From Sensorimotor to Higher-Level Cognitive Processes: An Introduction to Anticipatory Behavior Systems

Giovanni Pezzulo[1,2], Martin V. Butz[3],
Olivier Sigaud[4], and Gianluca Baldassarre[2]

[1] Istituto di Linguistica Computazionale Antonio Zampolli,
Consiglio Nazionale delle Ricerche,
Via Giuseppe Moruzzi, 1 - 56124 Pisa, Italy
giovanni.pezzulo@cnr.it
[2] Istituto di Scienze e Tecnologie della Cognizione,
Consiglio Nazionale delle Ricerche,
Via San Martino della Battaglia 44, I-00185 Roma, Italy
gianluca.baldassarre@istc.cnr.it
[3] University of Würzburg, Röntgenring 11, 97070 Würzburg, Germany
mbutz@psychologie.uni-wuerzburg.de
[4] Institut des Systèmes Intelligents et de Robotique (CNRS UMR 7222)
Université Pierre et Marie Curie
Pyramide Tour 55, 4 Place Jussieu - 75252 PARIS cedex 05 France
Olivier.Sigaud@upmc.fr

Abstract. This book continues the enhanced post-workshop proceedings series on "Anticipatory Behavior in Adaptive Learning System" (ABiALS), published as Springer LNAI 2684 and LNAI 4520 [3,5]. The proceedings offer a multidisciplinary perspective on anticipatory mechanisms in cognitive, social, learning, and behavioral processes, with contributions from key researchers in psychology and computer science. This introduction offers a conceptual terminology on anticipatory mechanisms and involved predictive capabilities. Moreover, it provides an overview of the book contributions, highlighting some of their peculiarities and complementarities.

Keywords: Anticipation, anticipatory behavior, prediction, simulation, goal-directed behaviour.

1 Introduction

This book is the third volume of extended post-workshop proceedings on "Anticipatory Behavior in Adaptive Learning System" (ABiALS). The previous two volumes were published as Springer LNAI 2684 and LNAI 4520 [3,5]. The theme of anticipation and anticipatory behavior continues to gather attention from scholars of many disciplines, including computer science, psychology, neuroscience, and philosophy.

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Anticipatory mechanisms are increasingly recognized as a key research area. At the European level, the EU Commission has recognized the relevance of the theme of anticipation by funding the MindRACES (from Reactive to Anticipatory Cognitive Embodied Systems) project (FP6-511931) in the area of Cognitive Systems research. One of the final outputs of the MindRACES project is a collective book on anticipation [10]. Successively, the theme of anticipation has been targeted by numerous EU-funded projects. For instance, the Technical Background Notes for Proposers document of the EU Commission (relative to FP7-ICT CALL 4, Work Programme 2009-10, Challenge 2: Cognitive Systems, Interaction, Robotics, pag. 10) indicates the following key research question: *How can we predict (and anticipate) future events in their environment (including, where relevant, the behavior of other agents - human or not - operating in the same environment)?*

The last edition of the ABiALS workshop was sponsored and hosted by the EU-funded Coordination Action *euCognition*: The European Network for the Advancement of Artificial Cognitive Systems (FP6-26408). Thanks to the euCognition's Executive Committee, and in particular thanks to David Vernon, the athors were able to organize an extremely stimulating two-days event (held on 26 and 27 June 2008 at Munich), which combined ABiALS 2008 and the Fifth Six-Monthly Meeting of euCognition"The Role of Anticipation in Cognition". The two-days event saw the participation of six invited speakers (four of whom contributed to this book), over twenty papers discussed either in oral or poster presentations, and the participation of over fifty researchers coming from several European nations and from outside Europe. Most of the contributors of this book participated to this event.

