From Sensorimotor Knowledge to Abstract Symbolic Representations

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The Development of Symbol Manipulation Capabilities in Children

Symbolic representations come in many different flavors: language, mathematics, logic, decision making, and others. 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 three 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 [2]. 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 [3].
We present here two experiments that make use of the same embodied robotic approach to model different aspects of relations between symbolic and motor knowledge.

Experiment 1: Toward the Grounding of Abstract Words

Development of Symbolic and Linguistic Skills through the Grounding in Sensorimotor Experiences

We propose a model based on **A**rtificial **N**eural **N**etworks (**ANNs**) for symbols manipulation that provides a useful tool for investigating and testing embodied theories of language learning [4]. Experiments, taking inspiration from the model proposed by Cangelosi and Riga [5], have been developed on a software environment for the iCub robot.

Cognitive robots have been successfully used for learning concrete concepts.

Figure 1: Illustration of Searle's Chinese Room argument from `http://www.macrovu.com/CCTMap4ChineseRm.html`.

1. **AIM**: to extend the symbol grounding mechanism to abstract words for a humanoid robotic platform.

2. **MODEL**: The training of the robot consists of three incremental stages (fig.2):

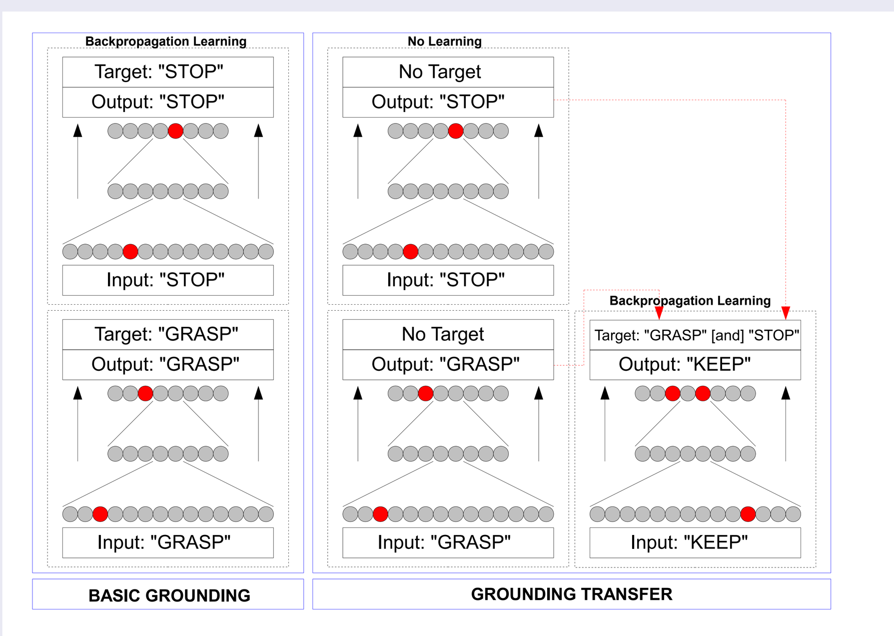


Figure 2: Representation of the procedure that implements the grounding transfer mechanism.

- (i) **Basic Grounding** (BG) stage: the robot learns to perform a set of basic action primitives and their corresponding names (e.g. "GRASP", "STOP", "SMILE").
- (ii) **Higher-order Grounding 1** (HG1) stage: the robot, via linguistic description, acquires higher-order words combining basic action primitives (e.g. "KEEP" [is] "GRASP" [and] "STOP").
- (iii) **Higher-order Grounding 2** (HG2) stage: 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").

