EUROPEAN SCIENCE FOUNDATION
SETTING SCIENCE AGENDAS FOR EUROPE

**Exploratory Workshop Scheme**

Standing Committee for Life, Earth and Environmental Sciences (LESC)

Standing Committee for Physical and Engineering Sciences (PESC)

# Scientific Report

ESF Exploratory Workshop on

# Modularity for versatile motor learning: from neuroscience to robotics and back

**Certaldo (Italy), 8-11 April 2009**


**Convened by:**
**Andrea d'Avella ①, Etienne Burdet ② and Auke Ijspeert ③**


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# SCIENTIFIC REPORT

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# Executive summary

How can the central nervous system learn diverse and complex motor skills? In this workshop, 14 participants from 5 European countries, as well as 2 participants from North America, working in the fields of neurophysiology, behavioral and computational neuroscience, robotics, neural networks, and machine learning have come together to explore the concept of modularity, the partitioning of the control process into sensorimotor primitives that can be flexibly combined, and how it may enable versatile motor learning in biological and artificial systems.

The participants arrived on Wednesday April 8 in the afternoon and a first session was held after dinner. To introduce and motivate the topic of the workshop, the convenors contrasted the richness and versatility of the motor skills of animals with the limited, predefined, and specialized motor repertoire of state-of-the-art robots. The key role of motor learning in biological systems was stressed and the hypothesis that modularity might be crucial for efficient motor learning was put forward. After the convenors' introduction, Astrid Lunkes gave a presentation on the ESF and its activities supporting the advancement of European research and the exploration of new directions for research at the European level.

Given the multidisciplinary nature of the workshop, to facilitate the scientific interaction among researchers with different expertise and background, the remainder of the workshop was structured into a first part (April 9) in which each participants presented a topic relevant to the workshop and useful to illustrate the state-of-the-art in his field and a second part (April 10-11) in which key open questions, novel multidisciplinary approaches, and possible new collaborative projects were discussed informally and extensively.

The presentations on April 9 were grouped in five sessions dealing with the following topics:

- Human motor control and motor learning: mechanisms, representations and evidence for modularity
- Neural implementation of motor control mechanisms and tools to investigate neural modules
- Sensorimotor computation in biological and artificial systems
- Neural networks and machine learning for motor control
- Modularity for the design of adaptable and versatile robots

Three discussion sessions took place on April 10 addressing the following issues and open questions:

- What is the definition of a module in biological motor control? Are different definitions compatible? How can modularity be tested? What is the possible neural implemention of a modular controller?
- What are the efficient methods for learning a controller? Does modularity help learning and how?
- What are the current challenges in robotics, in particular in the design and control of humanoid robots? Can biological motor control inspire new solutions? Can robotics bring new insights to the understading of biological motor control?

In the final April 11 morning session, current collaborative projects related to the workshop topic were presented and new ideas for future collaborations and follow-up activities were discussed.

In summary, this workshop allowed for an in-depth exploration of the role and importance of modularity in biological and robotic motor control. While modules come in different realizations, whether they stem from neurophysiology, behavioral studies or robotic implementations, modularity may be able to bridge some of these levels and give rise to efficient and versatile behaviors. For this, multidisciplinary research in this area is crucial for new advancements and this workshop fully succeeded in its primary goal of laying the foundations of a European multidisciplinary network.

## Scientific content of the event

Each participant gave on April 9 a 20 minutes presentation. The first session addressed modularity in human motor control and motor learning. Ferdinando Mussa-Ivaldi presented evidence for force and position control modules. Andrea d'Avella and Yuri Ivanenko showed how muscle synergies in reaching and in locomotion, respectively, capture the organization of the motor commands. David Franklin spoke about sensory-motor modules for learning appropriate force and impedance. The second session was on neural implementation of motor control. Stefano Ferraina presented neural data from non-human primates and neural networks models suggesting the existence of modular elements in the cortical circuitry. Hans Scherberger presented neurophysiological data on cortical mechanism of planning and exection of grasping movements. Etienne Burdet presented novel tools based on fMRI and EMG useful to investigate neural modules. In the afternoon, a third session on sensorimotor computation had Dinesh Pai describing a biomechanical model of hand control, Martin Giese a method based on movement primitives to represent walk in a flexible way, and Holger Krapp sensorimotor computations in the fly. A fourth session was dedicated to neural networks and machine learning for motor control. Jochen Steil presented a neural network approach, based on reservoir networks, to bootstrap the control of hand movements of the humanoid robot ASIMO in a biologically plausible scenario. Herbert Jaeger described new techniques to train efficiently a recurrent neural network together with a feedback controller. Wolfgang Maass described a control strategy for balance control of humanoid robots based on a linear superposition of multi-joint kinematic synergies. The fifth and final session dealt with modularity in the context of control theory and robot design. Francesco Nori presented a biologically inspired control paradigm based on the linear combination of a finite number of elementary control actions. David Johan Christiansen described the design of robots made of modular components and of distributed learning algorithms to acquire locomotor skills. Auke Ijspeert presented the design of robot controller using movement primitives implemented as dynamical systems.

