introduction: an age of scientific synthesis

In the history of humanity we observe ages that prove extremely prolific in the production of novel ideas. Analogous to most natural phenomena, the social process of cultural evolution seems to proceed through cycles. Phases of high intellectual achievements are followed by periods of sedimentation, when new understanding, in the form of brand new theories, seeds the social community, becoming accepted and exploited in terms of innovative applications and technologies. It would be insensitive to deny that the 20th century, so politically questionable, was characterized by a terrific intellectual enrichment in the scientific field. The science of the mind participated in this cultural process with obvious implications due to its striking immaturity. Nevertheless, a large body of theoretical work has been proposed and now urges a systematic effort of synthesis in order to introduce actual progress.

A common thread links several different sources of inspiration that strike us as researchers in cognitive systems. It can be formulated as: the whole is more than
(and qualitatively different from) the sum of its parts. Far from esoteric or vague, this assumption received sound mathematical formalization by the science of non-linear dynamic systems (e.g., see [1,2,3]) and pragmatic validation by physics in plenty of important findings, currently resulting in popular applications. It constitutes one of the core theoretical milestones of contemporary science and induced a more systemic attitude in the scientific study of complex systems, as opposed to the traditional reductionist approach 1.

The very same idea, in the form of intuition, permeates the general spirit of gestalt psychology [4,5] and ecological psychology [6], and the work of influential psychologists and philosophers like Piaget, Vygotsky and Merleau-Ponty. It also appears, with a more structured approach, in the seminal work of early cybernetics [7,8,9]. In its modern form, it originated a whole new scientific paradigm, namely the Dynamic Systems approach to the study of human and animal cognition (e.g., [10,11,12,13]).

Although perhaps stating the obvious, it is worth making explicit the relation between cognitive architectures and the phenomenon of biological cognition. Why, in the first place, should researchers interested in cognitive systems be interested in biological cognition? The quick answer is that, to date, nature offers by far the most remarkable examples of cognitive systems, in terms of performance, autonomy, generality and so on. Admittedly, this might sound naive. Yet, scratching beneath the surface of such an answer, we start realizing that biological cognition is deeply entangled in a specific form of organization of the living [14,15,16]. The exploration of this specificity might offer new perspectives and new understanding on cognition as a general phenomenon, as well as offering new ways to approach its practical implementation.

The remainder of our paper is organized as follows. Section 2 introduces the role of the body and its environment in the enactment of a cognitive process. The following two sections are linked to recent experimental results obtained in our Lab. Section 3 demonstrates the modulatory effect of non-neural bodily dynamics on the production of adaptive behavior. In Section 4, after introducing the theoretical context for anticipatory behavior in natural and artificial agents, we argue that non-neural internal dynamics can be powerfully involved in the anticipatory process. In the discussion, Section 5, we will critically analyze the ideas presented. The final Section 6 recapitulates the main contributions of our paper.

1 Our argument is not aimed at the trivialization of the scientific importance and achievements of the reductionist method. Indeed, the divide et impera approach proved as a powerful tool for scientific analysis. Nevertheless, it was culturally determined and fully justified by the computational limitations of the past centuries. The method is based on the decomposition of the system in elementary parts that are separately analyzed and finally recomposed. However, not all explanations can be reductionistic, and new phenomena can emerge at the global level of organization that cannot be foreseen at the level of isolated components. Nowadays, the large availability of computers endowed with appropriate computational power allows us to perform a non-linear analysis, that overcomes some of the intrinsic limitations of the linear methods, thus producing results of extended validity.
2 On coupling bodies, environments and finding a (scientific) place for emotions