Within this renewed interest on anticipation and anticipatory behavior, the goal pursued by the ABiALS workshop series is to foster interactions, mutual understanding, and effective communications and cooperations between scientists belonging to different disciplinary domains, which nonetheless work on the same subject. To do so, we believe that it is also necessary to continue developing the theoretical and computational foundations of the study of anticipation in natural and artificial agents, and to integrate insights from many disciplines into a principled approach for the study of living systems and the design of artificial systems – also termed the *anticipatory approach* [4,10].

The anticipatory approach aims to understanding and conceptualizing anticipation and anticipatory behavior in natural cognition and to implementing them in artificial systems. Anticipatory systems have capabilities that go far beyond those of purely reactive ones and anticipation is a strong prerequisite for various cognitive functions and for goal-directed behavior. This introductory chapter first revisits the terminology of anticipatory systems and then introduces the book's contributions and their key aspects.

2 Basic Terminology Revisited

Although anticipations and predictions are often used nearly as synonyms in natural language, in scientific realms there is a clear distinction between predictive systems and anticipatory systems. Generally, anticipatory systems are those that use their predictive capabilities to optimize behavior and learning to the best of their knowledge. Rosen [11, ch. 6] might have been one of the first who put this idea into a useful definition. According to this author, an anticipatory system is:

> [...] 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.

More precisely, he also states that:

> An anticipatory system S_2 is one which contains a model of a system S_1 with which it interacts. This model is a predictive model; its *present* states provide information about *future* states of S_1. Further, the present state of the model causes a change of state in other subsystems of S_2; these subsystems are (a) involved in the interaction of S_2 with S_1, and (b) they do not affect (that is, are unlinked to) the model of S_1. In general, we can regard the change of state in S_2 arising from the model as an adaptation, or pre-adaptation, of S_2 relative to its interaction with S_1.

The most peculiar aspect of anticipatory systems is thus their dependence on (predicted) future states and not only on past states. Although the definition provided by Rosen may be too strong (it excludes systems that coordinate with future states without explicitly representing them – we call this form *implicit anticipation*), it describes the kinds of systems we are mainly interested in: those able to realize behavior mediated by explicitly formulated expectations (*explicit anticipation*). In order to produce explicit expectations, anticipatory systems need predictive mechanisms, which may have different realizations, but nevertheless share the common feature of predicting future states.

Thanks to their predictive mechanisms, anticipatory systems can employ anticipatory behavior, which may be defined according to [2, p. 3] as:

> [...] a process or behavior that does not only depend on past and present but also on predictions, expectations, or beliefs about the future.

It is this capability to formulate predictions and to use them for own purposes that distinguishes an anticipatory system from a merely reactive one. For example, anticipation plays a key role in goal-directed and proactive behavior, since patterns of actions can be selected depending on their expected outcomes and not (only) on stimuli that are available here and now. While reactive systems can be functionally described with STIMULUS → ACTION (S-A) behavioral patterns, anticipatory systems are instead based on EXPECTATION → ACTION (E-A) behavioral patterns, which are permitted by the explicit prediction of a stimulus or an action effect (STIMULUS → EXPECTATION (S-E), or STIMULUS ACTION → EXPECTATION (S-A-E)). However consider that, as it will be clearly shown by the works presented in the book, anticipatory behavior can have different functional organization and can rely upon a multitude of different specific mechanisms.

A last important distinction needs to be drawn between "prediction" and "anticipation":

Prediction is a representation of a particular future event.
Anticipation involves processes underlying future-oriented action, decisions, and behaviors based on (implicit or explicit) prediction.

Thus, anticipation – the main focus of this book – includes prediction but goes beyond mere forecasting in that it refers to processes which use predictive knowledge to coordinate behavior and, more importantly, to act in a goal-directed fashion and pro-actively to realize achievable and desirable future states while avoiding unsuitable ones.

3 Overview of the Book

Due to the interdisciplinary nature of the theme of anticipation, and the variegated audience of the ABiALS workshop, the book includes a diverse range of contributions that vary from psychological theories to evaluation of computational frameworks based on anticipation and real-world applications. To ease reading, the book contributions, now reviewed one by one, are grouped into six categories.

