Anticipation and Future-Oriented Capabilities in Natural and Artificial Cognition

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Abstract. Empirical evidence indicates that *anticipatory representations* grounded in the sensorimotor neural apparatus are crucially involved in several low and high level cognitive functions, including attention, motor control, planning, and goal-oriented behavior. A unitary theoretical framework is emerging that emphasizes how *simulative* capabilities enable social abilities, too, including joint attention, imitation, perspective taking and communication. We argue that anticipation will be a key element for bootstrapping high level cognitive functions in cognitive robotics, too. We thus propose the challenge of understanding how anticipatory representations, that serve for *coordinating with the future* and not only with the present, develop in situated agents[1].

1 Introduction

Anticipation has the potential to become a key issue in designing and developing the artificial cognitive systems of the future. In this paper we review evidence of the roles of anticipation in enabling several cognitive functions, bootstrapping high level cognitive functions, and developing a truly autonomous mental life. We will then argue that understanding anticipation and the development of increasingly sophisticated anticipatory capabilities in natural cognition permits to design artificial anticipatory cognitive embodied systems capable of coordinating their current actions with future outcomes, planning in view of their future needs, and finally formulating and achieving abstract goals.

The situated approach now dominant in the 'new AI' [8,12,56] focuses on reactive mechanisms and agent-environment engagement. It has produced many results, most notably a clarification of the roots of cognition in sensorimotor interactions, and the relevance of embodied, situated and emerging aspects of behavior. At the same time, the emphasis on reactive behavior has drastically reduced the efforts in understanding future-directed behaviors which are widespread in natural cognition. Now that the situated, embodied approach is widely accepted in robotics, it is time to study how to deal in this theoretical framework

[1] Work funded by the EU project **MindRACES** (FP6-511931).

M. Lungarella et al. (Eds.): 50 Years of AI, Festschrift, LNAI 4850, pp. 257–270, 2007.

with the variety of anticipatory behaviors in natural systems, and how they can emerge from more primitive forms of coordination and interaction. We think that a theoretical, empirical and computational investigation of anticipation, and in particular of *simulative* theories [3,33,35], will permit an 'evolutionary leap' in cognitive robotics: from reactive to anticipatory cognitive embodied systems.

A popular definition of anticipatory system is provided by Rosen [64]: *A system containing a predictive model of itself and/or its environment, which allows it to change state at an instant in accord with the model's predictions pertaining to a latter instant.* Behavior which is not simply reactive, or driven by stimuli which are here-and-now, but includes an (implicit or explicit) evaluation of future states of affairs is surprisingly widespread in natural cognition, ranging from sensorimotor interaction to higher-level cognitive abilities only available to humans and possibly to other mammals, such as reasoning, imitation, and social learning. Even behaviors which seem to be simple acts of coordination, in fact, often require an estimation of future states of affairs, as reported for example in the motor preparation of the prey-catching behavior of the jumping spider [68], for compensating the dinamicity of the environment. The influence of expected stimuli for orienting attention has been reported not only in humans (see [2]), but also in pigeons [63] and monkeys [15]. On these basis, models of the visual apparatus including (hierarchical) predictions have been proposed such as *predictive coding* [58]. Increasingly sophisticated capabilities are enabled by the capability to process in advance expected stimuli; for example, Hesslow [35] describes how rats are able to 'plan in simulation' and compare alternative paths in a T-maze *before acting in practice.* Cognitive agents are in fact not only able to exploit *affordances* [31] which are immediately perceptible in the environment. They also act in the world to force it to show its hidden affordances, or even to produce affordances for future use. For example, monkeys can fulfill complex tasks requiring to discard the most immediate affordances of the environment (e.g., going directly toward food), and invent creative ways to use objects such as sticks, breaking *functional fixity* (i.e., the incapacity to exploit an object other than for its default function). Overall, a significant part of natural agents behavior is not present-oriented and stimuli-driven, but future-oriented in nature, and it is motivated by *goals* (i.e., anticipatory representations of future, desired state of affairs that have the potential to prescribe and regulate our actions). This surprising 'inversion' of the direction of causality, from future to present, from goals to actions, is acknowledged in psychology by James's ideomotor principle [39], in cybernetics [65], and in control theory by Adams [1], who argues that goals serve as reference signals "from the future".