Direct consequence of a more systemic view of cognition is the critical revision of the roles of body and environment in the cognitive process [17]. From mere input-output devices in a disembodied theory of the mind, their role has received a crucial upgrade. The systemic view conceives body and environment of the cognitive agent as constitutive of a largely distributed cognitive process, backing the brain in its operation by constantly offering cognitive support and tools [18]. Thus, the cognitive process is the result of the activity of the brain-body-environment triad, whose components, coupled in a global dynamic, are equally necessary to the creation of the mental process [11,19,20]. The body can be interpreted as an enduring pre/post-processor of neural information [19], and its interaction with the environment stores a wealth of knowledge about the "how to" of a cognitive activity [21]. Research in embodied and situated cognition investigates in theoretical and experimental terms the role of the body and of the environment in the cognitive process [22,23,24,25]. Therefore, these approaches tend to conceive and analyze cognition as a broadly distributed process, emphasizing attunement in cognitive aggregates, rather than in localized and proprietary processes. In this light cognitive robotics seems like the perfect candidate for the dirty work of generating an experimentally grounded synthesis, as it forces researchers to take very seriously the interplay among coupled bodies, control systems and environments [26,27,16].

Alongside the indisputable role of the body, projected towards its environment, there is a less obvious, less visible and consequently often neglected internal dynamic component of the body. We are referring to the plethora of background bio-regulatory mechanisms, aimed at the maintenance of a viable metabolic balance necessary for the organism’s survival. An increasing number of researchers investigate the potential cognitive role of this hidden dynamic. Early philosophical insights by, for example, Baruch Spinoza and the seminal work by William James [28], gave inspiration to contemporary neurologist Antonio Damasio for a view of cognition that is deeply rooted in a hierarchy of bodily processes and consistent with state-of-the-art neurological findings [29,30,31]. According to Damasio, emotions emerge from the complex hierarchy constituted by levels of automated homeostatic regulation - the basic evolutionary organization for the maintenance of the living organism (ref. Figure 1). Metabolic regulation (e.g., endocrine/hormonal secretion, muscle contraction facilitating digestion), basic reflexes (e.g., basic tropism or taxes) and the immune system constitute the lower level of the machine. At a higher hierarchical level come behaviors related to pleasure/reward or pain/punishment (e.g., feeling pain triggers a specific pattern of protective behaviors), drives and motivations (e.g., hunger, thirst, curiosity, play and sex). One step further in the hierarchy we find emotion proper (e.g., joy, sorrow, fear) as a subset of the homeostatic reactions that is triggered by emotionally competent stimuli (ECS), either actual or imagined. ECS are such in virtue of the evolutionary history or of the ontogenesis of the organism. Finally, at the top of the hierarchy, from the current body state mapped in
cortical body maps emerge (either conscious or unconscious) feelings. Feelings are perceptions of a certain state of the body, together with the perception of a certain mode of thinking and of attuned thoughts with certain themes. Similar approaches constitute the core motivations of somatic theories of emotions [32,33,34].

Conceiving emotions in physical (rather than mental) terms constitutes the entry point for their appealing robotic rendition. Domenico Parisi points to the necessity of a deep investigation of the relation between the control system and what happens inside of the body [27]. The emphasis on bodily parameters affecting bodily processes can be traced back further to the cyberneticist W. Ross Ashby, who focused on the behavioral consequences of a set of essential variables, critical to the organism’s survival (e.g., sugar concentration in the blood and body temperature). The organism’s implicit necessity to restrict their range within viable limits determines the random creation of new adaptive behaviors [8] (for an introductory discussion, see [26]). In order to implement robots endowed with genuine autonomy, agency, intentionality and grounded in a meaningful relation to their environment, focusing on the cognitive implications of bioregulatory processes might be a promising direction for scientific explorations [16,35,36,37,26]. Indeed, internal robotics in the here and now is not sufficient for modeling emotions. It requires the presence of emotionally competent stimuli that derive from the coupling of body and environment in an adaptive history of interactions. Consequently, a somatosensory theory of emotions only makes sense in a broad systemic perspective, as the result of the complex interactions between body and environment.
As a matter of fact, all the above is in apparent contrast to the traditional perspective on AI and cognitive science, i.e., the presumption that the description of the world in terms of related symbol structures and logical processing on such structures is the necessary and sufficient condition for general intelligent action by appropriate instances of physical systems [38]. A concept mapped in cognitive robotics onto the linear sense-plan-execute scheme [39], and conceptually akin to the functional approach of traditional computational neuroscience, focused on specific and decontextualized subdomains. In an intuitive image by Chiel, the change in perspective is as significant as the passage from the central control exerted by a musical director on a classic orchestra, to the self-governed coordination of several musicians in a jazz ensemble [19].