A technical note before starting. This section references to all the works of the book in terms of authors and title of the respective book chapters, but a whole reference of the works can be searched for (for example) as:

> Pezzulo G., Butz M.V., Sigaud O., Baldassarre G. (2009). From sensorimotor to higher-level cognitive processes: An introduction to anticipatory behavior systems. In Pezzulo G., Butz M.V., Sigaud O., Baldassarre G. (Eds.), *Anticipatory Behavior in Adaptive Learning Systems – From Psychological Theories to Artificial Cognitive Systems*, LNAI 5499. Berling: Springer-Verlag.

3.1 Anticipation in Psychology: Focus on the Ideomotor Principle

The book includes two (invited) contributions by two leading cognitive psychologists, Joachim Hoffmann and Bernhard Hommel, that put forward an *ideomotor* view of goal-directed action. They present their comprehensive frameworks *ABC (Anticipative Behavioral Control)* [6] and *TEC (Theory of Event Coding)* [7], which place anticipation at the very core of cognition. In addition, both contributions discuss in depth how their ideas are being implemented in robotic systems.

The first paper, contributed by Joachim Hoffmann (ABC: A Psychological Theory of Anticipative Behavioral Control), offers a complete ideomotor model of goal-directed action and discusses in detail the roles of action-effect contingencies: how are they acquired and contextualized, and how can they be arranged hierarchically to realized nested loops of control that permit the transformation of abstractly defined goals into motor patterns. The paper reviews recent empirical evidence in favor of the ABC theory, and discusses a recent computational implementation: the SURE_REACH architecture [1].

The second paper, contributed by Pascal Haazebroek and Bernhard Hommel (Anticipative Control of Voluntary Action: Towards a Computational Model), describes another theory based on the ideomotor principle: the Theory of Event Coding on human goal-directed action. Differently from Hoffmann's theory, one of the main tenets of the TEC is that integration of perceptual and motor codes is realized at a distal level; specifically, at the level of distal perceptual effects of actions, not their proximal ones such as reafferences. As a consequence, the TEC describes planning as operating on distal perceptual codes and on-line realization by different (automatic) processes. The paper discusses also a recent implementation of the TEC theory: the HiTEC computational model.

3.2 Theoretical and Review Contributions

The book continues with three theoretical and review contributions that explore multiple facets of anticipation and anticipatory behavior.

The first paper is a quite provocative invited contribution by Jurgen Schmidhuber (Driven by Compression Progress: A Simple Principle Explains Essential Aspects of Subjective Beauty, Novelty, Surprise, Interestingness, Attention, Curiosity, Creativity, Art, Science, Music, Jokes). The author introduces the principle of 'data compression progress', that is equivalent to an augmented capability to predict data, as a basic mechanism that makes data 'interesting in itself' and motivates exploratory behavior. This principle has the potential to be relevant for multiple domains, which range from art to science, and captures the slipping concept of 'beauty' in a rigorous and extremely interesting way.

The second paper is contributed by Fabio P. Bonsignorio (Steps to a Cyber-Physical Model of Networked Embodied Anticipatory Behavior). It sketches a modeling framework for embodied anticipatory behavior systems by using a wide range of formal notions such as entropy, complexity, and information. Although still rather preliminary, this paper introduces numerous essential issues toward the development of more autonomous artificial systems based on anticipatory capabilities.

The last paper is authored by Henrik Svensson, Anthony Morse, and Tom Ziemke (Neural Pathways of Embodied Simulation). This paper offers a deep discussion of the many facets of recent theories based on the idea of internal simulation. The main contributions of this paper are a comprehensive review of the multiple pathways in neural simulations and a discussion of the differences between procedural and declarative knowledge in covert simulation.

3.3 Anticipation and Dynamical Systems

Two papers explore anticipation in relation to internal agent dynamics, and discuss two kinds of anticipatory processes that are coupled to internal dynamics rather than responsible for the selection and triggering of overt behavior.