Anticipation is an important component of human cognition, too. Damasio [17] describes how during decision making humans engage in 'what-if' simulated loops of interaction with the environment in order to evaluate in advance, via *somatic markers*, possible future negative consequences of their actions. Increasingly complex uses of anticipation exist which lead us to *disengage* more and more from current sensorimotor cycle. Many species can build up and manipulate representations of future courses of events, for example in simulated planning; but typically they do that in order to satisfy their *present* drives or goals. As far as we know, only humans can endogenously formulate novel goals and planning in view of *future* needs; this includes abstract and distal ones such as having fun or becoming famous. Many of our individual and social practices ultimately serve to deal with future needs, and we accept immediately negative outcomes in view of distal positive ones (e.g., studying today for having a job tomorrow) –and the possibility to anticipate oneself could have lead to the capability to coordinate one's own actions in the present and in the future, and to have a sense of 'persisting self'. We can formulate expectations at an increasingly high level of abstraction, and to use them for regulating our actions. For example, we can decide whether or not to apply for a job depending on our expectations about the satisfaction it will provide us, the salary, the free time, etc. Not only we formulate such abstract expectations, but we also can 'match' them with imaginary futures and select among them. Another capability that is typical of human beings is *substitution* [57]. Probably several animal species are able to work on their *internal models* of the phenomena before (or instead of) acting in the real world, but we humans use that ability systematically. A mechanic can assemble and dismantle a motor in his mind before doing it in practice, and an architect can propose us different plans for restructuring our house. Thanks to anticipation it is possible to deal with entities also when they are not indeed present as stimuli: an ability that is crucial for defining an agent's *autonomy* [10]. One striking novelty of human cognition is our tendency to heavily modify and adapt the environment to us, and not only vice-versa. While other species adjust their representations for fitting the actual world, we often *act in the world in order to make it fit our representations of what we want, our goals*. Several animal species have the capability to adapt their environments, such as to build up nests, but typically they do that in a stereotyped way. We humans do not have not this limitation, and have heavily modified our environment to fit our present and future goals. Another feature of human cognition, that is its extremely sophisticated social life, depends on abilities that could be based on anticipation, too, such as perspective taking, imitation, and language [30,38,61].

In [55] we have argued that these capabilities are related. We have an unprecedented capability to endogenously produce internal representations of the (possible) future, and to flexibly manipulate them: selecting which ones to achieve (forming goal states), and deciding how to achieve them by only working on internal representations of our possible actions and their outcomes. Anticipation is the key mechanism for bootstrapping increasingly complex cognitive functions, and for this reason it has to be investigated in a unitary, developmental perspective. In this paper we put forward this perspective. We introduce anticipation from the theoretical point of view, we review how it is addressed both in the empirical literature, and we conclude by proposing the study of anticipation as a crucial challenge for cognitive robotics.

2 Anticipation: Coordinating with the Future

We propose to conceive *the mind as an essentially anticipatory device* [11,55] which serves for future-oriented behavior. It is nowadays widely assumed in the situated cognition literature that adaptive behavior both in natural and artificial systems depends crucially on the dynamics of interactions between brain, body and environment [12,51,77]. However, as above discussed, cognitive agents can break the boundaries of sensorimotor engagement. While adaptivity serves to coordinate with the present, *anticipation serves to coordinate with the future*.

Anticipatory behavior is not all-or-nothing ability, but comes in grades: the range of anticipatory capabilities is ample and new capabilities can be evolved on the basis of old ones. As a demarcation criterion we propose that the true mental life of a cognitive agent begins when it is able to *endogenously generate representations* which are not totally determined by actual sensed stimuli but derive from internal models, and to *use them in order to regulate its present behavior* (and in some species even future behavior). As pointed out by many researchers [14,55,73] even if connected causally to the environment, internal processes for dealing with representations do not share its dynamics. This permits representations to *detach* from the current sensorimotor cycle and to be used *instead of* the environment itself, for example when the environment is too noisy, or too rich of stimuli, or if not all the relevant information is (already) there, as in the case of future-oriented actions, which we stress here. In its more complex forms, detached representations are conceptual and not only perceptual, permitting more complex capabilities such as representing the non existent and reasoning.

