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The Role of Anticipation in Cognition

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Abstract. According to the standard definition of anticipatory systems, anticipation is based on a predictive model of the system itself and its environment. The paper abandons this perspective of weak anticipation in favor of what has been called strong anticipation. It is proposed that anticipation is a consequence of canalization caused by the organization of the structural building-blocks of which the system in question consists. Strong anticipation can account for the anticipatory behavior in animals to which we would not impute the ability of creating internal models of themselves.

1 INTRODUCTION

Anticipations are ubiquitous. Each time we switch on our TV, we anticipate that it will wake up and deliver some colorful moving pictures. Pressing a door handle should open the door, beautiful flowers are expected to grow when we put seed into soil. Astronomers move their telescopes to a certain position in order to observe a heavenly body. The list of examples can be arbitrarily extended.

According to the evolutionary epistemology of Lorenz [1], human beings feature a system of innate forms of ideation which allows the anticipation of space, time, comparability, causality, finality, and a form of subjective probability or propensity [2]. This so-called *ratiomorphic* apparatus has to be distinguished from our rational abilities since the former indicates that "…although this ideation is closely analogous to rational behavior in both formal and functional respects, it has nothing to do with conscious reason".

Each of these ideations can be described as 'innate hypotheses' [3]. These are mental adaptations to basic phenomena that enable organisms to cope with them. The 'hypothesis of the apparent truth' is one of these mechanisms—the ability of detecting or discriminating foreseeable and unforeseeable events. It guides the propensity of a creature to make predictions with different degrees of confidence, ranging from complete uncertainty to firm certainty. It produces prejudices in advance, or anticipations of phenomena to come. The capacity to anticipate is necessary for survival, and contributes to the success of every organism. As a consequence, animals and human beings behave as if the confirmation of an expectation makes the same anticipation more certain in the future. This is also the case in science where repeated confirmation of an expectation leads to certainty, commonly referred to as induction. As Maturana & Varela [4] put it, "A living system, due to its circular organization, is an inductive system and functions always in a predictive manner: what happened once will occur again. Its organization […] is conservative and repeats only that which works."

As many authors have complained, the concept of anticipation has long been neglected as a possible source of better understanding the mind (cf., e.g., Neisser [5], Glasersfeld [6], Ekdahl [7]). In this paper I will investigate two main questions: (1) What are the mechanisms behind anticipation?, and (2) Can we find an answer to the question of whether anticipation needs an internal model in the mind or whether it is an fundamentally embedded in the organization of the subject?

2 ANTICIPATION—A CONTINUUM?

There is much evidence that animals can anticipate future events. Whether they are snakes searching for mice, dogs hunting hares which hide behind obstacles, or geese trying to roll back their eggs, their behavior is based on the ability to predict future states in the space–time continuum in which the action is embedded. Naturally, this ability also extends to human beings. The way we navigate in known places or the patterns we display when asked to solve problems point at similar skills.

2.1 Anticipation in human problem-solving

Focussing on humans only, one might suspect that anticipation is an act of intention—cf. Ekdahl [7] who speaks of 'conscious anticipation'. This opinion is the consequence of what I want to call the *standard definition of anticipatory systems*. Rosen [8] characterized an anticipatory system as one "containing a predictive model of itself and/or of its environment, which allows it to change state at an instant in accord with the model's predictions pertaining to a latter instant". Similarly, Klir [9] maintains that systems which "…are able to develop a model of their environment and use it in an anticipatory manner […] are usually referred to in the literature as anticipatory systems." When walking through a familiar place in the dark this seem to be perfectly true. We have a cognitive map that predicts the location of furniture and thus guides our action of stepping through the known yet unperceivable environment. If, despite this map, it happens that we bump into one these obstacles, we are inclined to modify our map and thus to change our actions. But it is not just physical navigation that requires an external perturbation in order to deliberately alter our internal model. Problem-solving—the walking through an abstract space of subsequent decisions [10]—has similar properties. Let us assume that in order to solve a problem we have a repertoire of 100 available actions. The problem requires a sequence of 10 decision. The probability to find the correct sequence is thus $1:100^{10}$. This number is far to large for an exhaustive search of all possible paths through this search space [11]. Any evolutionary solution by a process of random variation and selection is also unable to cope with this situation.