In the first paper, Michela Ponticorvo, Domenico Parisi, and Orazio Miglino (The Autopoietic Nature of the "Inner World": A Study with Evolved "Blind" Robots) explore the internal dynamics of an agent that is deprived of any external stimulation. In these extreme circumstances, the agent cannot rely on external stimuli to predict the effects of its actions, but only on self-generated stimuli – an 'inner world'. The paper shows that, even in these conditions, artificial agents can be evolved that show significant adaptivity thanks to the coupling of their 'inner worlds' and the external environment.

The second paper is contributed by Alberto Montebelli, Robert Lowe, and Tom Ziemke (The Cognitive Body: From Dynamic Modulation to Anticipation). Here the basic agent architecture is characterized by the presence of a motivational internal state, having slowly changing dynamics, which modulates the agent's activity. This architecture is then augmented with an anticipatory mechanism, which is directly coupled to the internal unit. The anticipatory mechanism significantly enhances the agent's adaptivity. The most peculiar aspect of this paper is that – in contrast to standard implementations – anticipation operates through bodily mediation by modulating the internal dynamics, rather than by triggering direct behavioral responses.

3.4 Computational Modeling of Psychological Processes in the Individual and Social Domains

Four papers are devoted to modeling and interpreting specific psychological experiments. In particular, they investigate sustained inattentional blindness, the foreperiod paradigm, collision avoidance behavior, and cooperative dynamics in the Iterated Prisoner's Dilemma game.

Anthony F. Morse, Robert Lowe, and Tom Ziemke (A Neurocomputational Model of Anticipation and Sustained Inattentional Blindness in Hierarchies) present a model of how sustained inattentional blindness results from a process of anticipation of task-relevant features. In a simulated 'input tracking' task, the authors find that anticipation enhances performance of the task and simultaneously degrades detection of unexpected features, thereby modeling the sustained inattentional blindness effect.

Johannes Lohmann, Oliver Herbort, Annika Wagener, and Andrea Kiesel (Anticipation of Time Spans: New Data from the Foreperiod Paradigm and the Adaptation of a Computational Model) first review empirical and theoretical literature on the foreperiod paradigm, where subjects are asked to react to events that occur at more or less unpredictable times after a warning stimulus (foreperiod). Then in a model they systematically vary predictability of the foreperiods and find adaptation to different probability distributions with a pronounced adaptation for the peaked more-predictable one. Finally the authors discuss their results in relation to the computational model proposed by Los and colleagues [8].

Janneke Lommertzen, Eliana Costa e Silva, Raymond H. Cuijpers, and Ruud G.J. Meulenbroek (Collision-Avoidance Characteristics of Grasping: Early Signs in Hand and Arm Kinematics) have studied prehension kinematics and collision-avoidance strategies in grasping tasks. Their study shows that different forms of objects (small or large cylinders) elicits different approaching phases and subjects successfully avoid collisions by adapting the last phase of their movements (aperture overshoots) and by adjusting the movements of their distal joints. The authors relate their study to computational models of reaching and collision avoidance and succeed in replicating and interpreting the empirical results within a robotic set-up.

The last paper, contributed by Maurice Grinberg and Emilian Lalev (The Role of Anticipation on Cooperation and Coordination in Simulated Prisoner's Dilemma Game Playing) studies anticipatory strategies in a cooperative social task: the Iterated Prisoner's Dilemma game ("IPD"). The authors first describe the results of experiments on IPD obtained with humans and then investigate and interpret such data on the basis of a connectionist model. Within genetic simulations, the model shows how under certain circumstances anticipatory strategies emerge and lead to increased cooperation payoffs, therefore making the case that anticipation is a key ingredient for having a high level of cooperative coordination in simulated and real societies.

