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Action and language integration: from humans to cognitive robots.

Anna M. Borghi*~ and Angelo Cangelosi^
* Department of psychology, University of Bologna
~Institute of Cognitive Sciences and Technologies,
Italian National Research Council, Rome
^University of Plymouth

Abstract
The Topic is characterized by a highly interdisciplinary approach to the issue of action and language integration. Such an approach, combining computational models and cognitive robotics experiments with neuroscience, psychology, philosophy and linguistic approaches, can be a powerful means that can help researchers disentangle ambiguous issues, provide better and clearer definitions and formulate clearer predictions on the links between action and language. In the introduction we briefly describe the papers and discuss the challenges they pose to future research. We identify four important phenomena the papers address and discuss in light of empirical and computational evidence: 1) the role played not only by sensorimotor and emotional information but also of natural language in conceptual representation. 2) the contextual dependency and high flexibility of the interaction between action, concepts and language. 3) the involvement of the mirror neuron system in action and language processing. 4) the way in which the integration between action and language can be addressed by developmental robotics and Human-Robot Interaction.

Keywords: action language integration, mirror neurons, language grounding, cognitive robotics,

1. Introduction

The Topic provides a forum for the publication of the latest neuroscience and psychology experiments, computational models, cognitive robotics studies and theoretical papers on action and language integration. The selected papers present novel interdisciplinary approaches, based on empirical and computational methodologies on the cognitive and neural mechanisms linking action and language, and look at future research challenges and directions in this cross-disciplinary field.
Growing theoretical and experimental research on action and language processing in humans and animals clearly demonstrates the strict interaction and co-dependence between language and action (e.g. Cappa and Perani, 2003; Glenberg and Kaschak, 2002; Pulvermuller 2003; Rizzolatti and Arbib, 1998). In neuroscience, numerous brain imaging and TMS studies on language processing support the hypothesis that brain regions primarily involved in action recognition and control are also recruited in linguistic processing tasks (Pulvermuller, 2003; Buccino et al., 2005; D'Ausilio et al., 2009). Various reviews have recently appeared providing theoretical frameworks linking action and language (Jirak et al., 2010; Meteyard et al., 2012; Pulvermuller & Fadiga, 2010; Toni et al., 2008; Willems & Hagoort, 2007; see also Martin, 2007).
This neuroscience evidence is consistent with growing support in experimental psychology studies and related theoretical stances on the role of grounding of language in action and perception (Pecher and Zwaan, 2005; Glenberg and Kaschak 2002; Barsalou 1999; Scorolli et al. 2009; for reviews see Pecher & Zwaan, 2005; Barsalou, 2008; Fischer & Zwaan, 2008). Moreover, developmental psychology studies based on emergentist and constructivist approaches (e.g. Bowerman and Levinson, 2001; MacWhinney, 2005; Tomasello, 2003) also support a view of cognitive development strongly dependent on the contribution of various cognitive capabilities. This is further consistent with cognitive linguistics approaches (cf. Lakoff, 1987; Langacker, 1987) where

syntactic structures and functions, that is, symbolic structures in both lexicon and grammar, are constructed in reference to other cognitive representations.
Despite the increasing amount of collected evidence on action-language integration, this field has still many challenges to face. First, it should be clarified whether the activation of the motor system is necessary for language comprehension, or whether it simply represents an epiphenomenon (e.g., Mahon & Caramazza, 2008; Toni et al., 2008). Along this line, some authors have questioned the idea that the mirror neuron system can provide the basis for action understanding in humans (e.g., Hickok, 2009). Second, in some cases, even if evidence shows that the motor system is modulated during language comprehension, controversial results are obtained. For example, brain imaging and behavioural studies have demonstrated that processing action-related words can either facilitate or interfere movements compatible with them (interference vs. facilitation) (Chersi et al., 2010). Third, some notions, which are widely employed in the field, are differently defined. For instance, the notion of simulation has been employed in different ways - stressing either its re-enactment or its predictive aspect, and assuming the neural neuron system as its underlying neural basis or not (e.g., Barsalou, 1999; Borghi & Cimatti, 2010; Gallese, 2009; Decety & Grèzes, 2006; Grush, 2004; Pezzulo et al., 2011). Fourth, more sophisticated studies are needed, to understand which different (neural) mechanisms are involved in nouns and verbs processing; most importantly, one of the main challenges these views need to face concerns the way in which abstract words are represented (for a critical view, see Dove, 2009; 2011).
Building on this empirical evidence of the relation between language and action, open research challenges lie in the development of comprehensive theoretical frameworks and the subsequent formulation of more precise and constrained hypotheses.

