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EDITORIAL

Intentional action: from anticipation to goal-directed behavior

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Humans and other animals are able to guide their actions toward the realization of their own goals, both proximal and distal. Recently, cognitive neuroscientists, biologists and psychologists have begun unraveling, from different but converging perspectives, the organization of goal-directed, intentional action in terms of (brain, computational) structures and mechanisms.

Converging evidence indicates that several cognitive capabilities across the individual and social domains, including action planning and execution, understanding others' intentions, cooperation and imitation are essentially goal-directed. For example, goal representations have a crucial role in the planning and control of action, and action understanding and imitation are performed at the goal rather than at the movement level (Iacoboni et al., 2005; Wohlschläger, Gattis,& Bekkering, 2003). Moreover, it has been shown that these apparently unrelated abilities and others which were believed to be in the realm of abstract thought, such as language understanding, share common representational structures and mechanisms in the brain and involve significant use of the motor system (Fadiga, Craighero, Buccino, & Rizzolatti, 2002; Pulvermüller, 1999). Recent studies have revealed the crucial role of *canonical and mirror neurons* (Rizzolatti & Craighero, 2004; Rizzolatti et al., 1988) and *internal forward models* (Kawato, 1999; Wolpert & Ghahramani, 2004) in most of the aforementioned tasks.

These studies indicate a close link between (socio)cognitive abilities and situated action, and are shedding light on their neural underpinnings and mechanisms. Combined theoretical, empirical and computational research is revealing that during all the aforementioned activities, the motor system is highly engaged in *anticipatory, simulative and generative processes*. From a speculative point of view, a case could be made that the same predictive mechanisms provide both a "linkage with the future" required for taking goal-directed action, and a "linkage with others" required to act socially (Pezzulo, 2008; Pezzulo and Castelfranchi, 2007).

Another particularly intriguing aspect of these findings is the revelation that the two domains of perception and action, which are traditionally kept separate in the analysis of cognitive systems, cannot be disentangled. Again, anticipatory phenomena, such as expectations used to control action, and simulative processes, play a major role in the perception–action linkage, and give rise to *ideomotor* neural codes that relate actions and their effects (Hommel, Musseler, Aschersleben, & Prinz, 2001). This seems to happen at multiple levels and encompasses sensorimotor and higher-level cognitive tasks.

Overall, these recent studies (and others) have led to a profound rethinking of basic concepts in cognitive and behavioral sciences, and a common theoretical view (a *motor-based* (or *action-based*) view of cognition) is emerging across disciplines (Jeannerod, 2006). In this context, the abilities of action execution, its planning and understanding of others' intentions are all described as essentially goal-directed and served by the same representations, which are action-oriented and involve deeply the motor apparatus. *Simulative theories* of cognition add to

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this picture the idea that representing means engaging in simulated interaction with the environment and with others, something that could be done by using (online or offline) the same set of internal models implied in motor control (Grush, 2004). Along similar lines, a few unified frameworks have been proposed, based on the idea that an essential part of one's understanding of the dynamics of the environment, and of others' intentions, is in terms of one's own motor repertoire and intentions, with crucial involvement of anticipatory and simulative mechanisms (Gallese, Keysers, & Rizzolatti, 2004; Jeannerod, 2001; Wolpert, Doya, & Kawato, 2003).

This view was born in opposition to the methodology and concepts of traditional cognitive and AI theories, which have thoroughly investigated goal-directed action and the structures for their flexible planning and learning, without, however, linking them to the functioning of the motor system. Instead of stressing the differences between the two approaches, we believe that it is productive to focus on their overlapping traits and the high potential for cross-fertilization. Indeed, the theme of intentional action and its relations with anticipatory and simulative mechanisms has recently gained enthusiasm in several other disciplines, including philosophy, cognitive robotics and the social sciences, whose theories and methods are being profoundly influenced by the cognitive and behavioral sciences. The aim of this special issue is to focus the attention of leader scientists in all these areas to the combined effort of providing a unified, multidisciplinary perspective on intentional action and on the structure of goal-directedness in the brain and in behavior.