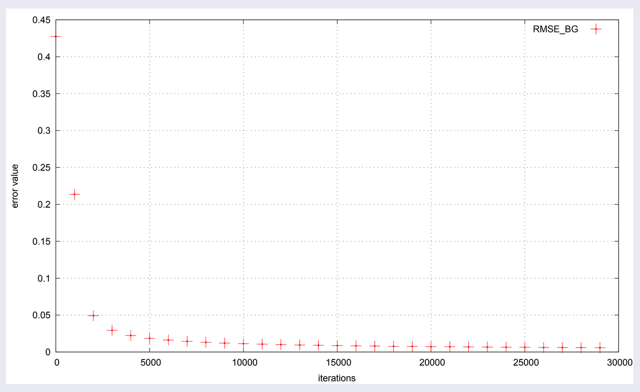
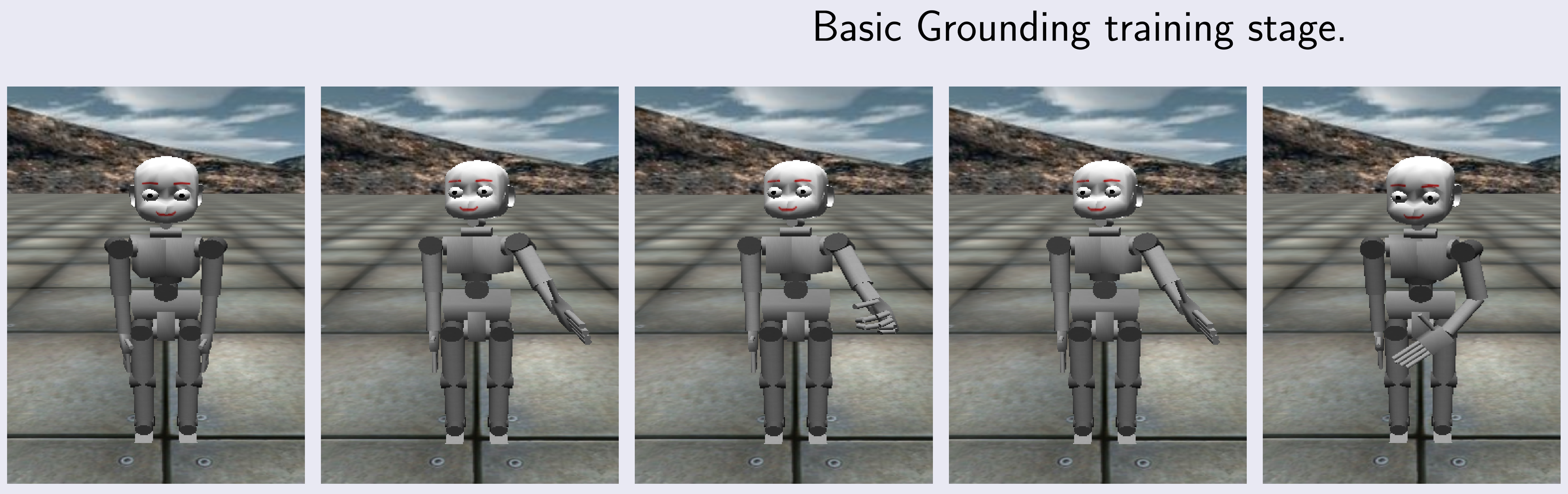


Figure 3: Root Mean Square Error after the Basic Grounding training stage.

3. **RESULTS**: Results show that the iCub is able to gradually acquire abstract representations via combinations of directly grounded concrete words.



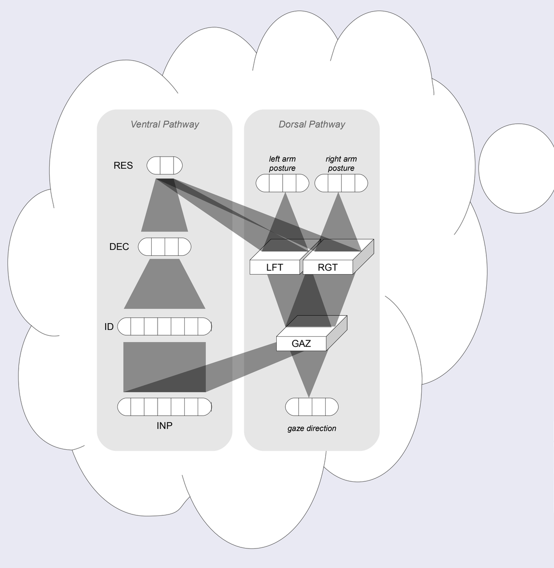
(a) (b) (c) (d) (e)

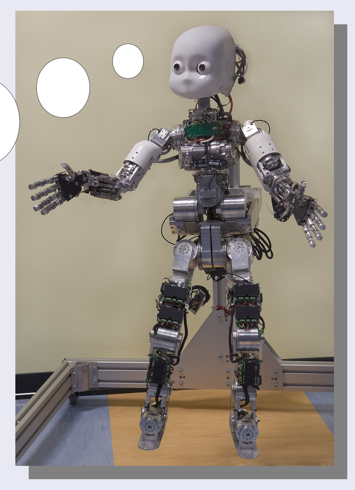
Figure 4: Execution of action primitives on the iCub: initial position (a), "MOVE_ARM_AWAY" (b), "CLOSE_HAND" (c), "OPEN_HAND" (d) and "MOVE_ARM_TOWARD" (e).

Experiment 2: Symbolic and Motor Representations

Interactions Between Numbers and Space

One way in which links between symbolic and motor representations manifest, is so-called SNARC effect (Spatial-Numerical Association of Response Codes, [7]). Experimental results suggest the existence of an internal link between (symbolic) numbers and (motor) space – small numbers are associated with the left side and large numbers with the right side.
Evidence for such associations comes from various domains: experimental psychology, neuroscience, studies of lesions and computational modelling.

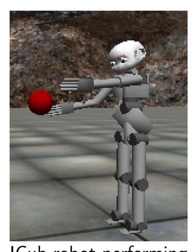




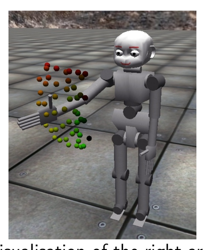
Our embodied robotic model, extending the approaches published in [8] and [9], integrates both symbolic and motor information (via the ventral and the dorsal pathway respectively).
Environmental correlations present in the proposed development process, lead to the emergence of particular patterns in certain parts of the model which allow it to reproduce such experimental phenomena as size and distance effects, SNARC effect and Posner-SNARC effect.

