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What is This?
Special issue on artificial mental imagery in cognitive systems and robotics

Alessandro Di Nuovo1,2, Vivian M De La Cruz3 and Davide Marocco4

1 Introduction

The present special issue of Adaptive Behavior is focused on exploiting the concept of mental imagery and mental simulation as a fundamental cognitive capability, as applied to artificial cognitive systems and robotics. The special issue is motivated by the fact that the processes behind the human ability to create mental images have recently become an object of renewed interest in cognitive science and, in particular, their applications in the field of artificial cognitive systems. With the aim of providing a panorama of the current research activity on the topic, this special issue presents seven selected contributions considered to be representative of the state of the art in the field.

In the section that follows, we give a short introduction on recent work on mental imagery in general, and in the field of artificial cognitive systems in particular, in order to help the reader to contextualize the topic. Subsequently, we summarize the new findings that this special issue presents.

Mental imagery has long been the subject of research and debate in philosophy, psychology, cognitive science, and more recently, neuroscience (Kosslyn, 1996), but only quite recently a growing amount of evidence from empirical studies has begun to demonstrate the relationship between bodily experiences and mental processes that actively involve body representations. This is also due to the fact that, in the past, philosophical and scientific investigations of the topic primarily focused upon visual mental imagery. Contemporary imagery research has now broadly extended its scope to include every experience that resembles the experience of perceiving from any sensorial modality. The underlying neurocognitive mechanisms involved in mental imagery, however, and the subsequent physical performance, are still far from being fully understood. Understanding the processes behind the human ability to create mental images of events and experiences, remains a critical issue.

Recent research, both in experimental as well as practical contexts, suggests that imagined and executed movement planning relies on internal models for action (Hesslow, 2012). These representations are frequently associated with the notion of internal (forward) models and are hypothesized to be an integral part of action planning (Wolpert, 1997; Skoura, Vinter, & Papaxanthis, 2009). Furthermore, Steenbergen, van Nimwegen, and Craje (2007) suggest that motor imagery may be a necessary prerequisite for motor planning. Jeannerod (2001) studied the role of motor imagery in action planning and proposed the so-called equivalence hypothesis, suggesting that motor simulation and motor control processes are functionally equivalent (Munzert, Lorey, & Zentgraf, 2009; Ramsey, Cumming, Eastough, & Edwards, 2010).

Advances in information and communication technologies have made new tools available to scientists interested in artificial cognitive systems and in designing robotic platforms equipped with sophisticated motors and sensors in order to replicate animal or human sensorimotor input/output streams, e.g. the iCub humanoid robot (Metta, Natale, Nori, Sandini, Vernon, Fadiga, et al., 2010). These platforms, despite the tremendous potential applications, still face several challenges in developing complex behaviors (Asada et al., 2009). To this end, increased research efforts are needed to understand the role of mental imagery and its mechanisms in human cognition and how it can be used to enhance motor control in autonomous robots. From a technological point of view, the impact in the field of robotics could be significant. It could lead to the derivation of engineering principles for the development of autonomous systems that are capable of...
exploiting the characteristics of mental imagery training so to better interact with the environment and refine their motor skills in an open-ended process.

Among the many hypotheses and models already tested in the field of cognitive systems and robotics, the use of mental imagery as a cognitive tool capable of enhancing robot behaviors is both innovative and well-grounded in experimental data. Experiments on internal simulation of perception using artificial neural network (ANN) robot controllers are presented by Ziemke, Jirenhed, and Hesslow (2005). The paper focuses on a series of experiments in which feed-forward neural networks (FFNNs) were evolved to control collision-free corridor following behavior in a simulated Khepera robot and predict the next time step’s sensory input as accurately as possible. The trained robot is in some cases actually able to move blindly in a simple environment for hundreds of time steps, successfully handling several multi-step turns. Nishimoto & Tani (2009) present a neuro-robotics experiment in which developmental learning processes of the goal-directed actions of a robot were examined. The robot controller was implemented with a Multiple Timescales RNN model, which is characterized by the co-existence of slow and fast dynamics in generating anticipatory behaviors. Through the iterative tutoring of the robot for multiple goal-directed actions, interesting developmental processes emerged. Behavior primitives in the earlier fast context network part were self-organizing, while they appeared to be sequenced in the later, slow context part. Also observed was that motor images were generated in the early stage of development. Gigliotta, Pezzulo, and Nolfi (2011) show how simulated robots evolved for the ability to display a context-dependent periodic behavior can spontaneously develop an internal model and rely on it to fulfill their task when sensory stimulation is temporarily unavailable. Results suggest that internal models might have arisen for behavioral reasons and successively exapted for other cognitive functions. Moreover, the obtained results suggest that self-generated internal states need not match in detail the corresponding sensory states and might rather encode more abstract and motor-oriented information. In recent work, Di Nuovo, De La Cruz, Marocco, Di Nuovo, and Cangelosi (2012), the authors present new results showing that the robot iCub is able to imagine or mentally recall and accurately execute movements learned in previous training phases, strictly on the basis of the verbal commands. Further tests show that data obtained with imagination could be used to simulate mental training processes, such as those that have been employed with human subjects in sports training, in order to enhance precision in the performance of new tasks through the association of different verbal commands. Finally in Di Nuovo, Marocco, Di Nuovo, and Cangelosi (2013) a model of a controller, based on RNN, is presented to allow the humanoid robot iCub to improve autonomously its sensorimotor skills. This is achieved by endowing the controller of a secondary neural system that, by exploiting the sensorimotor skills already acquired by the robot, is able to generate additional “imaginary” examples that can be used by the controller itself to improve the performance through a simulated “mental training”. Results of experimental tests in controlling a ballistic movement with the simulator of the iCub humanoid robot platform are presented as evidence of the opportunities presented by the use of artificial mental imagery in cognitive science and robotics.

