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Introduction

Special Issue on The Brain Mechanisms of Imitation Learning

1. Special issue composition

The special issue collects a subset of the best papers presented at the NIPS'05 nEUro-IT.net workshop on the *Brain Mechanisms of Imitation Learning*. The workshop took place on December 17 2004 in Whistler, Canada, at the occasion of the Eighteenth Annual Conference on Neural Information Processing Systems (NIPS'04). All papers were peer reviewed before publication in the special issue.

2. Motivation

For a long time, imitation learning has been a key topic of psychology and cognitive sciences. Recent progress in neurosciences has, however, opened the way to a better understanding of the neural foundations of the complex mechanisms of imitation and has formed the basis for computational studies of its neural correlates. A key event in this development was the discovery of the so-called 'mirror neuron system'. While evidence that specialized areas of the human brain contribute to imitation had long been suspected from results of various lesion studies (Nichelli, DeRenzi, & Motti, 1980; Serdaru, Lhermite, & Pillon, 1986; Shimomura & Mori, 1998), the mirror neuron system was found in normally behaving subjects. The mirror neuron system refers to a network of brain areas in premotor and parietal cortices that is activated by both the recognition and the production of the same kind of object oriented movements performed by oneself and by others—see Decety, Chaminade, Grezes, and Meltzoff (2002) Iacoboni et al. (2001) Rizzolatti, Fogassi, and Gallese (2001) for recent reports on this system in monkeys and humans, and its link to imitation.

Inspired by the mirror neuron system, imitation learning has also become again a core topic of research in robotics (Billard, 2001; Dautenhahn, 1995; Matarić, 2002; Schaal, 1999), after the original wave of robotic imitation based on symbolic artificial intelligence methods lost its thrust in the late 1980s. Endowing robots and other machines with the ability to learn from observing and interacting with humans would have numerous advantages as tool to accomplish flexible means of human–robot interaction.

First and foremost, imitation learning is a powerful mechanism for reducing the complexity of search spaces for learning. When observing either good or bad examples, one can reduce the search for a possible solution, by either starting the search from the observed good solution (local optima), or conversely, by eliminating from the search space what is known as a bad solution. Imitation learning is, thus, a powerful tool for enhancing and accelerating learning in both animals and artifacts.

Second, imitation learning offers an implicit means of training a machine, such that explicit and tedious programming of a task by a human user can be minimized or eliminated. Imitation learning is thus a 'natural' means of interacting with a machine that would be accessible to lay people.

And third, studying and modeling the coupling of perception and action, which is at the core of imitation learning, helps us to understand the mechanisms by which the self-organization of perception and action could arise during development. The reciprocal interaction of perception and action could explain how competence in motor control can be grounded in rich structure of perceptual variables, and vice versa, how the processes of perception can develop as means to create successful actions.

This special issue aims at assessing recent progress in modelling the cognitive or neural mechanisms underlying imitation learning in animals and the application of these models to controlling robots. The special issue covers pieces of work that are inherently biological in their approach and that provide hypotheses for further neurological and psychological studies of imitation in animals. Because imitation learning has at core motor learning, the special issue gathers work in both motor learning and imitation learning. Key questions that are discussed include:

- Can imitation use known motor learning techniques or does it require the development of new learning and control policies?
- How does imitation contribute and complement motor learning?
- Does imitation speed up skill learning?
- What are the costs of imitation learning?
- How could the metric of imitation learning drive the choice of learning techniques?
- How could we define a general metric of imitation performance?
- What is the role of visual attention and gesture recognition in imitation?
- Do models of human kinematics, used in gesture recognition, drive the reproduction of the task?

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- Can one find a level of representation of movement common to both gesture recognition and motor control?

3. Scanning the issue

The special issue starts with a comprehensive review by *Oztop, Kawato and Arbib* of computational models of the mirror neuron system. This article provides a comparative and critical overview of the contributions of each model to biology. Further, it proposes a list of key issues that remain to be investigated.

It is followed by five articles that present computational models of different human imitative skills. All models draw from the evidence of the existence of a mirror neuron circuit and of its application to explain multimodal sensori-motor processing. They, however, go further and tackle the issue of how the brain manages the complete flow of sensori-motor information at the basis of both observation and production of actions.

Next, we briefly summarize the main results of each of these articles.

Demiris and Simmons combine evidence of the mirror neuron system at the basis of recognition and production of basic grasping motion with evidence of the existence of forward models for guiding these motions. They present a neural model that can successfully reproduce the timing of neural activity during observation of various grasping motion, as well as reproduce the kinematics of arm motion during these movements.

Sauser and Billard address the principle of *ideomotor compatibility*, by which 'observing the movements of others influences the quality of one's own performance' and develop two neural models which account for a set of related behavioral studies (Brass, Bekkering, Wohlschläger, & Prinz, 2001). The model expands the basic mirror neuron circuit to explain the consecutive stages of sensori–sensori and sensori–motor processing at the basis of this phenomenon.

Hoffman, Grimes, Shon and Rao start from a cognitive model of the early development of gaze imitation in human infants, the AIM model (Meltzoff, 1990) and develop a probabilistic framework to account for the same competencies in a robot head. While the AIM model may in part be explained by a mirror-like system, it also goes beyond explaining the bi-directional multimodal flow of information in gaze imitation to address more generic issues such as gaze contingencies and shared attention.

Cuipers, van Schie, Koppen, Erlhagen and Bekkering take a more cognitive approach and investigate the encoding of goals. Understanding the way humans learn to both extract the goals of a set of observed actions and give these goals a hierarchy of preference is fundamental to our understanding of the underlying decisional process to imitation. In this article, Cuipers et al. apply a probabilistic framework to explain the derivation and sequential application of goals in an assembly task.

Finally, *Ito, Noda, Hoshino and Tani* follow a more engineering-based approach to solving the problem of learning manipulatory tasks by imitation, while constraining themselves to using a neural network representation. This work complements the probabilistic approach proposed by Cuipers et al. to address the same cognitive functionalities.

4. Links

The reader may be interested in two upcoming special issues that address complementary topics of Imitation Learning in Robotics, also known as *Robot Programming by Demonstration*.

Billard and Dillmann's special issue on 'The Social Mechanisms of Robot Programming by Demonstration', to appear in *Robotics and Autonomous Systems* (Billard & Dillmann, in press), reviews recent work in Robot Programming by Demonstration (RbD). This special issue covers works that are inherently interdisciplinary in their approach and that emphasize the role that social skills, such as joint attention, verbal and gestural deixis, play in RbD.

Demiris and Billard's special issue on 'Robot Learning by Observation, Demonstration, and Imitation', to appear in the *IEEE Transactions on Systems, Man and Cybernetics B* (Demiris & Billard, in press) will put forward novel learning techniques applied to solving RbD, from the perception and recognition of actions to their reproduction.

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