3 Bodily neuromodulation: a minimalist experiment

In order to start assessing the potential cognitive relevance of non-neural internal dynamics in a simple robotic agent, we recently carried out a series of computer simulations, reported in detail in [40,41]. A simulated standard Khepera robot was free to move in an empty square arena. It received its sensory input from an array of light and infra-red sensors. Two identical light sources, centrally located in the arena, provided the environment with a stationary light gradient. The robot could also sense its simulated energy level (e.g., the level of a battery charge), subject to linear decay, from a maximum value down to zero. This sensor has a biological analog in glucose neurons involved in glucose homeostasis [42], whose firing rate is correlated to changes in the local concentration of glucose. The entering of an invisible area centered under one of the two light sources, randomly selected for each replication, would provide an instantaneous full energy recharge. A simple feedforward artificial neural network (ANN) with no hidden layers would generate the motor output driving the left and right activation of the two wheels. Its parameters (weights and biases) were evolved using a standard evolutionary algorithm. The fitness function rewarded at each time step the maintenance of positive levels of energy, but this was only accredited when the robot moved outside the recharging area, in order to penalize static behaviors. At the end of each generation, the best individuals were selected for reproduction in order to create the new population for the evolutionary algorithm.

Indeed, the evolved agents performed well on this elementary task. The evolved agent would approach one light. In case it did not receive its reward it would move to the next light and as its energy level jumped to a maximum it would remain dynamically engaged in a to and fro movement across the boundary of the recharging area. The interesting part of the analysis came when, setting aside the evolutionary task, we used the energy level as control parameter of the system [11]. We clamped the energy level to a fixed value for the whole duration of each replication (therefore, during this analysis the energy mechanism

\[\text{We use the term system (here and in what follows) with reference to the triad composed by the coupled robot’s body (including its energy mechanism), its environment and its sensory-motor map (i.e., its ANN).}\]
was frozen and the recharging area absent in the replication), and systematically explored the robot’s behaviors for values ranging from empty to full in the different replications. Consequently, we were able to map the behavioral repertoire of the evolved agent as a function of its energy level. We observed three main classes of behavioral attractors (ref. Figure 2, left panels): exploratory behaviors (i.e., the agent engages in large loops from one light source to the other - attractor class 'A'), local behaviors (the agent’s loops are closely bound to a single light source - class 'C') and hybrid behaviors (combining the characteristics of both exploratory and local attractors - class 'B'). These three behavioral attractors proving to be neatly distributed as a function of the energy level. Exploratory behaviors dominated the lowest range of energy levels, whereas local behaviors the highest ones (Figure 2, right panel). For intermediate levels of energy we found the prevalence of hybrid behaviors.

Details on how the different behavioral attractors effectively amalgamated in order to accomplish the evolutionary task are given in Montebelli et al. [Montebelli:2008, Montebelli:2007]. What is remarkable is that:

1. As the energy level was left free to follow its natural dynamics, it constituted an effective, self-organized dynamic action selection mechanism. The appropriate classes of behavioral attractors that contributed to an effective behavior were locally available to the agent, depending on its energy level. For example (ref. Figure 2, right panel), an energy level of 0.7 led to the expression of attractor C3 (in 70% of the replications), C1 (20%) or B1 (10%). The actual selection of the specific attractor depended on the basin of attraction in which the combination of the starting position and the integrated effects of noise induced the system dynamics.

2. The system, although composed of extremely simple, purely reactive components, was able to integrate information over time, with no explicit representations or memory needed. We argued [43] that this capacity was derived from the interplay between the slower time scale of the energy level decay and the fast sensory-motor dynamics during the artificial evolution of the system parameters (see also Section 5.2).