2. Interdisciplinary approach

This topic shows that a highly interdisciplinary approach, combining computational models and cognitive robotics experiments with neuroscience, psychology, philosophy and linguistic approaches, can be a powerful means that can help researchers disentangle ambiguous issues, provide better and clearer definitions and formulate clearer predictions.
Important developments in the field of robotics and cognitive modeling provide support to such an integrative view of language, action and cognition (Cangelosi et al. 2010). Specifically, the field of developmental robotics (also known as epigenetic robotics, or autonomous mental development methodology) is a novel approach to the study of cognitive robots that takes direct inspiration from developmental mechanisms and phenomena studied in children (Asada et al. 2009; Cangelosi & Schlesinger, 2015; Morse et al. 2010a). This approach is based on the study of artificial embodied agents (e.g. either robots, or simulated cognitive agents) able to acquire complex behavioral, cognitive, and linguistic and communicative skills through individual and social learning. Specifically, with developmental robotics it is possible to investigate action/language integration by designing cognitive robotic agents capable of learning how to handle and manipulate objects and tools autonomously, to cooperate and communicate with other robots and humans, and to adapt their abilities to changing internal, environmental, and social conditions. The design of object manipulation and communication capabilities is directly inspired by interdisciplinary empirical and theoretical investigations of linguistic and cognitive development in children and adults, as well as of experiments with humanoid robots.
Recent advances in cognitive robotics have started to directly investigate the link between action and language learning. For examples, Morse et al. (2010b) have produced a developmental robotics model of early word acquisition based on sensorimotor biases. Following Smith and Samuelson’s (2010) child development experiments on the role of spatial biases in categorization and word learning, Morse et al. have demonstrated that a humanoid robot can learn the name of objects by relying of the integration of spatial cues with visual information. In a related model, Caligiore et al. (2010) propose the TROPICAL modeling framework to study microaffordances and demonstrate the existence of stimulus-response compatibility effects and action-sentence compatibility effects (e.g. Ellis et al. 2007; Glenberg & Kaschak 2002) in cognitive robots. Pastra and Aloimonos (2012) directly address the link between action and language knowledge through the adaptation of linguistics formalisms for the representation and classification of actions. This work supports a common representational structure for both action and language. Steels (2012)

developed an advanced cognitive linguistic model, the Fluid Construction Grammar, to carry our situated language learning experiments with cognitive robots. Fischer et al. (2011) has produced a cognitive linguistics analysis of the CHILDES database to define language acquisition scenarios for developmental robotics, and investigate the difference between child-directed and robot-directed speech. Other cognitive robotics models have focused on compositional language learning (Tikhanoff et al. 2011; Marocco et al. 2010), the interaction between number cognition and spatial representations (Rucinski et al. 2011) and motor chain for sentence processing (Chersi et al. 2010).

3. Contribution from the papers of this Topics issue

These developments in interdisciplinary approaches to cognitive robotics and computational modeling of action and language integration demonstrate the potential advantages of using embodied computational models of language and action learning and integration, directly inspired by empirical evidence. But so far experimental and modelling studies have tended to remain mostly separate. The present issue aims at filling this gap and presenting the latest interdisciplinary development of the investigation of action and language integration in natural and artificial cognitive systems.