Focus of the special issue

The focus of the special issue is the intentional, goal-directed structure of action and its implications: (1) for brain structures and functioning (ranging from biological details to grand functional schemes); (2) for action selection, execution, planning and simulation; (3) for social action (e.g., understanding others as intentional agents, collaboration, imitation); (4) in evolutionary perspective (e.g., the role of predictive capabilities in leveraging goal-directed action and cognition).

Specifically, the special issue explores the following themes (among others): What organization (brain, functional, computational) is needed for enabling and executing goal-directed action? How are proximal and distal goals coded? How is the intention-to-action hierarchy learned and neurally coded, and how do its different levels "stay together?" What are the specific mechanisms that permit an organism to (learn to) act purposefully, to activate the appropriate action depending on the organism's goals, to monitor and guide the action toward the goal's realization, to form and execute motor plans, and to evaluate the world as compliant or not compliant with an organism's goals (proximal and distal)? How are these mechanisms activated and coordinated? How do they permit the interrelation between intentional and social action, 'lower-level and 'higher-level' cognition? What are the relationships between anticipatory and simulative mechanisms and goal-directed action? How is it possible to pass from action *guided by* (representations of) the future to action *guided toward* (representations of) the future, and develop goal representations? What are the specific roles of anticipatory mechanisms and representations in the different stages/parts of goal-oriented action (e.g., choice, action selection, monitoring, control, orienting of attention, planning), and in the formation of different kinds of goals? What are the computational structures that permit an organism to flexibly plan and execute goal-directed action, and how are they learned? The range of perspectives of these papers offers biological, neurobiological and psychological evidence, as well as theoretical and computational models, in the investigation of these questions.

Contributions

This special issue presents a diverse range of work on intentional action by cognitive neuroscientists, computational neuroscientists, psychologists, biologists and cognitive roboticists. It includes papers that present novel results as well as papers that explore and illustrate the topic to a broad, interdisciplinary audience.

Arbib, Bonaiuto, Jacobs, and Frey (2009) present a review of neurophysiological studies of tool use and, in particular, how tools extend the body schema. They also relate evidence to a computational model of the visual control of grasping, proposing that tools *distalize the end-effector* from hand to tool.

de Wit and Dickinson (2009) present an *associative-cybernetic* (AC) model of goal-directed action selection that integrates outcome-response (O-R) and response-outcome (R-O) accounts developed in the fields of human ideomotor action, and animal learning.

Eskenazi, Grosjean, Humphreys, & Knoblich (2009) review evidence of the involvement of one's own motor system in the perception of actions performed by others. They also present a novel neuropsychological case study indicating that both action production and perception become impaired in the same way (following a Fitts's law) due to a frontal brain lesion.

Gallese (2009) reviews and discusses evidence on the neural bases of intention understanding abilities in humans and nonhuman primates, proposing the notion of *embodied* *simulation* to explain them, and focusing on recent findings revealing *motor abstraction*, or the coding of flexible goal hierarchies in the motor system.

Greene, Mooshagian, Kaplan, Zaidel, & Iacoboni (2009) present an fMRI study aimed at comparing the neural activity involved in social orienting to that involved in purely automatic nonsocial orienting. Their study reveals greater subcortical activity when nonsocial cues are presented and greater activity in occipito-temporal regions when social cues are presented; they also suggest an evolutionary trajectory (in terms of the brain regions involved) for automatic orienting.

Hommel (2009) discusses in-depth the Theory of Event Coding (TEC), and focuses on four of its main aspects: the *prepared-reflex principle*, automaticity of stimulus–response translation, the interconnections of action selection and execution, and the role of action effects in both processes. The result is a coherent, systematic framework that offers insights into almost all aspects of intentional action.

Imamizu and Kawato (2009) review functional neuroimaging, behavioral and computational studies of the brain mechanisms related to acquisition, modular organization, and the *predictive switching* of internal models, focusing on tool use. They then discuss how the same mechanisms regulating contextual shifting of internal models are essential for higher-order cognitive and social functions.