This idea of cognition entails a notion of representation that is intimately anticipatory. As discussed by Roy [66], representations are related to the environment with a double-sided relationship: causation (from environment to agent) and anticipation (from agent to environment). For example, concepts for 'reachable' or 'graspable' objects are grounded by schemas which regulate agent behavior and include predictions of the consequences of expected interactions. Once in place for regulating present-directed actions, those anticipation-based representations offer an unique evolutionary advantage to cognitive agents: *to work on them before, or instead of, working on external reality*, leading to future-oriented capabilities such as formulating, pursuing and reasoning about distal goals. The ability that defines a true mind, as opposed to a merely adaptive systems, is in fact that of building up representations of the non-existent, of what is not currently (yet) true or perceivable, for the sake of acting on them.

Implicit, or behavioral, anticipation. This is not to say that all anticipation depends on *explicit* representations of future states of affairs. Some anticipatory capabilities, which we refer as *behavioral* or *implicit* anticipation, are selected by evolution and encoded into the sensorimotor apparatus. Consider as an example a *grasshopper* apparently reacting to a noise and escaping. In this case the grasshopper's behavior has been selected by evolution not to react to the noise itself, but to predators. It reacts now to a danger in the future: this behavior, even if realized by a reactive mechanism, is functionally anticipatory.

Gibson [31] firstly proposed that vision is an active process in which anticipation is implicitly produced by learned patterns of sensorimotor transformations; there is no need of representing anything, neither present not future states, since the environment is used as *the best representation of itself*. Brooks [8] points out that, strictly speaking, continuously coupled reactive agents are not memoryless, since their memory is in the environment; and we would say that also their expectations are in the environment and in the dynamics of agent-environment interaction. Recently O'Regan and Noe [52] also propose to conceive all perception as coordination of an agent's perceptual apparatus with the dynamical structure of sensory stimuli. In their sensorimotor view the organism shows an anticipatory behavior, that is to attend to the next relevant stimuli, by learning the patterns of transformation of sensory stimuli depending on its motor operations, without an explicit representation of the next incoming stimulus.

Explicit, or representational, anticipation. In nature there is thus a range of behaviors which maintains a reactive appearance but is functionally anticipatory; but how many anticipatory capabilities can be explained without resorting to anticipatory representations? In the next Section we will review empirical findings indicating that *explicit* anticipatory representations are actually involved in many anticipatory behaviors. Also many theories, such as Clark's *minimal representationalism*, point in the same direction without denying the embodied and dynamical nature of cognition: *minds may be essentially embodied and embedded and still depend crucially on brains which compute and represent* [13].

Some capabilities seem to be out of the scope of behavioral anticipation: for example, acting both for the present and for distal goals (to coordinate both with the present and the future), or considering both own and other's perspective, or taking into account multiple possibilities for action. If a unique, non representation-mediated mechanism is in play, these activities should interfere, but we know that conceiving *now* the future does not hinder the possibility to act in the present, and conceiving the other's perspective does not imply losing one's own. All these phenomena seem then to be based on representations: for example, internal, emulating models can be in play in several cognitive operations, running on-line and off-line and providing a credible substratum for representational activity [14] (but see [43] for an account of how non-representational systems can deal with distal behavior). Moreover, the possibility to *internalize* external structures to work on them, including maps but also language and cultural practices, seem to be a distinctive trait of high level cognition (see [55]). In a sense, this is an old story coming back to attention. Even in the past, in fact, many studies in traditional AI were focused on resolving problems by working on 'internal' or 'small-scale' models before acting in the world. For example, Craik [16] discusses how internal representations permit to generate imaginary experiences and 'mental simulations' of external reality, and Tolman [78] discusses the role of imagination for learning 'as if' experience had really happened. However, the problem is that often representations as used in AI are *disembodied* and *not grounded* [34,56]. How to develop a concept of representation that it is integrated in a naturalistic framework and in continuity with situated action?

