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From object-action to property-action: Learning causally dominant properties through cumulative explorative interactions

Vishwanathan Mohan *, Ajaz Bhat, Giulio Sandini, Pietro Morasso

Robotics, Brain and Cognitive Science Dept, Istituto Italiano di Tecnologia, Genova, Italy

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Abstract
Emerging studies from neuroscience in relation to organization of sematic memory in the brain provide converging evidence suggesting that conceptual knowledge is organized in a distributed fashion in ''property specific'' cortical networks that directly support perception and action (and were active during learning). Though learning 'object-action' affordances and using such knowledge for prediction and planning is an active topic in cognitive robotics, this article urges to go beyond and look at ''property-action'' networks instead. To this effect, a brain guided framework for distributed property specific organization of sensorimotor knowledge for humanoid iCub is presented. Two simple learning rules namely 'elimination' and 'growth' are proposed to compare top down anticipation and bottom up real experience to abstract underlying causal relations. An engaging scenario how the robot cumulatively learns and abstracts causally dominant properties that influence motion of various objects when forces are exerted on them is used to validate the neural architecture. The implicit advantage is that such learnt ''property-action'' relations can be effortlessly generalized to a domain of objects for which the robot need not have any past experience/learning but nevertheless share the ''property''. Further, the study has relevance in both better understanding how common causal relations can be cumulatively learnt, represented and exploited, to providing novel embodied frameworks for analogical reasoning.
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Introduction

Affordances are the seeds of action. Being able to identify and exploit them opportunistically in the 'context' of other-

* Corresponding author.
E-mail addresses: vishwanathan.mohan@iit.it (V. Mohan), ajaz.bhat@iit.it (A. Bhat), giulio.sandini@iit.it (G. Sandini), pietro.morasso@iit.it (P. Morasso).

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wise unrealizable goals is a sign of cognition. Despite incessantly encountering novel exemplars of objects we have never interacted with before we can often anticipate about what can be done with them and even exploit them to realize our goals. Based on her past experience of bending flexible pipe cleaners about a year back, Betty the new Caledonian crow quickly fashioned a hook out of a piece of wire to pull her dinner basket trapped in a transparent vertical tube (Weir, Chappell, & Kacelnik, 2002). Studies from animal cognition (Visalberghi & Tomasello, 1997; Whiten, McGuigan, Marshall-Pescini, & Hopper, 2009) indicate that several other primates are able to flexibly reason about physical causality, exploit inherent properties of objects available in the environment: for example choosing a tool of a right length to push out a trapped reward (among others). How by cumulative and explorative interactions with different objects in the world, task relevant physical and causal relations are both abstracted and exploited flexibly in novel contexts is a problem that presents challenges both in terms of representation and learning. In this context, cognitive robots offer a unique opportunity to reenact the gradual process of cumulative learning and investigate the underlying computational basis. The value is both intrinsic i.e. better understanding our own selves and extrinsic i.e. creating a range of artifacts that can flexibly assist us in the environments we inhabit and create.

Learning 'object-action' relations and using such knowledge for prediction and planning is becoming an active topic of study in embodied robotics with approaches ranging from probabilistic Bayesian models, to neural associative networks and symbolic formalisms (Krüger et al., 2011; Montesano, Lopes, Bernardino, & Santos-Victor, 2008; Montesano, Lopes, Bernardino, & Santos-Victorm, 2007). Despite intriguing attempts, both applicability and generalization of the methods to novel contexts and the necessity to facilitate cumulative learning (like natural cognitive agents) have been known bottlenecks. In parallel, emerging results from functional imaging are beginning to provide useful information as to how conceptual knowledge about object concepts and causal relations is organized in the brain (Bressler & Menon, 2010; Buckner, Andrews-Hanna, & Schacter, 2008; Martin, 2007, 2009; Meyer & Damasio, 2009; Patterson, Nestor, & Rogers, 2007). The main findings emerging from these results is that conceptual information is grounded in a ''distributed fashion'' in ''property specific'' cortical networks (Martin, 2009; Patterson et al., 2007) that directly support perception and action (and that were active during learning). Same set of networks are known to be active both during real perception/action, imagination or lexical processing (Martin, 2007; Meyer & Damasio, 2009). Further, there is a fine specialization of areas representing conceptual information related to animate vs. inanimate objects as evident from functional imaging and TMS studies on both normal subjects and semantic dementia patients (Buckner et al., 2008; Patterson et al., 2007). It is also now known that ''retrieval'' or reactivation of the conceptual representation can be triggered based on partial cues coming from ''multiple modalities'': for example sound of a hammer retro activates its shape representation (Meyer & Damasio, 2009), presence of a real object (banana) or a 2D picture of it can still activate the complete network associated with the object (and that was active during learning of it in the first place). These results provide valuable insights to guide development of computational frameworks for organizing information related to perception—action and foster learning of causal relations, importantly in an embodied and cumulative learning setup. The present article is an ambitious adventure in this direction.

A biologically inspired framework for distributed property specific organization of sensorimotor knowledge for humanoid iCub is presented with an emphasis on learning ''property-action'' relations. The implicit advantage is that such learnt ''property-action'' relations can be effortlessly generalized to a do-main of objects for which the robot need not have any past experience/learning but nevertheless share the ''property''. An engaging scenario how the robot cumulatively learns and abstracts causally dominant properties that influence motion of various objects when forces are exerted on them is used to validate the neural architecture. It is known from studies on animal behavior that different species have different levels of understanding of the causality related to this task (Visalberghi & Tomasello, 1997; Whiten et al., 2009). In addition to the multiple utilities of the ''push/pull'' action itself in the context of day to day interactions with objects, what makes it interesting is the sheer range of physical concepts that have to be ''learnt'' and ''abstracted''. For example, it has to be learnt that contact is necessary to push, object properties influence pushability (balls roll faster than cubes and it does not matter what is the color of the ball or the cube), pushing objects gives rise to path of motion in specific directions (the inverse applies for goal directed pushing), pushing can be used to support grasping, bring objects to proximity. The requirement to capture/learn such a wide range of physical concepts through cumulative ''playful interactions'' of the robot with different objects makes this task both interesting and challenging.

The rest of the article is organized as follows: Section 'Distributed ''property specific'' organization of sensorimotor information and the basic Pushing forward/inverse model' describes the organization of sensorimotor information in iCub taking guidance from emerging results from neurosciences. How the basic Pushing forward/Inverse model i.e. anticipating how objects move and inversely generating goal directed pushing actions is learnt is illustrated. Section 'Cumulatively abstracting ''causal dominant properties'' related to pushing' introduces two learning rules namely elimination and growth' that augment the distributed property specific organization of sensorimotor information to facilitate the robot to abstract properties that are causally dominant through cumulative explorative interactions. A discussion concludes.

Distributed ''property specific'' organization of sensorimotor information and the basic pushing forward/inverse model

Emerging trends from the fields of connectomics, functional imaging studies in relation to organization of semantic and episodic memory in the brain (Bressler & Menon, 2010; Buckner et al., 2008; Martin, 2009; Patterson et al., 2007) now provide numerous insights to guide development of brain guided computational framework for organization

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