Nishimoto and Tani (2009) present a neurorobotic experiment, using a dynamic neural network with multiple time-scale dynamics, on the learning of goal-directed actions. Consistent with Piaget's constructivist view, their study indicates that behavior primitives are generated in earlier stages, after which they can be flexibly reused to generate sequences and achieve goals. The study also indicates a developmental trajectory from motor imagery to skill learning.

Pezzulo and Castelfranchi (2009) offer a conceptual framework that aims to reintegrate computational motor control theories (focusing on the idea of internal modeling), with theories of motivation and executive control, and make the case that thinking could consist in the control of mental simulations.

Poljac, van Schie, and Bekkering (2009) present a behavioral study indicating that reversed facilitation effects, or the tendency (arising in specific contexts) for automatically executing actions that are dissimilar from those observed, occur because subjects have to maintain a set of memory-activated task rules They also argue in favor of flexible learning of arbitrary S–R associations, and therefore of flexible cognition, not only in motor control but also in imitation and action observation.

Wenke, Gaschler, Nattkemper, and Frensch (2009) present behavioral evidence indicating that subjects can exert strategic control over the implementation of verbal instructions. They also found that, once implemented, S–R associations influence behaviour independent of potentially lost task relevance.

Wenke, Waszak, and Haggard (2009) investigated how the mode of action selection (internally generated versus externally specified) affects the subjective experience of action, observing a stronger temporal binding (i.e., the subjective compression of the interval between actions and their effects) when actions (right or left key press) and their timing (two time intervals) were both freely chosen or both externally cued.

Intentional action: an interdisciplinary enterprise

The theme of intentional action is currently producing impressive scientific advancements; we would say that it is one of the "hot topics" of today. Not only is current research on the nature of intentional action highly interdisciplinary; the striking novelty is that it breaks through the traditional boundaries of cognitive psychology and neuroscience. One such boundary is the distinction among three kinds of brain functions: perceptual, cognitive and motor. In reality, these three systems interact with great regularity to realize intentional action. Another distinction has existed between the individual and social levels: intentionality is an essential mechanism not only for individual, but also for social action. Recent evidence reveals that other's action understanding and imitation are highly goal-oriented. The last distinction is among the sensorimotor and the higher-order cognitive domains: anticipatory mechanisms required for situated action appear to be much more involved in so-called cognitive tasks than ever dreamed (or feared) before. consider, for example, prospective reasoning realized by simulation, imagery and tool use. Within only the past few years, a combined, multidisciplinary effort (from the empirical sciences mainly, but also in other communities such as cognitive robotics) has produced drastic advancements in the understanding of the goal-directed nature of action and the roots of cognition in sensorimotor abilities.

For all these reasons, we believe that the theme of intentional action is extremely relevant today, not only within several disciplines, but also in its potential to bring about truly cross-disciplinary advancements. Neuroscientific findings and models are having a significant impact on AI and psychology, while simultaneously research in cognitive robotics and computational neuroscience greatly influence empirical investigation of the brain's structure and functioning.

In this sense, the scientific community has proceeded in two diverging directions. Neuroscientists, who first proceeded from the bottom-up, that is from the recognition of simulative and emulative processes in behavior and cognition (including social cognition), are now proceeding toward the more abstract goals (including distal ones). At the same time, traditional cognitive scientists and AI researchers, who have often proceeded from the top-down, from intentions to actual actions realization, have exploited methodologies and concepts that are now being grounded in neural terms. Now, these two paths are converging and consensus is growing on ideas such as the action–perception linkage and the relevance of anticipatory and simulative mechanisms. Still, questions remain that ask for a multidisciplinary perspective, such as how the "lower" and "higher" levels of the intention-to-action hierarchy stay together, and how to pass from action to intention and back from intention to action. We believe that this special issue will contribute to providing a united view on intentional action, highlighting all its challenging aspects and fostering further research in this multidisciplinary theme.

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