In sum, we have shown how:

- minimalist non-neural bodily states (e.g., the energy level in our experiment) can modulate the sensory-motor map implemented by an ANN, and thus the general behavior of the simulated robotic agent coupled with its environment;
- this modulation can be exploited as a dynamic action selection mechanism;
- the cooperation between dynamics at different time scales can boost the cognitive potential of the system, in the case of this experiment, endowing a collection of purely reactive components with the capacity to integrate information over time.
Anticipatory dynamics

Operative definitions of anticipatory behaviors stress the role of expectations and belief about the future, on the determination of the current behavior \[44,45,46,47\]. According to Braitenberg, the anticipatory behavior of an organism is dictated by expectations together with desires, thus underlining the role of a meaningful relation between an agent and its environment \[48\]. Much has already been said about the adaptive role of anticipation. In particular it can allow faster and
smoother action execution, facilitate action initiation, improve information seeking, decision making, predictive attention and social interaction [49,46,50,51]. In a recent paper, Butz argues in favor of an anticipatory tension that characterizes biological agents, a natural tendency towards the prediction of the consequences of their own actions and of the dynamics of their environment. This drive might influence both the development of neural structures and bias the agent to anticipatory behavior [52]. In spite of its strongly representationalist orientation (which clashes with some, e.g., enactive, theories of embodied cognition), we consider the author’s general hypothesis quite intriguing, and an affinity with the spirit of our own work in its dynamical view on sensory-motor interactions. In a dynamical system perspective, we suggested that [43]:

... a cognitive system settled on its behavioral attractor constitutes an important instance of an implicitly anticipatory system.

In fact, the engagement with the attractor binds the system to a stable and fully determined dynamic flow. An autonomous and viable dynamic is inherently endowed with anticipatory power. For example, this capacity can be exploited by an agent to navigate in a known environment once all sensory inputs have been discontinued (e.g., see [53]).

4.2 The bodily-anticipation hypothesis

In recent work [43] we extended the framework sketched in Section 3, introducing a general scheme for an anticipatory architecture. In the previous experiment we have seen how non-neural internal dynamics can influence the current modality of engagement of an agent with its environment, i.e., its current behavioral attractor. On the other hand, the current behavior determines the current non-neural internal dynamics (e.g., an effective behavior that satisfies the experimental task maintains the energy level at high levels). This bidirectional relation is expressed by the arrows connecting the blocks labeled SENSORY-MOTOR FLOW and NON-NEURAL INTERNAL DYNAMICS in Figure 3. The former block represents the dynamic of the degrees of freedom relevant to the current sensory-motor engagement between the agent and its environment [11]. Similarly, the latter embeds the relevant non-neural internal dynamics. In parallel, current sensory motor flow and internal dynamics drive a neural emulator block (labeled ANTICIPATION) that is capable, in virtue of its evolutionary history and/or ontogenetic adaptation, of dynamic anticipation in the sense introduced in the previous subsection. The main practical function of this emulator is to tune to the current sensory-motor flow and dynamically perturb the bodily dynamics with the anticipated consequences of the current interaction.

For example, consider a specimen agent, a caveman engaged in a relaxing and innocuous activity, e.g., picking berries in a forest. Out of the blue, an emotional stimulus, e.g., an apparently hungry, massive dinosaur, loudly enters the scene.³