Four common themes can be identified from the papers included in this issue of Topics. The first theme focuses on the role of language for concept and knowledge representations. A second set of articles concerns the flexibility in the relationship between concepts, words and sensorimotor information. A third pair of papers proposes neurocomputational models of the involvement of the mirron neuron systems on action and language processing. The fourth issue relates to the use of developmental robotics approaches and human-robot interaction experiments to the integration of action and language learning in artificial cognitive agents.

3.1 Role of language in concept representations

One of the most important issues raised and debated in the last years concerns the role played by natural language for our representations. Embodied cognition approaches have typically rejected the idea, promoted by classical cognitive science, that we represent entities in propositional terms. It has been argued, instead, that no transduction is necessary, from the sensorimotor and emotional experience of the world, to abstract, amodal and arbitrary symbols (e.g., Barsalou, 1999). This view has sometimes led to undermine the role played by language for our representations, since the majority of research efforts were devoted to demonstrate that language was grounded in the sensorimotor and emotional systems (see Borghi et al., 2013, for a more extensive analysis of this phenomenon). The situation is changed in the very last years, as some of the papers in our issue testify. We will outline below some of the main reasons and consequences of this recent shift in perspective, in light of the analysis of some papers of our issue.

At an epistemological level, the increased attention for the role of linguistic information for our representations is testified by the increase in popularity of distributional models outside computational disciplines. Distributional models, according to which meaning is captured by co-occurences of words in large corpora, were indeed mostly widespread and popular in computational linguistics and computer science. In the last years they are becoming increasingly popular also in psychology, neuroscience and other areas of cognitive science. More importantly, while embodied and distributional models were seen as opposite approaches to meaning, recent studies are increasingly showing their complementarity. The interest for distributional models occurs in parallel with another phenomenon: Scholars of different disciplines, as for example psychology (Barsalou et al., 2008; Louwerse, 2011; Connell & Lynott, 2013) and philosophy (Clark, 1998; Dove, 2011), who adopt an embodied approach, are reconsidering the importance of linguistic and not only of sensorimotor information for our representations. An important epistemological consequence of this is the cross-fertilization between disciplines.

In this issue the paper by **Andrews** et al. focuses exactly on the possible synergies and advantages emerging from the combination between embodied and a distributional approaches to meaning. The paper gives an overview of recent approaches to the study of meaning. The authors argue that two approaches characterize recent literature: the embodied cognition account, according to which cognition is grounded in sensorimotor states, and the distributional account, which claims that meaning is extracted from the statistical distribution of words. These two approaches, which are grounded and have become increasingly popular in different disciplines (psychology and cognitive neuroscience vs. artificial intelligence, machine learning, and computational linguistics) are usually considered as separate and opposing. The authors stress instead the complementarity of these approaches: distributional approaches have less problems in explaining abstract concepts representation, while embodied approaches have less problems in anchoring words to their referents. Their data are therefore "not independent, but mutually reinforcing". The authors review recent literature from different fields - philosophy, cognitive neuroscience, computational modeling - trying to bridge these two approaches, showing that they are deeply interrelated, thus opening new research directions.

The reasons why language plays such an important part in our representations are multifaceted, as different papers in our issue recognize. One is that language provides an important mean to extend our mental capabilities. Representing entities both in sensorimotor and in symbolic terms allows us to benefit from the advantages a symbolic system offers to us. This is what claimed in the paper by **Dove** which focuses on the role played by natural languages for our representations. Without assuming a propositional view, the author explores the possibility that the acquisition of natural languages offers us the opportunity to benefit of a symbolic representational format, hence extending our cognitive capabilities. Dove's proposal builds on the idea that language can be seen as a kind of cognitive scaffolding, as originally proposed by Vygotsky; furthermore, his view has some affinities with dual-coding theories of representation and with theories that aim to reconcile distributional and embodied approach to cognition. The author suggests that the language system carries out two semantic functions: it activates sensorimotor simulations and promotes symbolic associations and inferences. According to Dove, this view leads to the prediction that representations derived from our experience with objects and entities are functionally relevant for language comprehension, as demonstrated for example by studies showing that action words activate the corresponding effectors. Furthermore, it allows us to face one of the most important challenges for embodied theories, namely the explanation of how abstract concepts are represented.

