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From Sensorimotor Knowledge to Abstract Symbolic Representations☆

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Abstract

We present two cognitive robotic experiments looking at different aspects of relations between symbolic representations and sensorimotor knowledge.

Keywords: Developmental cognitive robotics; Mathematical cognition; Symbol grounding

Developmental cognitive robotics permits the modeling of different brain and behavioral processes that take place during child development. In contrast to purely computational modeling methods, the principal advantage of the robotic approach is that it enables inherent inclusion of different aspects of sensorimotor control and representation in the model, consistent with the embodied view of cognition. Traditional cognitive robotic modeling research puts however a lot of emphasis on the processes connected with motor behavior itself. We would like to extend this view by looking at the relations between motor actions and abstract symbol manipulation capabilities.

The development of symbol manipulation capabilities in children such as productive language use is preceded by the establishment of a variety of both verbal and non-verbal communication routines with their caregivers. Such routines are grounded in multi-modal interaction practices that are temporally coordinated and contingent with the interlocutor's feedback. E.g. Nomikou and Rohlfing [1] found that when speaking with their 3 month old infants, mothers vocalize in a tight temporal relationship with action over a considerable part of the overall interaction time, thereby making the vocal signal both perceivable and tangible to the infants. In later practices, adults use combination of pointing, showing and words to describe an action or an object and highlight its specific features. The child acquires the symbolic meaning of these words and actions by a frequent observation of the parents and reception of their feedback in response to their own actions. All these observations suggest the existence of a strong link between the sensorimotor knowledge and the abstract symbol manipulation abilities which has been the topic of two cognitive robotic experiments described below.

The first issue addressed in our experiments is the development of linguistic skills. Language capabilities are one of the most powerful tools of an agent for understanding situations and interacting with other agents in the environment. In the framework of cognitive science, psychological experiments that focus on the relationship between language

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development and other cognitive capabilities (e.g. perception, action) have been presented. According to the results of these experiments, the development of linguistic skills requires different cognitive processes working together; nevertheless, other models proposed in the field of language learning systems mainly focus on the idea that language is an independent and autonomous capability of agents. In our experiments, we propose a model based on Artificial Neural Networks (ANNs) for symbols manipulation that provides a useful tool for investigating and testing embodied theories of language learning. Experiments take inspiration from the model proposed by Cangelosi and Riga [2], in which a simulated robot was trained first by using the mechanism of the *direct grounding* for learning a set of action primitives and their corresponding name and then by the mechanism of the *grounding transfer* by which the grounding of basic words is transferred to higher-order words via linguistic description.

Simulation experiments have been developed on a software environment for the iCub robot. A set of words, that express general actions with a sensorimotor component, were first taught to the simulated robot through direct grounding mechanism; subsequently, by combining words grounded in sensorimotor experience, the simulated robot acquired more abstract concepts. In particular, the training of the robot consisted of three incremental stages: (i) Basic Grounding (BG) phase for learning to perform a set of basic action primitives and their corresponding names (e.g. GRASP, STOP, SMILE), (ii) Higher-order Grounding 1 (HG1) stage when the robot, via linguistic description, acquires higher-order words by combining basic *action primitives* (e.g. KEEP is GRASP and STOP) and (iii) Higherorder Grounding 2 (HG2) stage during which the robot learns *high-level behaviors* through the combination of action primitives and *higher-order words* (e.g. ACCEPT is KEEP and SMILE and STOP). Simulations results demonstrate that higher-order symbolic representations and behaviors can be indirectly-grounded in basic action primitives directly-grounded in sensorimotor experience. This model is being extended to test other embodied cognition theories of language learning such as the Action-sentence Compatibility Effect.

The second experiment focuses on one of the most established psychological phenomena that suggests the existence of a link between symbolic numbers and motor space representations in the brain, that is so-called SNARC effect (Spatial-Numerical Association of Response Codes). The effect means that when responding to a small number, the reaction time for a left hand response is faster than for the right hand, and conversely for a large number it takes longer to respond with a left hand than with a right hand. The existence of number-space associations is also supported by data from other disciplines like neuroscience, studies of patients with lesions and computational modeling [3].

Building on the results from previous modeling experiments, we formulated an embodied developmental robotic model of interactions between numbers and space. It is composed of a *ventral* pathway, responsible for symbolic tasks, i.e. language processing, coding of the identity of objects as well as task-dependent decision making, and a *dorsal* pathway, involved in processing spatial data about locations of objects in different frames of reference and allowing for appropriate transformations. The latter pathway implements the aspect of embodiment, as its elements are designed to map various parts of the iCub robot, namely positions of its two arms and the gaze direction. We also proposed a developmental process for the model that resembles that of a human child. First, in a process alike to *motor babbling*, space representations in the dorsal pathway and links between them are constructed. Next, the model is taught number words and their meaning. Then, the robot is taught to count, in a way resembling the real-life cultural biases: even though the objects being counted are placed randomly in the visual field of the robot, the process always proceeds from left to right. Finally, the robot is taught to perform tasks like parity judgment and magnitude comparison that enables assessment of various effects of embodiment. The model developed using the described process successfully reproduces major effects known from psychological studies, such as the already mentioned SNARC effect, as well as the Posner-SNARC effect, and size and distance effects in number comparison. This suggests that numbers-space associations may be the result of cultural biases present in the environment during the course of child development. In future we plan to extend the model to allow for investigation of the importance of gesture in learning to count.

In our experiments we looked at two aspects of relations between sensorimotor knowledge and symbol manipulation capabilities. Apart from delivering new results in respective areas of cognitive science, both studies demonstrate the potential of cognitive robotic models for the investigation of the human cognitive development. Embodied character of such modeling approach allows for a more accurate analysis of the corresponding biological processes.

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