³ The enormous time gap that separates the extinction of dinosaurs and the appearance of the first hominids is part of our example. We want to make sure that our
The caveman’s anticipatory system has no difficulty in predicting the most likely future scenario. The sensory-motor flow correspondent to the ongoing activity (picking berries) must be inhibited and redirected to a more conservative attitude. How will the next viable behavior (e.g., an impulsive fleeing) be selected? In [43] we argued against a direct causal connection with the anticipation block directly eliciting the appropriate fleeing behavior. The main motivation for this rests on the complexity of the search space that the nervous system should face in building the right chain of correlations. We found a much simpler pathway in order to select an adequate behavior, passing through the body. We considered that the anticipatory block might directly influence the non-neural bodily dynamics. In our prehistoric example that means that once perceived the ECS, our caveman’s body would experience as if actually torn by the fangs and nails of the dinosaur. It is likely that the caveman’s evolutionary history and his ontogenesis had already created viable correlations between his dramatic visceral reaction and his fleeing for life, although the specific situation had never been experienced before. This constitutes the essence of our bodily-anticipation hypothesis: the selection of the next viable action is off-loaded onto the bio-regulatory dynamics of the body. Destabilized by the anticipated effect of the current interaction, the body reacts as if actually engaged in such sensory-motor experience. The bodily perturbation elicits reactions, already stored in the potential of bodily and neural interactions, that tend to pull the system back into viable regions.

4.3 A minimalist implementation of the bodily-anticipation hypothesis

In [43] we tested a minimal implementation of our anticipatory architecture. The previous experimental setup was extended to a go-no go task, loosely inspired by [54]. In a first experimental condition nothing changes with respect to the setup described in Section 3: the two light sources would determine a steady gradient of environmental luminance (continuous sensory regime), correlated with a rewarding area randomly located around one of the lights for each replication. However, during each replication this regime alternated according to a fixed schedule with an intermittent sensory regime, where the light sources were obscured every third time step. Under this new condition, the randomly chosen area determined a punishment in the form of an energy leak. As a biological metaphor, this alternation between regimes models the case of a succulent berry whose external pigmentation is different when unripe (and toxic) or ripe (and energizing). Again, the goal consisted in maintaining a positive energy level. We compared the performance of the simple architecture described at the previous section (a feedforward ANN with no hidden layers) with a more articulated one, our novel minimalist anticipatory architecture shown in Figure 4.

In the former case, the evolutionary algorithm adapted the ANN’s weights and biases on the new task, starting either from the final population evolved in...
the previous experiment or from a randomly generated population. In the case of our anticipatory architecture the original ANN (i.e., the simple ANN, whose weights and biases were extracted adopting the final population evolved during the previous experiment) was backed by a pre-adapted mixture of recurrent experts [55,56,57] that processed the sensory flow. During its pre-adaptation, each expert competed with the others in order to generate the best prediction of the sensory state at the next time step. By doing so, two different experts became specialized by tuning to the specific dynamic flow of the two different regimes. Of course the discrimination could be accomplished by much simpler architectures. However, through this design choice we wanted to emphasize the agent’s engagement with the different sensory dynamics in the two sensory regimes. Crucially, in the new architecture the activation of the expert tuned to the intermittent sensory regime triggered a new energy mechanism that overrode the original one. The decay rate of the overriding energy mechanism, rather than hardwired as

Fig. 3. Illustration of the bodily-anticipation hypothesis. During its daily roaming, our agent gets engaged with a potentially noxious interaction. Neural sensory-motor anticipatory dynamics, here conveniently isolated within the global coupled system (box labeled ANTICIPATION), predict the risk by physically perturbing the current non-neural bodily dynamics (NON-NEURAL INTERNAL DYNAMICS) through path a-b and from there, indirectly through a further path b-sm, the actual sensory-motor dynamics (SENSORY-MOTOR FLOW). Following a quick reorganization of its behavioral attractor, our agent is attuned to face the novel danger thanks to the mediation of its body, without any direct influence of anticipation on the selection of the new behavior. Adapted from [43].
before, is the one single parameter adapted by an evolutionary algorithm on the new task.

In short (a detailed analysis is available in [43]), we found that:

1. The systems provided with the anticipatory architecture developed an effective dynamic relation with its environment. They demonstrated a straightforward engagement with the rewarding light source during the continuous sensory regime, and a swift disengagement from the penalizing area during intermittent regime (ref. Figure 5, right). On the other hand, systems provided with the original ANN architectures (both trained from random weights or from the population at the last generation of the previous experiment) tended
to cope with the new task by relying on stereotypical behavioral attractors (Figure 5, left). During the continuous sensory regime they engaged in loops containing both light sources, approaching them close enough to enter their potential rewarding areas. During the intermittent regime they simply relaxed their trajectories with respect to the light sources, keeping at a slightly larger distance from them and consequently clear from the critical area, thus avoiding the punishment. This behavior ignores the effect of the recharging area on the energy level, merely relying on light sensor information and geometrical constraints. Such strategy lacks of robustness, failing as soon as even minimal geometrical variations affect the environment.