Encoding information not only in sensorimotor but also in linguistic terms has further advantages. Language can provide a shortcut, allowing fast access to information in linguistic task (see LASS theory by Barsalou et al., 2008, and converging evidence: e.g., Pecher & Boot, 2011; Louwerse & Connell, 2011). The paper by **Connell and Lynott,** which will be discussed in Section 3.2, emphasizes this peculiarity of our linguistic system. A further advantage language has is that it can help explain how we represent abstract concepts. Recent theories on abstract concepts posit that sensorimotor and linguistic information are differently distributed in concrete and abstract concepts (Borghi & Cimatti, 2009; Borghi & Binkofski, in press; Recchia & Jones, 2012; Dove, 2009; 2011; Kousta et al. 2011). Many papers in this issue of Topics recognize the peculiar role played by linguistic information for abstract concepts. **Andrews** et al. argue that distributional approaches have less problems than embodied ones in explaining abstract concepts representation.The paper by **Dove** reviews psychology and cognitive neuroscience evidence that shows that language information plays a major role in abstract concepts representation. **Thill**'s et al. contribution, which will be discussed in Section 3.4, also focuses on the importance of a rich embodiment in the grounding of concrete and abstract concepts.

3.2 Flexibility in the relationship between concepts, words and sensorimotor information.

Embodied theories have typically assumed that language is grounded in perception, action and emotional systems, hence that during concepts and words processing the sensorimotor system is automatically activated. However, recent studies are challenging this view, highlighting the dynamical nature of our concepts and stressing the importance of the context for activation of motor information during language processing. Future research on natural and artificial agents should take into account this intrinsically dynamical and flexible character of our representations. Three contributions in our issue, one theoretical and two experimental papers, focus directly on this; a further paper, by **Myalchykov et al.**, stresses the importance of context in the framework of a general theory of knowledge.

The paper by **Connell and Lynott** focuses on concepts and representations and explains why we cannot represent the same concept twice. The authors use the term representation to refer to specific and contextually determined instantiations of one or more concepts. A representation includes both online and offline information, and is based both on simulations and on linguistic labels since it incorporates activations across sensorimotor, linguistic, emotional and other neural areas.Compared to a representation, a concept is context-free, and is formed when particular aspects of experience have been attended to rather frequently, so that they can be easily reactivated offline. The authors outline three principles according to which it is not possible to represent the same concepts more than once: 1.Online processing affects offline representations. Conceptual simulations are shaped by a variety of factors, such as task, goals, motivations, environment and body configuration. 2. Language is a facilitator of offline representations. The fast linguistic system complements the simulation system, which is slower. Depending on the task, goals and resources, the representation can occur through simulation or through language, it is not possible to represent the same concept twice. 3.Time itself is a source of representational change. Concepts vary continuously and are continuously updated, both within and between individuals. These three principles underlie a highly dynamic and variable view of concepts and help the authors clarify why the same concept cannot be represented twice. Modeling work should therefore take into account that humans are linguistic entities with limited attentional resources, changing continuously over time.
The paper by **van Dam et al.** investigates the effects of context on language processing. The authors start describing the main tenets of embodied theories of language (ETL), according to which the sensorimotor areas are automatically recruited during language comprehension. Then, they illustrate some studies that challenged this view, suggesting that motor activation is highly flexible and modulated by the context (e.g., Raposo et al., 2009; van Dam et al., 2012). The EEG study they report is focused on the temporal dynamics of context effects during language comprehension, and is aimed at verifying whether the effect of context influences early (lexical access) or late stages (integration) of information processing. Participants were required to perform a lexical decision task in which they had to prepare a response toward or away from the body to words referring to manipulable objects. The words were presented in a context that highlighted the dominant action-features of the object or not (e.g., thirst-cup vs. sink-cup). EEG results suggest an early action of sensorimotor information and indicate that contextual effect are at play during the early stages on information processing.
The two aforementioned papers stress the variability and flexibility of our conceptual system and reveal the contextual dependency of the relationship between language and motor system. One further contribution highlights the variability in time of the relationship between words and action, as it investigates the differences between younger and older children and adults in responses to words with which it is possible / impossible to interact. The paper of **Wellsby et al.** focuses on the development of the facilitatory BOI effect in children. The BOI variable (Siakaluk et al., 2008) takes into account the easiness in which a human body can interact with the referent of a word. Studies on adults have revealed faster and more accurate responses for words with high BOI (e.g., mask, belt, desk) than with low BOI (e.g. Roof, ship, cloud, brain) across a variety of tasks (lexical decision, phonological lexical decision, semantic categorization), and brain imaging studies have revealed an association between high BOI and activation of the left inferior pariental lobule, revealing its role for the sensorimotor system. The authors aim to investigate how the bodily experience influences children's reading of isolate words. They submit a naming task with a sample of high and low BOI words to 3 groups of participants: younger children (age 6-7), older children (age 8-9) and adults. After the task, children's reading ability was measured. The authors computed a composite measure reflecting latency and accuracy in BOI; they found a facilitatory effect in older children and adults. The emergence of the effect was related to reading abilities, in particular letter recognition and meaning comprehension. Overall, results reveal that the BOI effect emerges at around 8, once reading abilities are well developed and the world experience is consolidated.
The paper by **Myachykov et al.** stresses the dynamical character of our cognitive system in a more general framework. The contribution focuses on the dynamic interrelation between world specific, body specific, and context specific components of representations. The authors illustrate the main tenets of TEST, a taxonomy of knowledge representations, divided into tropic, embodied and