Despite this combinatorial explosion, humans *are* able to solve problems. At a general scale, I want to join the argument of others that anticipation is necessary to outfox these astronomical numbers. However, as I will outline later in this paper, my perspective is slightly different. What is of interest for us now is the fact that, once we have found a solution to a hard problem, we are very likely to keep this recipe for puzzles of the same kind. The water-jug problem, studied by Luchins [12], provides empirical data for this assumption of 'mechanization of thoughts'. He asked test subjects to measure out a specific quantity of water using a set of three jugs with known volume. The first two problems Luchins posed could be solved by applying a certain sequence of pouring water from one jug into another. Test subjects had no problems discovering this procedure. Quite the contrary. They got used to it and tried to apply it to further tasks. With reference to the adage, I called this aspect of human problem-solving "It ain't broken so don't fix it"–psychology [13]. What the test subjects overlooked was that much simpler procedures would have led to the same result, simply because their inductively working mind was set to the previously successful strategy.

An important consequence of this 'stubbornness' in reasoning is that in our everyday life things are used in a particular context, e.g., we use a hammer to drive nails into a wall, matches to light a fire. In fact, things do not seem to exist 'outside' their domains of functionality. Already decades ago, this phenomenon was investigated by psychologists. Duncker [14] posed the task to support a candle on a door. The available items were matches and a box filled with tacks. Since the test subjects considered the box as a mere container they failed to empty it and to tack it to the door where it could serve as a support for the candle. In general, our thinking is canalized (or fixed) with respect to the way we have learned to deal with things.

What can be learned from these results? Obviously, we implicitly anticipate that similar issues have similar causes, and thus similar solutions. It makes us fail to notice other, probably much simpler answers. Is this an indication that anticipation is not based on an internal model, that it goes beyond what Dubois [15] called 'weak anticipation', i.e., anticipation which "is based on a model of the system and thus is a model-based prediction and not a system-based prediction"? If it was, we could easily consult this model for retrieving alternative and better solutions, rather than conservatively sticking to an approved yet overly complicated way of handling tasks. As we'll see in the following section, not only this observation provides us with doubts about the correctness of the standard definition of anticipatory systems.

2.2 Weak anticipation in anmials

Without question, anticipatory behavior can also be found in the animal kingdom. This urges us to pose the question: Do anticipating animals places themselves in such an internal model of their surrounding? While we might still be willing to attribute such an ability to intelligent pets like dogs and cats, we find it difficult to speak of internal models in reptiles. When chasing their prey, snakes base their anticipation on a fixed sequence of recognition in different modality channels. Let us take a closer look at how a snake perceives its prey, as provided by Sjölander [16]. "A snake hunting by sight will not pursue a prey the way a dog does, by anticipating movements and predicting routes. If the prey disappears the snake remains activated and it may even search actively at the spot where the prey has last been seen, but the snake does not look for the prey in the place 'it ought to be by now'. Once the prey is struck, the snake uses its sense of smell to localize it and it relies solely on this sensory channel for that purpose. The behavior thus is wired to this modality and to no other. This is particularly evident in snakes like boas or pythons, where the prey often is held fast in the coils of the snake's body when it, e.g., hangs from a branch. Despite the fact that the snake must have ample proprioceptory information about the location of the prey it holds, it searches stochastically for it all around only with the help of the olfactory sense organs. When the prey is located, its head must be found to enable the snake to swallow it. The prey's mouth could obviously be found by smell or, even by sight, but this process is governed by touch only—yet another instance of a single-modality connection between stimuli and behavior… In the snake's world … there are 'things' that give certain visual input which triggers a strike, other 'thing' giving certain olfactory stimuli that one searches for after having struck, and, finally, 'things' giving certain touch information that one swallows."

An observer will evidently get the impression that the hunting strategy of the reptile is like a relay race in which each modality passes the courier over to the next one, trusting that the predecessor did its job correctly, and provided a context in which the current modality will suffice.

Also, so-called 'insight-free' instincts, which serve as a priori adaptation to recurring environmental changes, can be interpreted as anticipatory performance [17]. Hibernation is an example of such inborn anticipations. The anticipation here is not the result of cognitive reasoning. Rather, the behavior is evolutionarily shaped; animals prepare for the winter even if they have never experienced the season before.

We can thus argue that there are at least three different types of anticipation: inborn, emotional, and intelligent. *Inborn anticipation* occurs as the result of some phylogenetically acquired patterns. An anticipation is *emotional* if it is driven by some instinct, such as hunger. From experiments with great apes, we know that they are able to imagine a future state which would satisfy the current need [18]. We may speak of *intelligent anticipation* if the ability to think of a remote future does not depend on the current state [17]. Together with Gibson [19], we could thus postulate that there is a continuum of 'mental constructional ability' from inborn and inflexible anticipation to intelligent and deliberate anticipation. Its 'degree' seems to be dependent on the cognitive abilities of the creature. Insects and reptiles can be found towards the lower end of this continuum. What about more highly developed animals?