2. In the case of the anticipatory architecture, the adaptive process for the new task proved easy, as even a random search could immediately generate agents with satisfactory performance. The evolutionary search was much more problematic for the original ANN, evolved from both starting conditions.

5 Discussion

5.1 On the internal/external dichotomy

We hope to have clarified enough the importance of conceptualizing the phenomenon of cognition as emergent from the coupling of body (with its external morphology and the richness of its internal bio-regulatory mechanisms), nervous system and environment. Within this systemic view, the boundary separating each subsystem is nothing but a useful artifice, functional to the analysis of a complex system dominated by circular relations. Each component participates in the global cognitive process with equal weight. In this sense, even defending the traditional labels of cognitive robotics, where the nervous system would be assimilated the control system, would be problematic. What is controlled? What is doing the controlling? From our example it seems clear enough that different parts of the system mutually influence and are influenced by others (e.g., the energy level can modulate the behavior of the sensory-motor map, that in return affects the energy level).

This tight coupling casts a light an interesting point. What is internal? What is external? Of course we have no difficulty at drawing a line from our distal, anthropomorphic perspective. Nevertheless we can easily argue that a simple agent, even substantially more complex than our elementary model, might find defining such a boundary difficult. We prefer to avoid such dichotomy, as we consider more useful focusing on the global system composed of dynamically interacting parts. At any given time its dynamic balance will be perturbed by stimuli coming from different sources (e.g., the external environment, the agent’s regulatory mechanisms, its nervous system). Each perturbation would produce a consonant reaction of the system’s trajectory in its phase space. Each time, according to the needs of the analysis, we will have to properly redraw the boundary between input and output, cause and its effect. Parisi suggested objective
Fig. 5. Typical spatial trajectories developed by the different architectures during evolutionary adaptation. **top left** - Simple feedforward ANNs tend to deploy a stereotypical strategy, i.e., the robot’s trajectories systematically engage in exploratory loops between the two light sources (small circles to the left and to the right of the arena), entering the recharging area (large circle to the left of the arena) during the continuous regime (continuous line) and slightly relaxing in order to avoid its punishment during the intermittent regime (dashed line). **top right** - On the other hand, the behaviors that tend to emerge from our minimal anticipatory architecture dynamically engage and disengage with the rewarding/punishing area according to the different sensory regime (again, continuous/dashed lines represent the trajectories during continuous/intermittent sensory regimes). For a better resolution of details in the trajectory, the two pictures zoom in the area of main interest surrounding the light sources. **bottom** - The left and right panels exemplify, respectively for a feedforward and an anticipatory architecture, the activation of the two motoneurons (LM and RM), of the light sensors (LS1-8) and of the energy level sensor, during 600 time steps that include a double regime transition (continuous-intermittent-continuous) occurring at time steps 700 and 1000. Adapted from [43].
criteria for partitioning the inside and outside of the body in natural agents, on the grounds of the physical-chemical processes that tend to dominate the two interfaces [27]. Local and specific interactions with fast dynamics, archetypal of physical processes, tend to characterize the interface with the external world. Global and diffused variations with slower time scales, characteristic of chemical processes, tend to take place inside the organisms. Although this is just a generalization, the focus on the different time scales prepares us for the next fundamental observation.

5.2 On the role of multiple time-scales

An obvious objection can be raised against our model. What is it that determines the distinction between neural and non-neural? Could the non-neural internal dynamic be translated into purely neural mechanisms? After all, the work of other groups (e.g., [58,59,60,55]) seems oriented in that direction.