situated components. The authors focus on the notion of simulation used within embodiment theories, and address the issue of which body/world parameters are simulated. The most general and stable component is tropism, while embodiment and situatedness are more specific and are not hierarchically organized. The notion of tropism is borrowed from biology, and it refers to the way the plants adapt to changes in the environment (e.g., light, temperature, etc.), and with the tropic component they refer to constraints put on representations by the physical world. Given the proposed hierarchical structure, representations can be tropic without being embodied or situated, but when they are embodied and situated they are necessarily tropic as well. Representations are embodied when they encode bodily states, both shared by a given species or specific for each organism. Furthermore, representations can be situated as they reflect the context (physical, social, introspective) in which they are formed and used. Importantly, with the notion of context the authors do not intend something objective, but they refer to the way on which the environment is reflected in the agent's goals. They discuss three examples of experimental results corresponding to tropic, situated, and embodied representations: abstract language, numerosity, and perspective taking. They argue that deriving constraints from these 3 aspects allow the formulation of more precise predictions compared to the more generic view, shared by all embodiment theorists, that body, environment and context are all interrelated.

3.3 Computational models of the mirror neuron system for action and language processing

The two papers by Badino et al. and Chersi et al. directly focus on the modeling of the mirror neuron system involvement in action and language processing. **Badino** and colleagues review a series of studies offering a computational validation of the mirror neuron hypothesis, and specifically on models of the motor contribution to speech perception. The mirror neuron system is a parieto-frontal network that matches visually presented biological motion information onto the observer's own motor representations and thus is involved in action recognition. Since speech is a particular type of (acoustic) action, this is also expected to activate a mirror neurons mechanism. As a matter of fact, in speech perception motor centers have been shown to be causally involved in the discrimination of speech sounds. The main claim of this paper, supported by machine learning studies from the authors and from other works in the literature, is that in automatic speech recognition (ASR) systems, the phoneme recognition is significantly improved when motor data are used during training of classifiers, as opposed to training the system purely with auditory data. At a more general level, this supports the hypothesis on the key contribution of the motor system to speech perception. **Chersi's et al**. paper also concerns the link between the motor system and the linguistic one, and directly relates to the involvement of the mirror neuron system to support the integration of action and language. In particular, they propose a novel computational neuroscience model, based on Temporal Self-Organizing Maps (TSOM) and prediction learning, to show that language processing may have exploited, and co-opted, the neural organization, functional and learning mechanisms typical of pre-motor circuit and the mirror neuron system. The mode is trained on sequences of either motor or linguistic stimuli. This leads to the self-organization of independent neuronal chains for both language and motor sequence representations. The model also reconciles neurophysiological motor data with established behavioral evidence on lexical acquisition, access and recall. Overall the simulations support the hypothesis that common computational principles of memory self-organization and predictive learning may underlie storage and processing of lexical and action chains.