3.5 Behavioral and Cognitive Capabilities Based on Anticipation

As discussed in the introduction, anticipation plays a major role in the acquisition and use of multiple behavioral and cognitive capabilities. The three papers of this section address the role of anticipation in learning a stand-up posture, in space perception, and in planning.

The first paper, contributed by Camille Salaun, Vincent Padois, and Olivier Sigaud (A Two-level Model of Anticipation-based Motor Learning for Whole Body Motion) presents a model of motor learning that combines Operational Space Control and Optimal Control. The paper demonstrates the efficacy of the latter approaches in a simulated robotic task that consists in learning to stand-up. In the model anticipation has a two-fold important function, namely learning the dynamics model of the system and coordinating the two types of control.

The paper contributed by Wolfram Schenck (Space Perception through Visuokinesthetic Prediction) follows the "perception through anticipation" approach of [9] and demonstrates how objects can be localized by generating a visuokinesthetic (iterative) simulation of reaching with a robotic arm. Within this framework, space perception arises from the knowledge of how to move (e.g. push) an object. Anticipation is used for sensory prediction and novelty detection.

The last paper in this section, contributed by Irene Markelic, Tomas Kulvicius, Minija Tamosiunaite, and Florentin Worgotter (Anticipatory Driving for a Robot-Car Based on Supervised Learning) may be the most applicative of the book. The authors construct a database that couples look-ahead sensory information and action sequences. The constructed knowledge is the used to train a car-like trajectory planning robot that runs at real-time by issuing steering and velocity control commands in a human manner.

3.6 Computational Frameworks and Algorithms for Anticipation and Their Evaluation

The last section of the book includes three papers that discuss basic issues of anticipatory mechanisms and algorithms.

Birger Johansson and Christian Balkenius (Prediction Time in Anticipatory Systems) have run simulated robotic experiments in a guard-and-thieves scenario with the aim of assessing what is the best length of the future time interval in which thieves should anticipate the movement of the guard in order to successfully trick them and steal a treasure. Their results show that it is not always better to predict long into the future and that the best performance is indeed achieved when the time spent planning is comparable to the time it will take to perform the tasks.

The paper contributed by Matthias Rungger, Hao Ding, and Olaf Stursberg (Multiscale Anticipatory Behavior by Hierarchical Reinforcement Learning) presents a two-level hierarchical reinforcement learning scheme that combines a discrete representation (finite state automaton) at the higher layer, and a continuous representation at the lower layer. The results of the test of the model within in a robot grasping task show that the iteration between both layers permits to autonomously determine suitable solutions to new tasks.

Olivier Sigaud, Martin V. Butz, Olga Kozlova, and Christophe Meyer (Anticipatory Learning Classifier Systems and Factored Reinforcement Learning) compare both conceptually and empirically Factored Reinforcement Learning (FRL) and Anticipatory Learning Classifier System (ALCS) techniques. Their empirical comparison reveals that an instance of the latter (XACS) scales much better than an instance of the former (SPITI) in two benchmark problems. The authors conclude the work by analyzing what are the key mechanisms in XACS that permit better performance, and propose importing them into FRL systems.

4 Conclusions and Important Open Issues on Anticipation

As diverse as the included contributions are, as overarching their perspective and inclusive the highlighted aspects of anticipatory mechanisms and behavior. While the benefits of anticipatory mechanisms and the ubiquitous presence of anticipatory behavior in various levels of perceptual processing and motor control becomes increasingly clear, the challenge of combining these different anticipatory mechanisms appropriately and efficiently appears to be the next challenge in anticipatory processing systems.

In this respect, it is hoped that the next years will provide theoretical and implementation advances on the interactions between different anticipatory functions and mechanisms, with a particular emphasis on the different sensory-motor feedback loops and the learning mechanisms which might allow both the acquisition of predictive capabilities and their exploitation for guiding action. The book shows that several ideas do exist on these issues in various forms, so in the near future it is paramount to invest research efforts to organize them within comprehensive frameworks and, more importantly, within whole integrated architectures.

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