Rather than taking a defensive stance, we will simply redirect the problem and dissolve it in its abstract computational formalization. What we consider crucial to our model is the interplay of the different time scales that characterize the energy mechanism and the other sensory-motor interactions with the environment. In the experiment reported in Section 3, during the artificial evolution of the system, the slower dynamic of the energy level organized the continuous sensory-motor flow in dynamically related events. This endowed the system, composed of purely reactive elements, with the capacity to integrate information over time. On a more general level we formulated the following hypothesis [43]:

... The access to a collection of attuned dynamic sub-systems characterized by intrinsic dynamics at different time scales and the exploitation of such differences, constitutes a powerful mechanism of embodied cognition, widely operating at the different levels of organization of biological cognition. A mechanism providing the cognitive system with the capacity to structure information on events which are relevant to its survival, with no need for explicit representations, memory or consciousness.

With this in mind we can look at the plethora of bio-regulatory phenomena with new eyes. The characteristic time scales of non-neural bodily processes, so different from the normal dynamics of the sensory-motor interactions between an agent and its environment, might provide exactly that dynamical richness that we are advocating. The role of multiple time scales is currently attracting the attention of the scientific community, both in computational neuroscience [61,62] and cognitive robotics [63,58,59,60,64,65,55]. Interestingly, Maniadakis showed how an evolutionary algorithm can self-organize multiple time-scales in a hierarchy of recurrent neural networks [66].

5.3 Experimental evidence for the bodily-anticipation hypothesis

The paths in the general scheme sketched in Figure 3 are actually less arbitrary than they might look at first glance. In the present subsection, we report some
experimental evidence that supports our bodily-anticipation hypothesis, from natural and artificial systems. Our own and related work in cognitive robotics [40,41,58,59,60], motivates the arrows representing the relation between the non-neural internal dynamics and the sensory-motor flow blocks (paths sm-b and b-sm). The claim that in organisms the internal dynamics of the body (e.g., a sudden injection of adrenaline) affect the behavior and that behavior affects the body (e.g., eating or declining the fifth slice of your birthday cake) shouldn’t strike us as bizarre. The capacity of the brain to anticipate sensory-motor correlates (path sm-a) is currently object of intensive research in neuroscience (e.g., see [47]). Examples in cognitive robotics are in [55,60]. Interestingly, Ziemke et al. show how a viable anticipation doesn’t have to be identical to the anticipated phenomenon [53]. An example of how anticipation, i.e., a neural event taking place in the nervous system, might affect the body is given in [30]. The case of a professional musician is reported, who could systematically control her emotional machinery in experimental conditions. Also the seemingly arbitrary switch between the natural energy dynamic and the overriding energy mechanism taking over during intermittent sensory regime is inspired by neurophysiological analogs. False bodily information can sometimes substitute for the actual state, for example, in the case of endogenously altered nociceptive signals. There is an obvious advantage for a wounded organism to ignore the pain when it is fleeing from the danger that produced it [31].

5.4 The bodily path for search-space compression during re-adaptation

Obviously, our bodily-anticipation hypothesis doesn’t deny the possibility of a purely neural pathway between anticipation and sensory-motor flow (the missing path a-sm in Figure 3). Nevertheless, we point to the fact that our minimalist anticipatory architecture drastically simplifies the problem of readapting to a new task. Our proposal focuses on the knowledge that is already embedded in the body after the long history of biological evolution and ontogenesis, and might be exploited during readaptation. The search space during readaptation, characterized by the potentially enormous number of degrees of freedom of an ANN, is reduced by our bodily-anticipation hypothesis to the much smaller dimensionality of the bodily neuromodulators (the energy level in our minimalist example). We believe that the bodily-anticipation hypothesis could be of help at least in virtue of such drastic compression of the adaptive search space, particular in circumstances that require, for example, fast, non-deliberated decision making. Rather than searching the massive space of the system’s degree of freedom for the proper associations supporting the a-sm pathway, the system can limit its exploration to the subspace of the bodily parameters. Pragmatically, even a random search of the appropriate decay rate of the overriding energy dynamic in our anticipatory architecture can swiftly readapt the system to the new problem, whereas such readaptation proves slow with the original architecture. This is obviously related to Ashby’s work on ultrastable agents. A random change in the
behavioral coupling between the agent and its environment is induced whenever a variation of an essential variable threatens its survival [8,26].