Development

I. First, spacial representations are built. This is equivalent to motor babbling, in which children are believed to refine their internal motor representations.
This results in formation of Self Organising Maps which represent visible and reachable space around the robot.

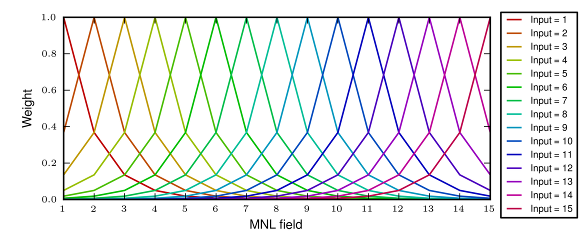


ICub robot performing motor babbling



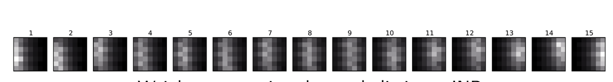
Visualisation of the right arm reachable space map

II. Second stage of the model development involves learning number words and their meaning. Similarly to the approach of [8], numbers are coded on a mental number line with linear scaling and constant variability.
It has been shown that such a representation can be obtained using simple supervised learning techniques.



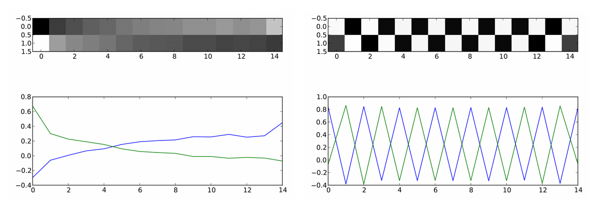
Weights from the INP to the ID layer

III. This phase of the model development, learning to count, is crucial. Here the real-world cultural biases are simulated. The robot repeatedly counts objects in its visual field in left to right order. In effect, small numbers get associated with the left side of space, and large numbers with the right side.



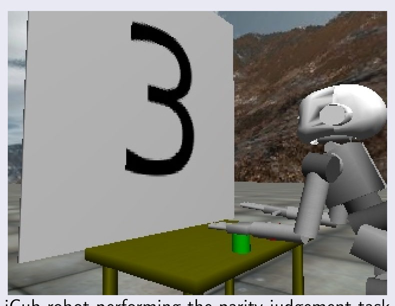
Weights connecting the symbolic input INP with the visual space map GAZ

IV. In the final stage of the model development, the robot is taught to perform simple mathematical tasks, like comparing two numbers or judging the number's parity. This enables us to test the model in tasks routinely used by experimental psychologists and compare the results with human data.

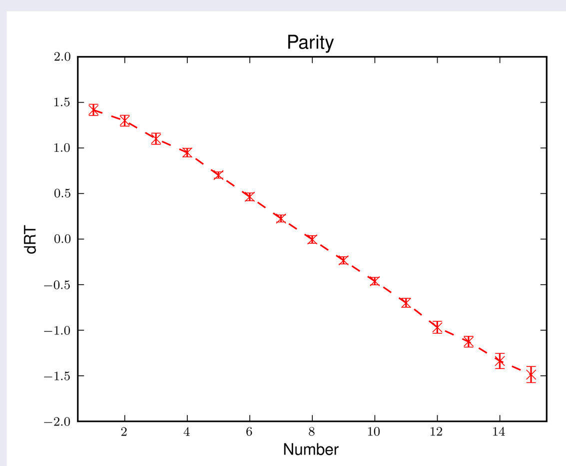


Weights obtained for the comparison task (ID to DEC)

Weights obtained for the parity task (ID to DEC)



iCub robot performing the parity judgement task



Response times of the robot in the parity task.
Negative slope indicates the presence of the SNARC effect.

After the development is completed, the robot successfully exhibits the following experimental phenomena:
- size and distance effects in number comparison
- SNARC effect in parity and comparison tasks
- Posner-SNARC effect

This demonstrates the potential of cognitive embodied robotics for modelling high-level interactions between symbolic and motor representations. For example, the experiment described here allowed us to hypothesize about the sources of neural gradients found in the human brain, which are believed to be responsible for the SNARC and similar effects.

Conclusions

The above studies demonstrate the potential of cognitive robotics models for understanding the development of abstract symbol representations. The simulations described in Experiment 1 show that higher-order symbolic representations and behaviors can be *indirectly-grounded* in basic action primitives *directly-grounded* in sensorimotor experience. Currently, this model is being extended to test other embodied cognition theories of language learning such as the Action-sentence Compatibility Effect [6]. The experiment 2 has shown that interactions between symbolic and motor representations can be shaped by the environmental biases. This work will serve as a basis to understand the role of gesture in learning to count.

RobotDoC Initial Training Network

The RobotDoC Initial Training Network (ITN) gathers leading European and international laboratories for doctoral training in cognitive and developmental robotics (`http://robotdoc.org/`).

RobotDoC Collegium

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