Based on this background, on April 10 three discussion sessions investigated a number of issues and open questions concerning modularity in biological motor control, in motor learning, and in the relationships between robots and neuroscience. The first discussion examined the functional role and neural implementation of a modular controller. An important part of this discussion was devoted to determining a definition of modules. It was noticed that modules are related either to a physical structure of the nervous system, or to functions of the motor system, in which case we can list necessary functional properties for these modules. Ideally, modules would be both related to precise functions and have a clear physical implementation, however it appears difficult to relate both. The second discussion analyzed the relationships between modules and learning. Existing learning methods were first examined, and it was found that most efficient neuroscience and robotic models are related to supervised learning paradigms, though motion planning cannot be fully explained in this way and requires other methods. Modules generally should help learning, though robotic modules may not be biological, and modules may actually limit learning, which gives us with a way to detect putative modules in human behaviors. The third discussion examined possible fruitful interactions between neuroscience and robotics, especially humanoid robotics. It was agreed that specific problems of humanoid robotics such as locomotion on flat terrain and manipulation of simple objects were currently more or less solved, and that some of the most important problems that remain to tackle include (1) the control of full body motion (e.g. interactions between locomotion and manipulation), (2) handling multiple contacts with objects and unstructured environments, and (3) learning new behaviors (i.e. approaching the richness of motor skills of animals). The concept of motor primitives (i.e. decomposing complex movements into combinations of simpler movements) seems like one of the most promising approaches to solve these complex computational problems. Robotics could be a very useful scientific tool to study human motor control. In particular, we advocated a synthetic approach in which various control architectures based on motor primitives are tested on a humanoid robot and compared with related experiments on human subjects.

Finally, a discussion on possible collaborative projects and follow-up activities stemming from the workshop took place on the morning of April 11. First a number of active or planned collaborative activities among the participants were reviewed. Joechen Steil presented the proposal AMARSi submitted to the ICT-2009-4 call of FP7, which involves 7 of the participants. Dinesh Pai and Andrea d'Avella described a collaborative project funded by HFSP to test modularity in the context of motor adaptation. Francesco Nori and Etienne Burdet described ongoing FP7 projects involving IIT and Imperial College. Then topics for new collaborative and interdisciplinary projects based on the issues explored in the workshop were discussed. These included: 1) the neural correlates of motor primitives, the plasticity of their neural representation, and the importance of modularity for the design of novel neuroprosthetics and brain-machine interface systems; 2) comparative approaches to modular control, from insects to vertebrates; 3) the use of neuromorphic chips for simulation of modular neural networks and for brain-machine interaction in closed sensorimotor loops; 4) the development of a model of sensorimotor task (e.g. reaching with an human arm) and neural controller based on dynamical systems (e.g. Reservoir Networks) to investigate modularity and learning.

## Assessment of the results, contribution to the future direction in the field

This exploratory workshop successfully brought together scientists from a broad range of disciplines sharing a common interest in the understanding motor function yet working at different levels and on different systems. Putative modules in biological motor control and possible use of modules in robot control were discussed in depth. While different approaches in each fields appeared from the discussions, there was a general agreement on the importance of bridging the gaps from neuroscience to control and robotics. Thus, the workshop fully achieved its primary goal of starting to build an interdisciplinary European network investigating motor control.

Complex robot behaviors must be structured into modules. These robotic modules are generally functional, based on a hierarchical organization, e.g. motion planning, kinematics, and dynamics. Similarly, current electrophysiology and most brain imaging studies data are generally analyzed in similar functional modules. For example, cortical neurons are classified according to their correlation with force, velocity or movement direction. However, biological motor control can be analyzed in behavioral modules. Typically, these modules should be independent and able to generate complex behaviors. Such sensorimotor modules may lead to versatile robotic behaviors so far characteristic of biological motor control.