The egg-retrieving behavior of the greylag [20] provides an example for an evolutionarily successful application of anticipation: If an egg falls out of the nest, the incubating goose rolls it back into the nest with its bill. While retrieving the egg, the animal pays great care to the not necessarily flat ground and compensates for any sideward rolling of the egg. Interestingly, during this process the goose seems to neglect environmental events. Once the action sequence of egg-retrieving has been triggered, the processing of sensor information is reduced until the pattern terminates. One can easily prove this by removing the egg midway through the action. The bird will continue with its behavior until its bill has reached the border of the nest. At first glance, the goose seems to live up its reputation and displays a mindless behavior. But given that eggs can fall out of nests, and the species of geese has not gone extinct, it appears that this inborn anticipation is useful.

At even higher levels of development we can find indications of emotion-driven anticipation. If a mouse vanishes into a mouse hole it no longer exists for a snake, while a cat, for instance, remains in front of the hole and waits for the mouse to re-appear. Following Sjölander [16], a dog, hunting a hare "…does not need a full picture of a recognizable hare all the time to conduct a successful hunt. It is able to proceed anyway, guided by glimpses of parts of the hare, by movements in vegetation, by sounds, by smell, etc. If the hare disappears behind a bush or in a ditch the dog can predict the future location of the hare by anticipating where it is going to turn up next time, basing this prediction on the direction and the speed the hare had when seen last."

Certainly, such observations lead directly to the assumption that those animals—as well as humans—employ an internal model in order to formulate anticipations about the future and act according to this expectations. Such a proposal is in accordance to the standard definition as presented above. How could such a model look like?

The goal of any scientific investigation must be a formal model of the proposed mechanisms and structures. We are therefore challenged to find an appropriate mathematical or computational framework for the assumption that an inner *probierbühne* (trial stage) exists upon which anticipations can be formulated. Fortunately, artificial intelligence research has already been trying to find such a formalism. Even more, it collected evidence that such an internal model representing the outside world can't possibly exist[1] due to the frame-problem [22]. It testifies to the fruitless hope that we could formulate knowledge about the world and possible actions therein in an appropriate symbolic way. Dennett's well known analogy [22] illustrates the shortcomings of the assumption that creatures can tackle their struggle for life in terms of model-based planning. Too many logical implications of even the simplest actions have to be taken into account in such a framework. This results in endless computations that prevent creatures from finding a solution and taking those actions. Even if you want to consider only relevant implications, telling the important consequences from irrelevant does nothing but increase the computational effort. Therefore, instead of insisting in the existence of a (deliberately built) internal model of the environment and oneself which serves as a foundation of anticipation, we have to find another mechanism that can account for it.

3 THE NATURE OF ANTICIPATION

The alternative I would like to propose arises from a common characteristic of the various forms of anticipation introduced so far. Let's consider the case of the snake again. The presence of a prey triggers the hunting behavior of the hungry animal. Employing its typical, relay-like interplay of different single modal channels, the snake can safely (yet unreflectedly) anticipate the success of the action sequence. A greylag does the same. The escaped egg triggers the egg-retrieving schema which anticipates the return of the egg. The disappearance of the hare behind a rock triggers the behavior (and anticipation) in the dog to wait for it at the opposite side. Finally, the subject in psychological tests finds a particular problem situation resembling another one. This triggers the same problem solving strategy previously employed for the other task. In all these cases a large number of alternative behavioral pattern could have been chosen by the respective creature. But these would be new and untested schemata which could not provide any anticipation with regard to the result.

Imagine being in an aquatic theme park, standing on top of the water-chute tower and three chutes inviting your for a ride. Regardless of which one you chose, once you are in the chute you have to follow its meanders in order to see your anticipations come true: to arrive safely in the basin at the bottom.

3.1 Anticipation as a consequence of canalization

I propose that anticipation is caused by the canalization which is a consequence of the system's organization. Dubois [15] calls this form 'strong anticipation', i.e, anticipation which is fundamentally embedded in the physical system. As such, it does not rely on an explicit internal model.