An opposite hypothesis seems to be brought forth by Damasio, as he introduces the as-if body loops [30,31]. The emotional machine, deeply grounded in the homeostatic process as we saw in Section 2, is in Damasio’s theory central even to highly logical functions, e.g., decision making [30,67]. Its support can be elicited directly, but after repeated exposure the brain can build consistent causal associations and thus totally bypass the body in the decision process. Nevertheless, Bechara refers to preliminary results showing how in the process of decision making the role of the as-if body loop might be restricted to the most predictable situations (choice under certainty). As the decision drifts from certainty to risk or ambiguity (full uncertainty) the body loop mode of operation, where the bodily mechanisms are directly engaged, becomes prominent [67]. We find this observation perfectly tuned with the intuition inspiring our model.

5.5 Future work

We consider our minimal anticipatory architecture as a promising and complete illustration of our bodily-anticipation hypothesis, although still at its initial stage of development. Nevertheless, together with a few answers, it suggests plenty of supplementary questions. Accordingly, we admit that it needs and deserves further investigation and validation.

Our model might be accused of being an ad hoc arrangement, built on the basis of the previous experiment. In other words, it might be suspected that we embed built-in solutions in our minimalist anticipatory architecture: First, for the arbitrary decision to override the original non-neural internal mechanism (although we have demonstrated in the previous subsection how the same strategy can be found in natural agents); Second, for selecting the decay rate of the overriding energy mechanism as critical parameter to be adapted by the evolutionary algorithm. This is a reasonable criticism. Nevertheless, given the extreme simplicity of our current setup, such design choices were necessary. In our model, simplicity constitutes a deliberate preference. For the sake of a detailed analysis, we try to implement the minimal model capable of producing the phenomenon under study. However, we welcome such objection, confident that it can be more easily confuted given a slightly more complex model, both in terms of task and architecture. In particular, future work will specifically address the implementation of more realistic internal dynamics, inspired by natural metabolic systems as well as by the work on prototypical robotic agents endowed with microbial fuel cells [68].

6 Conclusions

This paper takes on and extends the tradition of a more systemic view of AI research [40,17,16]. Cognition is conceived and analyzed in terms of coupled systems: the body (encompassing both its external morphology and its internal
bio-regulatory mechanisms), the nervous system and the environment constitute a cognitive aggregate. Such interpretation dissolves the internal-external dichotomy into a computational formalization in terms of coordinated multiple time-scales. The cognitive role of the body is taken in account with special and novel emphasis on what happens inside of the body. Biological cognition, more than simply inspiring problems and solutions, is seen as the living implementation of the basic organizational principles of intelligence, still mostly to be unraveled.

In a first experiment (Section 3) we showed how non-neural internal dynamics, following a slow time scale, can modulate the activity of an ANN and consequently the behavior of an agent coupled with its environment. A traditional evolutionary algorithm self-organized this modulation, implementing a dynamic action selection mechanism. The analysis showed how the coordination of multiple time-scales might support the emergence of more sophisticated cognitive capacities, such as the capacity to integrate information over time in a system composed of purely reactive parts. In a second experiment (Section 4) we extended the previous system to an anticipatory architecture, offering a minimalist implementation of the bodily-anticipation hypothesis presented in this paper. The novel architecture provided flexible and dynamic engagement of the agent with its environment, as a swift adaptation to a brand new task was accomplished. Crucially, the search for novel behaviors was drastically simplified, as it operated on the limited subspace of the non-neural internal parameters, rather than on the high dimensional space of the ANN. We believe that this work illustrates promising results in terms of basic organizational principles of cognition that can be explored by minimally cognitive architectures.

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