An example of the essential role mental imagery can play in human–robot interaction was recognized by Roy, Hsiao, and Mavridis (2004). They presented a robot, called Ripley, that is able to translate spoken language into actions for object manipulation guided by visual and haptic perception. The robot maintained a dynamic “mental model”, a three-dimensional model of its immediate physical environment that it used to mediate perception, manipulation planning and language. The contents of the robot’s mental model could be updated based on linguistic, visual, or haptic input. The mental model endowed Ripley with object permanence, remembering the position of objects when they were out of its sensory field.

2 Contributions in this issue

Svensson, Thill, and Ziemiłke explore the idea of dreams as a form of mental imagery and the possible role they might play in mental simulations and in the emergence and refinement of the ability to generate predictions on the possible outcomes of actions. They consider whether certain aspects of dreaming as a type of mental imagery, could be simulated in robots by way of the inception of simulation (InSim) hypothesis. The InSim hypothesis, focuses on the crucial role the phenomenological experience of dreams might have on mental simulation abilities, especially during infancy and early childhood. In brief, what the authors propose is that robots might first need to possess some of the characteristics related to the ability to dream (particularly those found in infants and children) before they can acquire a robust ability to use mental imagery. This ability to dream, according to them, would assist robots in the generation of predictions of future sensory states and of situations in the world. The authors present an experimental setup, in which they use a simulated robot to test their hypothesis on whether dream-like mechanisms can contribute to research on the development of simulations and imagery-like
abilities. Initial results obtained with the model are discussed, in which periods of dream-like sensations seem to improve the robot’s ability to simulate. The authors interpret these results as initial proof of concept that these sensations are instrumental in rendering learning based on real sensory input more efficient.

Kaiser, Schenck, and Möller present a computational model, that is based on internal simulations, to solve the stereo matching problem. The problem of stereo matching can be briefly defined as the problem of finding correspondences in a pair of images depicting the same scene, albeit from slightly different viewpoints. The novelty of this paper is that authors operate on the sensorimotor domain, with retinal images that mimic the cone distribution on the human retina, in contrast to classical matching algorithms that work on image information alone. Authors present experiments with the arrangement of simple objects located on a table in front of the cameras, that show a good reliability in matching salient objects in a pair of stereo images. The performance of the model is evaluated through a large number of experiments on an image database and compared to a widely used approach from computer vision. Authors conclude that predictive matching is competitive to classical approaches from computer vision, and it has moreover the considerable advantage that it is fully adaptive and can cope with highly distorted images. This is accomplished by applying internal sensorimotor simulation and (subconscious) mental imagery to the process of stereo matching.

Chersi, Donnarumma, and Pezzulo present a computational model of mental simulation that includes biological aspects of brain circuits that appear to be involved in goal-directed navigation processes and supports the view of the brain as a powerful anticipatory system, capable of generating and exploiting mental simulation for predicting and assessing future sensory motor events. The model takes into account the most recent biological findings on the brain areas involved in the imagination process, such as the hippocampus, the ventral striatum, and the sensory-motor cortex. In particular, the authors show how mental simulations can be used to evaluate future events in a navigation context, in order to support mechanisms of decision making. The proposed mechanism is based on the assumption that choices about actions are made by simulating movements and their sensory effects using the same brain areas that are active during overt actions execution.

Iizuka, Ando, and Maeda present an interpretation of mental imagery based on the context of homeostatic adaptation, where the internal dynamics of a highly complex self-organized system is loosely coupled with a sensory-motor dynamic guided by the environment. This original view is supported by the analysis of a neural network model that controls a simulated agent facing sensor shifts. The agent is able to perceive a light in the environment through some light sensors placed around its body and its task is that of approaching the light. When the sensors are swapped, the agent perceives the light in the opposite direction of its real position and the control systems has to autonomously “detect” the shifting sensor and act accordingly. The authors speculate that mental imagery could be a viable way for creating self-organized internal dynamics that is loosely coupled with sensory motor dynamics. The loose coupling allows the creation of endogenous input stimulations, similar to real ones, that could allow the internal system to sustain its internal dynamics and, eventually, reshape such dynamics while modifying endogenous input stimulations.