3.4 Developmental robotics and Human-Robot Interaction for action and language

Natural language plays an essential role in human-robot interaction, especially within an experimental framework where the robot has to develop a common, shared understanding of the interaction tasks and action-based interactions. This issue includes two human-robot interaction studies, respectively on the demonstration and linguistic description of path-oriented actions and manner-oriented actions (**Lohan et al.**), and on the use of spatial descriptions for robot companions' interaction with elderly users (**Carlson et al.**). It also comprises a paper by **Broz et al.** summarizing the main results from a large scale project on action and language learning in developmental robots. The paper by **Lohan et al.** and collaborators concerns human-robot and child-adult interaction and tutoring situations, in which action demonstrations are accompanied by speech. Specifically, their study focuses on the distinction between two kinds of motion events: *path*-oriented actions and *manner*-oriented actions. These two kinds of actions can be communicated via two different linguistic utterance styles: in path-oriented utterances, the source, trajectory or goal is emphasized, whereas in manner-oriented utterances, the medium, velocity or means of motion are stressed (e.g. Talmy, 1991). The paper reports analyses of gaze, motor and linguistic strategies in a video corpus of adult-child interactions (with three child age groups: pre-lexical, early lexical and lexical) and two different tasks respectively emphasizing manner and path actions. The results demonstrate that age is an important factor in the development of these action categories. For example, the pre-lexical infants have a low rate of anticipative gazing behavior, so the caregiver tends to use also less path-oriented utterances and the highest rate of attention getter utterances, together with looming movements. On the contrary, the lexical infants show more anticipative gaze behavior and thus receive more path-oriented utterances. These analyses further contributed to the design of new effective feedback strategies in the "tutoring spotter system". This is a human-robot interaction tool capable to emulate children's behaviors in a tutoring situation, facilitating the elicitation in human subjects of a natural and effective behavior in teaching a robot.

The work by **Carlson et al.** and colleagues also concerns the domain of human-robot interaction. In particular, they focus on spatial descriptions for the development of robot companions for the elderly. This study contributes to the identification of the requirements to comprehend linguistic instruction to in an interaction scenario where the robot has to fetch objects for the old person. The paper uses a corpus of naturally occurring descriptions elicited from a group of older adults within a virtual 3D home that simulates the eldercare setting. Two main conditions were considered: (i) giving descriptions to a human versus a robot avatar, and (i) instruction on how to find the target versus telling where the target is. The paper also includes a discussion of the key cognitive and perceptual processing capabilities necessary for the robot to establish a common ground with the human. For example, it shows the best strategies to resolve the perspective ambiguity problem and the need to recognize furniture items as landmarks. Overall, the study offers the key building blocks of a robust system that takes as input natural spatial language descriptions and produces instructions to help the robot succeed in the interaction task.

The paper by **Broz et al.** presents a summary of the results from a large multidisciplinary research project on the integration and transfer of language knowledge into robots (italkproject.org). The paper uses three key research themes to review the various achievements in this field: (i) individual learning about one's own embodiment and the environment, (ii) social learning from other individuals, and (iii) developmental learning of linguistic capability. Moreover the paper uses the milestones of children's linguistic and cognitive development to map the experimental results, building on a research roadmap on the developmental robotics modeling of action and language integration (Cangelosi et al. 2010). The paper also discusses the directions for future work using the integrated framework for understanding the mutually scaffolding of social learning, individual learning, and linguistic development processes as a basis for modeling cognitive development in humans and robots.