Recently representations begin to be seen in a different way in cognitive science, which we could call a *motor-based* perspective. As suggested in particular by the discovery of *mirror neurons* [62], they are mainly *action-oriented*, originate in the sensorimotor apparatus and remain intimately related with it [13,14,55]. As an example of the coupling of representation and action, Gallese [29] argues that *the goal is represented as a goal-state, namely, as a successfully terminated action pattern*. The *ideomotor principle* [39], which recently received a number of empirical confirmations, [37,44], suggests in a similar way that *action planning takes place in terms of anticipated features of the intended goal*. It is thus not surprising that in this action-based view of cognition anticipation has assumed a crucial role, since it is a bridge between representation as traditionally conceived, and situated action. Anticipation permits in fact to look at representations not as abstract and disembodied symbols, as it was the case in traditional AI, but as structures enabling agent-environment coordination that arise for the sake of guiding behavior and remain intimately coupled with the sensorimomtor apparatus. Interactivism [4], for example, describes representations as *ways for setting up indications of further interactive potentialities*: representations serve thus for future interactions. This approach is reminiscent of the Kantian *productive* perspective of cognition, according to which we do not passively process environmental stimuli but actively produce representations by means our categorical apparatus; the novelty is the emphasis on the situated and action-based origin and nature of representations.

3 Anticipation in Natural and Artificial Cognition

How does the brain formulate expectations? Which brain structures and which mechanisms are involved? There are currently multiple directions of research, which emphasize different aspects. The ideomotor principle and related models [39,37,44] stress the formation of associative, *action-effect* rules, mediated by a common neural coding. Similarly, stimulus-stimulus associative links (e.g., lightning - thunder) might be involved the prediction of regularities of the environment. The reenactment of sensorimotor structures used for the control of action is instead stressed in the literature on the mirror system [29,62], that codes for both observed and executed actions. Reenactment and generative capabilities are central in the literature on internal forward models [42,81], that actively produce expectations and do not only explain statistical regularities in the stimuli, but include hidden states. Different anticipatory mechanisms and brain structures could then co-exist and have complementary powers and limitations [22]. For example, important distinctions are among prediction of events that we can or can not produce ourselves [69] and among prediction of action effects or behavioral goals [48]. See also [25] for a recent, comprehensive review of the neural correlates of anticipation in the mammalian brain.

In artificial systems research, one very influential model is that of Wolpert, Kawato and colleagues [42,81], that has the advantage to be well grounded in standard control theory. They propose that the brain uses *internal models*, which mimic the behavior of external processes, for motor control of action. In particular, *forward models* permit to generate expectations about the next sensed stimuli, given the actual state and motor command. *Inverse models* instead take as input actual stimuli and the goal state and provide as output the motor commands necessary to reach the desired state. Taken together, inverse and forward models permit not only to perform motor plans but also to control it and in general to regulate behavior in noisy and dynamic environments. In neurosciences forward models have been claimed to be involved in compensating for delays in sensory feedback, cancel the self-produced part of the input from sensory stimuli, etc. [81,82] and empirical evidence exists for their involvement in visuomotor tasks [46]. Similar structures have also been claimed to be involved in visual attention [2] and imagery [40].

Thanks to these findings *motor* and *simulative* theories of cognition are now widespread: for example, according to the *emulation theory* of Grush [33], representation is the ability to emulate internally part of external reality by means of internal models such as Kalman filters, that can also be nested to obtain abstraction. Similarly, the *simulation hypothesis* of Hesslow [35] argues that representing is engaging in simulated interaction with the environment by means of internal predictive models which can be chained and form ‘loops’. Barsalou proposes the *perceptual symbol system* theory; arguing against amodal and disembodied notions of representations, proposes a situated view in which they retain part of their original sensorimotor structure. On the basis of perceptual systems, Barsalou proposes that concepts emerge as productive, simulative structures that can be used by the agent in order to *simulate* actual or expected sensorimotor engagements on the basis of past situated action, producing understanding of perceptual and abstract concepts. Similarly Gallese [27] claims that *looking at objects means to unconsciously 'simulate' a potential action.*

Internal models for simulating actual sensorimotor engagement can also be exploited for increasingly complex future-oriented activities. For example, this approach explains quite naturally one of the distinctive points of human cognition, the possibility to test potential actions ‘in simulation’ and for example avoid dangers [17]. Recent evidence suggests in fact that imagined and performed actions share a common timing and neural substratum [18]. Moreover, a comprehensive model of how impairments in anticipating the consequences of one’s own actions produces diseases such as the ‘anarchic hand’ and schizophrenia has been proposed [26] that unifies a number of empirical findings under a common, anticipatory framework. Another capability that is often associated to internal, generative models is formulating and comparing in simulation multiple alternative courses of actions. It has been proposed in [50] that the possible neural substratum is a ‘loop’ between the *cerebellum*, which is supposed to be able to produce sensory predictions (see e.g., [6]), and the *basal ganglia*, that are involved in action selection and movement initiation (see e.g., [60]). Recently the chemical basis of such neural predictions have been investigated, too. For example a role of dopamine has been advocated in reward prediction [70] and signaling unpredictability of actions [59].