Lalle and Dominey in their contribution suggest the idea that mental imagery can be seen as a way for an autonomous system of generating internal representation and exploiting the convergence of different multimodal contingencies. That is, given a set of sensory-motor contingencies specific to many different modalities, learned by an autonomous agent in interaction with the environment, mental imagery constitutes the bridge toward even more complex multimodal convergence. The model proposed by the authors is based on the hierarchical organization of the cortex and it is based on a set of interconnected ANNs that control the humanoid robot iCub in tasks that involve coordination between vision, hand–arm control, and language. The paper also highlights interesting relations between the model and neurophysiological and neuropsychological findings that the model can account for.

Declerk pursues another approach to the topic of mental simulation. He presents arguments that call for a reconsideration of whether the motor simulation framework widely adopted in neuropsychology and subsequently in robotics research, which he refers to as the simulation theory of affordance perception or STAP, can adequately explain affordance perception. While STAP considers motor simulation to be the only way to develop knowledge of affordances, the author presents a series of reasons for why he believes this not to be the case, claiming that other mechanisms must be hypothesized.

Seepanomwan, Caligiore, Baldassarre, and Cangelosi, tackle a classic task in mental imagery research, that of mental rotation. Using a neurorobotics and embodied cognition approach to mental rotation processes, the authors present a system-level computational model and propose an operational hypothesis of the sensorimotor mechanisms that might be underlying mental rotation. Their hypothesis draws from existing theory and evidence on motor affordance encoding, motor simulation and the anticipation of the sensory consequences of actions. They extend an existing neurocomputational model
Starting from the fact that some evidence in experimental psychology has suggested that imagery ability is crucial for the correct understanding of social intention, Lewkowicz, Delevoye-Turrell, Bailly, Andry, and Gaussier present an interesting study to investigate intention-from-movement understanding (this article will appear in issue 21.5). The authors’ aim is to show the importance of including the more cognitive aspects of social context for further development of the optimal theories of motor control, with positive effects on robot companions that afford true interaction with human users. In the paper, the authors present a simple but thoroughly executed experiment, first to confirm that the nature of the motor intention leads to early modulations of movement kinematics. Second, they tested whether humans use imagery to read an agent’s intention when observing the very first element of a complex action sequence. Experimental data demonstrate that it is possible to read motor intention through the simple observation of kinematic deviants, because of this the authors argue that reading intentionality may not depend on high-level cognitive function as suggested in the psychological literature, because results suggest that low-level motor indices afford intention reading without the need for motor imagery. Human agents, however, may use imaging beyond simulation to create an embodied sense of interactivity. As a first step to support this hypothesis, the authors discuss a study, in which an artificial (neural network) classifier was able, after learning the meaning of kinematic deviants, to classify the three categories of actions with the same degree of accuracy as human participants, without the need of complex cognitive processes.

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**References**


About the Authors

**Alessandro Di Nuovo** completed his PhD in computer engineering at the University of Catania in 2009, with a thesis entitled ‘Computational intelligence for the design of embedded computer systems.’ After that he continued to work in academia as contract lecturer (2009–2010) for the University of Enna “Kore” and then, in 2011, as a research associate for the University of Catania. From 2012 he was a research fellow with Plymouth University (UK) and with the University of Enna Kore (Italy). Even at his relatively young age, he has tackled several research activities within different application domains, authoring more than 40 articles he has presented at top international conferences as well as publishing in several well-reputed peer-reviewed journals. His current research activities are devoted to cognitive robotics, in particular on the application of the mental simulation and practice to develop the iCub humanoid robot motor skills. Furthermore he is interested in applications of computational intelligence and cognitive architectures for robot companions.

**Vivian M De La Cruz** received her doctorate in cognitive science at the University of Messina, Italy in 2007. She is currently a researcher at the department of cognitive science, education and cultural studies of the University of Messina, Italy. Her research interests focus on the use of both theoretical and computational models to explore the development of language and cognition. She is also involved in research focused on the development of mental and motor simulation abilities, number cognition and the impact of language on the emergence of these capacities, as well as how they may be implemented in artificial systems.

**Davide Marocco** received his doctorate in artificial intelligence at the University of Calabria, Italy, in 2004. He then joined as a researcher the Institute of Cognitive Sciences and Technologies of the Italian National Research Council. He is currently lecturer of cognitive robotics and intelligent systems at the University of Plymouth, UK and a member of the Centre for Robotics and Neural Systems (CRNS) of the same University. His research interests are focused on cognitive and evolutionary robotics and artificial life models of behavior and cognition, embodied cognition and active perception and evolution of communication and language with evolutionary robotics and artificial life techniques.