Finally, **Thill's et al.** contribution focuses on the importance of a rich embodiment in the grounding of concrete and abstract concepts, in particular through a joint effort combining embodied cognitive science and computational linguistics approaches. Although this article does not directly uses cognitive robotics approaches, in it the authors argue that there is a need for the domain of cognitive robotics and cognitive models to explicitly extend the concept of a sensorimotor system beyond the simple case of direct sensorimotor experience in the study of symbol grounding, especially for abstract concepts. They illustrate this by using an example from the Distributional Memory method in computational linguistics. Their analysis shows that even concepts describing the usage of concrete words go beyond those that could be grounded in pure sensorimotor experience. Further, Thill and colleagues propose a "division of labor" approach between an essentially unsupervised "perceptual" layer associating basic, concrete concepts with sensorimotor information (typical of current robotics approaches) and a relational layer to indirectly ground more complex and abstract concepts in relation to basic expressions (as in distributional linguistic approaches).

4. Conclusion

This issue of Topics addresses and proposes many challenges that research on action and language integration is currently facing and has to face.

The experimental and theoretical papers highlight, among others, two very important phenomena characterizing language processing. First, they show that we do not simply represent objects, entities and situations using the sensorimotor and emotional systems but they suggest that also natural language (linguistic distributional information) enter into play in conceptual representation, particularly when linguistic tasks are used. Language can play multiple roles: it contributes in extending our computational and thought abilities, it can provide a shortcut to access meaning in linguistic tasks, and it can help us representing abstract concepts. literature from different fields - The richness of our representations is underlined in different disciplines, such as philosophy, psychology, cognitive science and neuroscience, computational modeling. Further research adopting an interdisciplinary approach should help us in clarifying the role played by linguistic, sensorimotor and emotional information in different domains and tasks.

A second important contribution of these papers is the emphasis on the highly dynamical, flexible and contextual dependent character of the interaction between concepts, language and action. This leads to a reconceptualization of the notion of embodiment. Furthermore, this opens a challenge: further research should address in detail how this flexibility is instantiated. We should indeed try to better understand in the light of novel experimental and computational evidence, for example on timing, whether the view according to which the motor system is automatically activated during language processing and the view according to which activation of motor information is context-dependent are conflicting or compatible.

The set of computational and robotics modelling papers shows the importance of highly interdisciplinary approaches where the parameters of the computational model, and the results of robotic experiments and computer simulations, can be directly constrained on empirical data. For example, Chersi's computational neuroscience model reconciles motor neurophysiology data with behavioral evidence on lexical acquisition, access and recall and it support the hypothesis that lexical and action chains provide common computational principles of memory self-organization and predictive learning. Moreover, the many developmental robotic modeling results discussed by Broz and collaborators show the benefit of direct collaboration, e.g. between developmental psychologist, developmental linguistics and robotics.

The robotic studies in the papers of Lohan, Carlson and Broz offer important insights on social interaction between humans and robots. These range from both child-robot and adult robot interaction for the understanding and imitation of different types of actions (path, manner) in Lohan's et al. study, to spatial description with elderly people in Carlson et al. work. In Broz's et al. paper, various human-robot interaction scenarios are investigated, as models exploiting caregiver-robot tutoring and teaching interaction, as well as neurorobotics models of the parallel developmental acquisition of action and language concepts. Another important contribution of this issue concerns speech technology for human-robot and human-machine interaction. Badino et al. provide evidence that to overcome the limits of current automatic speech recognition (ASR) systems, the inclusion of motor data during the training of classifiers can significantly improve the phoneme recognition.

In sum: this issue of Topics reveals how lively is the embodied cognition research on language and action integration. Many research challenges are open, and promising interdisciplinary approaches can be used to address them.

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