The anticipatory construction of reality as a central concern for psychology and robotics

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Understanding and reproducing the organization of animal and human behavior has been one of the central problems in the life and engineering sciences throughout the centuries. It is still largely unresolved.

The life sciences approach consists in designing experiments that may reveal underlying principles of this organization in living systems. A key requirement for such experiments is that the interpretation of their results is unequivocal. The complexity of natural behavior is an obstacle to this requirement because the more complex the context and the behavior, the greater the number of potential interpretations of any set of results. Furthermore, in order to compare their favored principle with possible alternatives, researchers in sub-domains such as motor adaptation tend to all use the same experimental paradigms (for instance, planar reaching movement with one arm under a force field), generating cumulative data out of which they produce evolving interpretations. Consequently, they focus on extremely elementary phenomena, yielding a biased picture of more general aspects of the organization of behavior.

By contrast, the engineering approach to the organization of behavior is synthetic. It starts from principles whatever their origin, implements them on robotics platforms or simulators, and then evaluates the properties of the resulting systems. The purpose of engineering-oriented research is to produce functional systems. Consequently, the more elaborate the generated behavior, the better it is.

The principles that the life sciences researchers carefully extract from experimental data and that the engineers use for designing their systems are the meeting point between the two approaches. Nevertheless, synthetic systems still fall far short of living systems in their abilities to interact appropriately with their environment. Thus researchers in the engineering sciences hope to improve their systems by calling upon better principles revealed by research in the life sciences.

Reciprocally, experimental research in the life sciences benefits from the theoretical investigations of the principles led by engineering researchers and from demonstrations that the principles can generate the observed behavior in synthetic systems. The theories built in the engineering effort provide useful tools to conceptualize the results of life science experiments. An example of this process is the case of trial-and-error learning, which was first studied by experimental psychologists, then formalized by computer scientists as reinforcement learning algorithms, eventually leading to the discovery of neural processes that were consistent with the predictions of the theory (e.g., Schultz, Dayan, & Montague, 1997).

Schack and Ritter (2012) stress the inadequacy of studying elementary behavioral phenomena in isolation. In order to transfer the corresponding concepts to robotics, one must rather frame them into more general theories and control architectures that cast additional constraints on them. Thus, an outstanding benefit of interactions between engineers and life scientists is that engineering goals push the life science research towards more integrative studies of complex behavioral phenomena.

Such interactions have been further promoted since the emergence of humanoid robotics. Given the complexity of controlling a humanoid robot so that it achieves most of the tasks a human being is capable of, it has become mandatory for engineers to call upon the principles of human motor control, learning, and decision making – to cite a few – that are studied by psychologists and neurosciences researchers. For the study of simple behavior, the connection between the engineering sciences and the life sciences in these domains is becoming quite tight, as illustrated by many trans-disciplinary conferences, journals and research organizations. But researchers from both disciplines have now entered more complex domains of investigation where a lot remains to be done.

One such difficult domain is our feeling that there is a steady world and an underlying space around us. In developmental psychology, the issue of “the child’s construction of reality” was raised more than 70 years ago by Piaget (1937/1954); philosophical and mathematical investigations, by authors like Husserl (1939/1970) and Poincaré (1905/1907), go even farther back in some cases. The question can be stated as follows: How is it that, given our diverse sensors that are moving at any moment, we get to the idea that there is a more or less permanent world around us that contains objects and living beings and that is endowed with spatial and temporal properties? This is a difficult question because it does not seem trivial to extract these properties from our sensors. The importance of this question for explaining the performance of a soccer player is nicely framed by Sandamirskaya et al. (2012). Part of the answer to this question seems to rely on our dynamic interactions with this world: It seems that we need to act on it to form a notion of its existence.

This difficult question is also crucial from the standpoint of “developmental robotics.” If we want a robot to plan its actions in a complicated setting, it has to reason in a space appropriate for such a plan; i.e., “external” space and the objects it contains. But if we want this approach to work in unprepared environments, providing the robot with a detailed representation of what is around it is not an option. The robot has to be able to build its own representation of its environment through its interactions with it.

This special issue of *New Ideas in Psychology* addresses such difficult questions from a transdisciplinary standpoint. The articles derive from the workshop on Anticipatory Behavior in Adaptive Learning Systems (ABiALS) that was held at the Center for Interdisciplinary Research (ZIF) in Bielefeld, Germany, in February 2011. The topic of the workshop was “Spatial Representations and Dynamic Interactions.”

Since the first ABiALS workshop, which took place in 2002 in Edinburgh, Scotland, participants have worked from the shared assumption that predictions and anticipations play a key role in organizing behavior (Butz et al., 2003; 2007). Recent research using empirical, theoretical and computational methodologies is increasingly revealing that brain function and cognition are essentially anticipatory(e.g., Berthoz, 1997/1999). The view of a proactive brain continuously generating and evaluating predictions has been put forward in a number of interdisciplinary initiatives, including but not limited to the ABiALS conferences. The view of the brain as an anticipatory device can inform and cross-fertilize neuroscientific, psychological, and engineering studies. It can advance our understanding of the representation and construction of reality in much the same way as theories of reinforcement learning have advanced our understanding of reward and motivation.

Some of the contributions to this issue are more concerned with spatial representation; others focus to a greater extent on dynamic actions or interactions with the world; still others are dedicated to the anticipatory processes involved in learning and using the corresponding representations.