The idea of canalization can be traced back to the work of Waddington [23]. He emphasized the importance of the epigenetic system. It is responsible for the development of biological structures out of the genetic material in interaction with the environment. Two classes of genes interact here. Structural genes encode single features, while control genes encode programs of how to interpret structural genes. Their regulatory effect in the epigenetic system can be illustrated through the downward rolling of a ball in what Waddington called the 'epigenetic landscape'. Starting at the highest point, the ball follows a certain path downward through a continuously ramifying system of valleys. These valleys are synonymous for the developmental paths of various body components. The analogy expresses the fact that the embryonic development is canalized to certain attractors. At the crossing of two departing valleys are control genes which decide which direction to take. In this scenario, the degree of freedom is thus very low. Environmental perturbations or mutations may force the ball uphill from the bottom of the valley. As long as it does not transcend the ridge to the neighboring valley, it will roll back downhill to the bottom. Consequently, switching on or off a control gene alters the subsequent development of the organism as can be demonstrated in laboratory experiments. Legs instead of antennae grow on the heads of drosophila because the experimenter modified the settings of the control gene in charge

[1] Frustrated by the negative result some scientists arrived even at an extreme opposite proposal, to take the world "as its own model" and not some internal representation of it [21].

to conduct the orchestra of sub-ordinated structural genes. In other words, triggering the appropriate control gene raises the anticipation that a complete sub-structure will develope. The interplay of many control genes, in turn, makes it possible that the organism is formed in its entirety. As in a music orchestra, the carefully chosen canalization of the parts a 'correct' organism emerges out of a large number of possible forms.

Let's see whether the concept of canalization goes beyond genetics and also applies to behavior and reasoning.

3.2 Behavior and reasoning as canalized activity

Sacks [24] provides us with an interesting study of a man named Virgil whose eye-light was restored after 50 years of being blind. In contrast to the general expectation, gaining the ability to see was no help for Virgil. The way he has been living as a blind person was incompatible with the way normal sighted people perceive and organize their world. With effort and practice, he was able to interpret some of the visual data in terms of the world as he had known it through his other senses, but he had immense difficulty in learning these interpretations. For instance, visually he couldn't tell his dog from his cat. For him, due to the lack of visual impressions, the temporal aspect of his world had priority. He recognized things by feeling their surface in a particular order. He didn't get lost in his apartment because he knew that after entering he would encounter the various pieces of furniture in a particular sequence which he perceived in a temporal order. To put it differently, he was living in world of anticipation, of subsequent checkpoints which act like the handing-over in a relay race. A particular cupboard was followed by a table, so once he reached the cupboard he anticipated to go to the table with the next step. We may compare this with navigating through a dark room, as described above. If we bump into an obstacle we will changes our future path; that is, we will turn left instead of walking straight.

When solving a problem, we always take the same bifurcations in the abstract space of decisions until we notice that our solution is plainly wrong. Of course, as humans we are able and used to reflect on our problem-solving and navigating. In successful cases, this makes us believe that we were able to anticipate the correct way through the physical or abstract space. If we have to change our path because we run into an obstacle and nevertheless arrive at the goal, we say that we anticipated the solution, since we were able to generate an alternative plan which carried us to the solution. However, we do not share this *a posteriori* reflection on decision-making with anticipating animals. We have therefore to assume that anticipation does not necessarily involve consciousness and intention. Anticipation arises from the properties of basic components and their relationships which impose mutual dependencies and thus canalization. An example illustrates how this works. By car, you can reach only those points which are connected to the road network. By foot, all the points in between can be accessed, but only if they are within walking distance. The basic component in both cases is the means of transportation which canalizes the availability of reachable destinations. When solving a problem, the previous experience and present stage of the solving-process canalize the way a solution is found. As we have seen, a dog which sees a hares disappearing behind a rock will wait at the other end as it anticipates from its experience that the prey will re-appear there. However, the dog will fail to anticipate the case in which the hare disappears through a tunnel behind the rock. Likewise, the incubating goose which is about to roll back an egg that fell out of its nest anticipates that its retrieving behavior will bring the egg back to the nest. And like the dog, it will fail to predict that a present ethologist might take away the egg. The retrieving action will let this anticipation fail.

4 COMPUTATIONAL MODELS OF THE ANTICIPATORY MIND

As we have seen, there is clear evidence that the ability to anticipate future events does not rely on an internal model which evolve faster than the system it models. Rather, anticipations are the result of internal canalizations which inevitably 'force' a particular path, whether in the physical or the abstract realm. Neisser's [5] characterization of perception as a schemata controlled 'information pickup' corresponds to this perspective. An organism's schemata determine the way it is looking at the environment, and are therefore anticipatory. The schemata construct anticipations of what to expect, and thus enable the organism to actually perceive the expected information.