The use of anticipatory and simulative capabilities also extends to the social sphere. The neural substrates involved in performing, observing, simulating and imitating actions in fact largely overlaps, and evidence exists for a role of mirror neurons and simulative processes for imitation [38], distinguishing self from others [19], mind reading [28], language production and understanding [61]. Several researchers have proposed that the same generative mechanisms for controlling action can be reenacted endogenously for perceiving, understanding and imitating actions performed by other agents, for understanding behavior, and for inferring intentions from actions [5,38,40,80]. According to Rizzolatti and Arbib, *Individuals recognize actions made by others because the neural pattern elicited in their premotor areas during action observation is similar to that internally generated to produce that action* [61, p. 190]. Altogether, the beauty of the motor-based approach is in its power to unify spheres of cognition that are traditionally kept separated: action and perception, individual and social.

Anticipation in Artificial Systems. Recently anticipation has received attention in situated approaches to artificial systems, and principled design approaches have been proposed. For example, on the basis of the psychological literature, and in particular Hoffmann's theory of *anticipatory behavioral control* [37], a taxonomy of four kinds of anticipations for artificial systems is proposed in [9]: *implicit*, *payoff*, *sensorial* and *state* anticipation. At the same time, many mechanisms for predicting have been proposed in cognitive robotics, such as recurrent neural networks (RNN). For example, Jordan's type RNN [41] use expectations produced by forward models for 'vicarious' trial-and-error learning. Kalman filters have also been widely used; they incorporate many functionalities such as estimation and filtering, and for this reason Grush [33] considers them prototypical emulators. Bayesian predictors have also been used in the literature of motor control [82], and rule based systems such as the *schema mechanism* [24] and *anticipatory classifier systems* [9] have been shown to autonomously learn action-effect rules and chain them for planning and action control. The roles of reward prediction and surprise in action learning and in metalearning strategies such as curiosity are being studied [72], with convergent ideas between reinforcement learning and neuroscience [22,23]. Moreover, *predictive state representation* [45] has been proposed for substituting the classical concept of state.

Many cognitive functions related to anticipation, having different levels of complexity and sometimes nested in one another, are being studied in cognitive robotics. Anticipation plays in fact a crucial role in attention, conceived as 'selection of information relevant for action' [2,54]. The role of anticipation for the control of attentive strategies has also been demonstrated with hierarchical architectures combining the top-down contribute of expectation and the bottom-up one of incoming stimuli [53,58]. Several functions related to the *control of action* have been claimed to include anticipatory components, too, such as stabilizing perception [79], canceling the predictable part of the feedback [49], erasing stimuli produced e.g. by the body of the agent [21], producing a reference signal for the control of voluntary acts [1]. Many of them have been modeled in artificial systems, too. For example, the robot Murphy can [47] exploit efference copies of motor commands for generating simulated perceptual inputs and thus maneuver its arm robustly even in partial absence of sensory stimuli. Similar anticipatory strategies are widely used in the *Robocup* competition (e.g. [32]) for coordinating with the ball in dynamic environments: prediction is required for compensating the delays of the sensors. Combinations of *forward* and *inverse* internal models have also been widely used for action execution and control both in distributed, dynamic systems approaches [75] and in localist ones [20,54,76,82]. They permit to generate multiple competing motor plans, and select the one most appropriate to the context depending on its predictive accuracy. One example is choosing the most appropriate behavior to deal with 'full' or 'empty' glasses, the weight being the context [82]. Action understanding and imitation has also been demonstrated in artificial systems by running 'in simulation' the same generative mechanisms used for motor control [20].