In the first category, Wolfram Schenck (2012) examines the anticipatory visual processing of the environment when the eyes are performing saccadic movements. Schenck postulates that a visual forward model predicts the visual input to the eye after a saccade is performed, which would correspond to mentally centering an object seen at the periphery before actually making a saccade towards it. The neurophysiological phenomenon is called “predictive remapping” and may play a central role in our feeling that there is a steady world around us. With a robotic set-up, Schenk shows that predictive remapping strongly enhances the performance of a grasping module. He then discusses the biological relevance of the resulting control architecture, in light of such phenomena as attention and mental imagery.

As Piaget (1937/1954) clearly pointed out, building a representation of the external world further implies building a representation of ourselves in this world. Where the spatial position and posture of the body are concerned, the representations to be acquired are called the *body schema* and the *body image* (see e.g. Hoffmann et al. (2110)). When we are interacting with the world, particularly when we do this with tools, is the representation of the tool included in the representation of the world or in the body schema? Two contributions are dedicated to this topic.

Cristina Massen (2012) investigates two questions about tool use that requires some planning capabilities. First, when we are using a tool, do we incorporate it as an extension of our body schema, or do we call upon a central representation that maps between body movements and the environmental effects of the tool? Second, is the potential central representation of the tool abstract or concrete? Her survey provides arguments in favor of rather abstract central representation, based on the study of precuing, bimanual coordination, and observational and priming effects. The role of anticipation in motor preparation is particularly important in the precuing paradigm.

The contribution from Christine Sutter et al. (2012) is complementary to Massen’s. The authors focus on technologies that give rise to complex visuomotor transformations, such as laparoscopic minimally invasive surgery tools with an external visual feedback display. In that context, they study the respective influence of proximal feedback (proprioceptively and visually related to the hand) versus distal feedback (related to the end effector of the tool). They show that the dominance of distal effects in action control is a major precondition for controlling tools successfully. It allows for a wide range of flexible sensorimotor adaptations and it gives the user the feeling of being in control. However, this mechanism seems to be subject to boundary conditions: it breaks down when there are extreme discrepancies in perception-action feedback. Here the conflict in information processing makes the behavior slower and more error-prone; moreover, action control mostly based on distal effects shifts to action control based on proximal effects. Thus, action-effect control principles play an important role for understanding the constraints on acquiring and dealing with tool transformations.

Beyond the representation of tools, we must study the representation of actions themselves. Thomas Schack and Helge Ritter (2012) investigate the impact of the organization of cognitive representation of actions on motor performance. They introduce the notion of *Basic Action Concepts* (BACs) as elementary components of the agent’s possible representations of his/her own actions and study the relationship between the structure of a set of BACs and performance in motor tasks. In addition, they investigate how this general framework derived from studies in experimental psychology can be applied in a robotic context, by providing key elements of a control architecture.

Action representation is also central to *Action Simulation Theory* (AST). Laura Barca and colleagues (2012) provide a survey of this theory, before sketching a computational model. One of the key ideas in AST is that the representation of an action is not a static content stored in a memory register – as would be the case for the representation of a variable in a computer – but rather a dynamic process involving the re-enactment of the action. AST casts new light on motor phenomena, but it may also be applicable to the representation of space or even to social contents.

The next two contributions are more concerned with the selection, coordination, and control of dynamic interactions with the world.

Oliver Herbort (2012) studies the sequential planning of movements, focusing on the impact of the next movement on the way a previous movement is performed. For instance, we would not grasp a knife the same way in order to put it on a table, to cut something with it, or to give it to someone else. The most commonly accepted explanation for these phenomena is based on the optimal control framework. Herbort shows the limitations of this explanation, which is neither necessary nor sufficient to account for the properties of movement. He proposes an alternative model, based on a collection of simple biases, which better explains the data.

At a more abstract level, Martin Butz (2012) investigates the modular decomposition within an anticipatory framework between an action selection module that determines which goal should be pursued and a control module that determines how to achieve the current goal. He shows how the representation of goals may emerge from the combination of such modules and concludes that the emergent goal representations may be a key to the development of behaviorally grounded, pre-linguistic structures.

The contribution from Lommertzen et al. (2012) studies the interactions between perceptual and motor processes. The authors compare the impact of the Rod and Frame Illusion (RFI) in two contexts that imply very different motor involvement from the participants. They show that participants are similarly affected by the illusion independently of the amount of motor involvement, arguing for a common representation level for the perceptual and the motor systems involved in the tasks.

The contributions reviewed so far would normally be considered research in psychology and/or robotics. The last two bring in computational models of phenomena studied in the neurosciences.

First, Dynamic Field Theory (DFT) models the dynamics of the populations of neurons involved in sensory-motor phenomena at a rather abstract level. It can be seen as an intermediate formalism facilitating the transfer of principles between neurosciences and engineering. Yulia Sandamirskaya et al. (2012) explain how DFT can be extended to perform more cognitive operations: creating or activating an instance of an abstract representation from sensory data (i.e., the capacity to recognize an object), changing a reference frame, and performing a sequence of recognition operations by storing the sought objects in memory until they are found. These very basic cognitive capabilities are illustrated in a robotic context.

Finally, the paper from Keith Downing (2012) presents an overview of the neural mechanisms involving anticipatory or predictive processes in different brain areas (the cerebellum, the basal ganglia, the hippocampus, and the neocortex). He applies the theory of *cognitive incrementalism,* which states that high-level cognition is built on top of lower-level sensorimotor behavior.

Taken together, all these papers give an up-to-date picture of research at the intersection between the representation of space and complex, interactive behavior. We believe that the different viewpoints collected in the special issue shed a complementary light on the corresponding questions and we hope that the edition of this special issue will contribute in strengthening the growing community of researchers concerned with them, both from the life sciences side and from the robotics side.

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