4.1 Explicit anticipations

A straight-forward implementation of anticipatory cognition has been provided by several authors, among them Drescher [25], Kharma & Riegler [26] and Stolzmann[27]. Without going to much into details, I want to outline their common assumption. Schemata—the basic structure of their models—are composed of three components, a context, an action and a result. A schema manifests the anticipation that in a given context the associated action will yield the expected result. If the result is not achieved, the schema can be adjusted by negative feedback: Change the context or the action appropriately to arrive at the desired result.[2] Unfortunately, the algorithm to determine when and what to change turns out to be quite expensive as in real-world situations a large number of reasons may held responsible for not reaching a desired goal—we are back at the frame-problem, as described above.

This begs the question for alternative approaches.

4.2 The constructivist-anticipatory principle

Based on the constructivist concept of 'operationally closed systems'[3] [4], I arrived at a different solution which I called the 'constructivist-anticipatory principle' (see, e.g., [28–30]). It assumes that the mind is populated by schemata which consist of merely two parts, a set of conditions and a sequence of actions. Schemata can be mutually embedded. So can conditions and actions. The purpose of the condition part is to provide context matching which allows the schema which fits best the present context to execute its action sequence. Since conditions can also be part of a sequence, they act as checkpoints for determining whether the anticipation embodied by the schema is still on the right track. After a schema and all its sub-ordinated elements finished, the cycle starts anew. It is important to note that during the execution of the schemata, environmental events are largely ignored. A schema asks for specific sensory or internal data only when it becomes necessary in the course of its action sequence. This leads to a significant decrease in computational costs since the simulation algorithm need not provide the full environmental context information to the agent at every time step. The pick-up of information is solely directed by schemata which implement (implicit) anticipations in the sense that a certain context calls them up expecting that the execution of the schemata is beneficial to the system. In other words, for any given situation, there exists a schema which is anticipated to improve the situation. In contrast to other computational models (exemplified above by the work of Drescher [25], Kharma & Riegler [26], Stolzmann [27]), there is no *explicit* formulation of an expected result. The incubating goose doesn't have any explicit expectations about the result of the egg-retrieving action either. When we solve a problem we rely on approved strategies. Therefore, the ultimate evaluation criterion for schemata is their reliability and hence frequency of use.

While the information processing metaphor creates a 'computational bottleneck' by claiming that the flow of information is unidirectional from perception to action, the constructivist-anticipatory principle reverses the proceedings. It is not the entirely available information from outside which is filtered for relevant issues in order to control the behavior of an organism (cf. also [5]). Instead, the constructivist-anticipatory principle guides perception and behavior. Schemata act as internal hypotheses which carry anticipations the organism has with respect to the environment. Therefore, instead of trying to reduce the complexity of all sensory data, the schemata merely need to check whether a sensory detail is present.

Such conceptual models can account for the fact that we find anticipations not only in humans but also in animals of various levels of complexity. Furthermore, due to the algorithmic nature of the constructivist-anticipatory principle, it provides the possibility to implement anticipatory behavior in artifacts which might help us to further investigate its working.

5 CONCLUSION

There is clear evidence that the ability to anticipate future events does not rely on an internal model which evolve faster than the system it models. Rather, anticipations are the result of internal canalizations which inevitably 'force' a par-

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[2] As Glasersfeld [6] pointed out, in experimental science we do this in a systematic manner—variation of possible causes until we arrive at the one which is responsible for an observed phenomenon.

[3] The operational closure of the nervous system means that it is a self-referring system which operates on its own states. Nervous signals are unspecific, e.g., visual stimuli produce the same kind of internal signals as tactile ones.

ticular path, whether in the physical or the abstract realm of behavior and reasoning. This provides an answer to question 1 in the introduction. The constructivist–anticipatory principle not only offers the guideline for a robust implementation of an anticipatory system, but also is closely related to the notion of schema-directed information pick-up of Neisser [5]. The idea of employing the concept of canalization has not only roots in the biological structure of organisms but is also related to work in psychology, such as that of Kelly [31] who maintained that "[a] person's processes are psychologically channelized by the ways in which he anticipates events".

The answer to question 2 follows from the characterization of anticipatory systems as being canalized. Behavioral and cognitive processes, and therefore the mind, seem to be strongly anticipatory—the ability is firmly rooted in the system rather than being dependent on (deliberately) built internal models.

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