Internal predictive models serving for the control of action have been used for other functionalities, increasingly disengaging from current sensorimotor cycle. In fact, if expectations produced by forward models are chained, and expected input is supplied in spite of actual input, it is possible to use the same machinery involved in online visual and motor planning for generating off-line, 'simulative' planning. In cognitive robotics this capability has been exploited for generating the sensory consequences of multiple possible plans and selecting the 'best' one [74,83], like in the *simulation hypothesis* [35]. It has also been used for generating long-term predictions related to the current course of actions in order to receive an evaluation from the future [71], like in the *somatic markers* hypothesis [17]. Another use of internal predictive models is understanding the boundaries of the personal sphere. Piaget [57] discusses how distinguishing self-produced motion from sensory stimuli which are caused by interaction with objects in the environment leads to develop a *body schema*; some of these ideas have been also used in robotics [7]. It has also been shown by schema-based architectures [24,54,66] that anticipation, as argued in constructivist theories [4,57], can bootstrap the acquisition of new concepts by interacting with the environment, as in the case of Drescher's *schema mechanism* [24] which learns *synthetic items*. Another related use is grounding concepts such as 'far', 'heavy', 'obstacle' or 'predator' as simulated interaction potentialities [36,66].

Computational studies have demonstrated that anticipatory mechanisms for the control of action can also be used for enabling social capabilities such as action understanding, imitation, joint attention, perspective taking (e.g., [20,67]). This fact parallels the huge empirical evidence that a common neural substrate, enabling anticipatory and simulative capabilities, is in place both for individual and social cognition [38,62]. The similarities between many of the above mentioned studies indicate that anticipatory capabilities are highly related both at the functional and at the mechanism level. This is an important reason for conceiving *anticipation as a unitary phenomenon*, which is fundamental in natural cognition and should inspire artificial systems design, too.

4 Conclusions

While the 'new AI' is nowadays mainly focused on reactive behavior, we argue that a crucial theoretical and computational challenge is putting in a naturalistic framework our ability to deal not only with the present but with anticipated, or desired futures, and make them happen for our sake. In artificial cognitive systems, as in natural ones, *implicit* and *explicit* anticipation permits an evolutionary leap from present-oriented to future-oriented capabilities, bootstrapping high level cognitive and social capabilities [55]. To imagine, to reason about the possible and the non existent, to evaluate in advance the results of one's own actions, to change the world according to one's own goals and, at the same time, to build up deceptive and illusory worlds, to dream and hallucinate: those are all features of a truly cognitive mind. We argue that a presupposition for autonomous mental life are anticipatory capabilities permitting to *disengage* from sensorimotor loops and to break the boundaries of adaptivity: (1) to *pursue autonomously generated goals*; (2) to regulate behavior according to *future and not only present potentialities for action*; (3) to *learn regularities in the environment* depending on the agent's (actual or possible) actions, and independent from them; (4) to *deal with entities even 'in their absentia'*, when they are not among the currently attended stimuli; (5) to *form conceptual representations* that are however grounded in (potential) interaction; (6) to *adapt the world to fit the agent's own goals*; (7) and *to boostrap high level cognition.*

Much theoretical, empirical and simulative work remains to be done in order to fully understand the phenomenon of anticipation in natural cognition, and how to endow artificial systems with future-oriented capabilities. We would conclude by anticipating some of the challenges that we envisage if we want to build anticipatory artificial systems. Perhaps the most basilar one is to understand the passage from reactive, to simple, and then increasingly complex anticipatory mechanisms, with a caveat: arguably, these mechanisms do not replace each other in full-fledged cognitive agents, but coexist and coordinate. Another crucial challenge is understanding which cognitive functions depend on anticipatory capabilities, and in particularly which ones are exaptations of the capability to predict. For example, the capability to conceive discrete objects and events could depend on the fact that we necessarily have to predict them at a high granularity, since fine-grained prediction fails when the time span is too long. Another relevant challenge is understanding if motor-based and simulative view of cognition (exemplified by the motto *the mind is an anticipatory device* [11,55]) will be really able to provide us with a unified perspective on cognition. Assuming that the motor apparatus of a robot can be used for predicting and understanding objects, events, and actions, the robot could internalize these predictions and use them independently of the current state of the world, for example reenacting them for planning, conceiving novel goals, comparing possible outcomes of its actions, or imagining the reaction of another robot to its actions. Several cognitive abilities could depend on the same anticipatory mechanisms.

Overall, we think that anticipation is a necessary condition in natural cognition for developing several individual and social abilities, and the motor-based, simulative view of cognition should inspire the way robots are designed, too [14,55]. Robots of the future should not simply adapt to their environment, but predict it, and their generative mechanisms will be the key for bootstrapping increasingly complex cognitive capabilities.

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