Finding modules which are independent, generative of rich behaviors, and related both to neural structures and complex actions, is a difficult task. In particular, this requires the interaction of researchers measuring brain activity, analyzing movements, and designing synthetic learning controllers, i.e. an inter-disciplinary approach of physiology and control/robotics. To avoid a-priori suppositions concerning the structure of these sensorimotor modules, tackling them will likely require learning experiments in which traces modularity might appear as a constraint in adaptation leading to sub-optimality.

Novel insight in neuromotor control will likely be obtained by observing electrophysiological and imaging (in particular fMRI) data in the context of such sensorimotor modules. In turn, the discovered sensorimotor modules will help designing intuitive Brain-Machine Interfaces able to adapt to specific subjects and evolve with their neural capabilities, as is required for example by cerebral palsy or traumatic brain injury patients to control their wheelchair. In addition, decoding and recombining the output of sensorimotor modules may lead to the design of efficient interfaces based on myoelectric signals. Some of the participants are thus planning to  to prepare a proposal on these topics, targeting FP7 ICT calls (in the context of FP7 ICT challenge 7.2 and in the context of a FET-open).

# Final program

## Wednesday 8 April 2009

Afternoon *Arrival*

19.30-21.00 *Welcome dinner*

21.10-21.25 **Introduction by Convenors**

**Andrea d'Avella** (Santa Lucia Foundation, Rome, Italy)

**Etienne Burdet** (Imperial College London, United Kingdom)

**Auke Ijspeert** (EPFL, Lausanne, Switzerland)

21.25-21.45 **Presentation of the European Science Foundation (ESF)**
**Astrid Lunkes** Standing Committee for Life, Earth and Environmental Sciences (LESC) / Standing Committee for Physical and Engineering Sciences (PESC)

## Thursday 9 April 2009

7.30-8.30 *Breakfast*

**08.30-10.10** **Modularity for biological motor control and learning**

08.30-8.50 **The modular representation of arm motions and contact forces**
**Ferdinando Mussa-Ivaldi** (Northwestern University, Chicago, USA)

08.50-09.10 **Control of reaching and catching by muscle synergy combinations**
**Andrea d'Avella** (Santa Lucia Foundation, Rome, Italy)

09.10-09.30 **Modular control of limb movements and motor patterns in human locomotion**
**Yuri Ivanenko** (Santa Lucia Foundation, Rome, Italy)

09.30-09.50 **Learning involves adaptation of both feedforward and feedback control**
**David Franklin** (Cambridge University, United Kingdom)

09.50-10.20 **Discussion**

10.20-10.50 *Coffee / Tea Break*

**10.50-12.40** **Neural implementation of motor control**

10.50-11.10 **A network of reverberating neuronal populations encodes motor decision in macaque premotor cortex**
**Stefano Ferraina** (University of Rome "La Sapienza", Italy)

11.10-11.30 **Coding and decoding of hand grasping movements**
**Hans Scherberger** (ETH, Zurich, Switzerland)

11.30-11.50 **fMRI and EMG as tools to investigate neural modules?**
**Etienne Burdet** (Imperial College London, United Kingdom)

11.50-12.20 **Discussion**

12.30-14.00 *Lunch*

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| **14.10-15.40** | **Sensorimotor computation in biological and artificial systems** |
| 14.10-14.30 | **Computational Models of Biomechanical Systems**<br>**Dinesh Pai** (University of British Columbia, Vancouver, Canada) |
| 14.30-14.50 | **Movement primitives in the execution and perception of emotional body expression**<br>**Martin Giese** (University Clinic Tubingen, Germany) |
| 14.50-15.10 | **Sensorimotor computation in biological and artificial systems**<br>**Holger Krapp** (Imperial College London, United Kingdom) |
| 15.10-15.40 | **Discussion** |
| 15.40-16.10 | *Coffee / tea break* |
| **16.10-17.40** | **Neural networks for motor control** |
| 16.10-16.30 | **Efficient online learning for inverse kinematics of full body movements**<br>**Jochen Steil** (Bilelefeld University, Germany) |
| 16.30-16.50 | **Minimal energy control of recurrent neural networks**<br>**Herbert Jaeger** (Jacobs University, Bremen, Germany) |
| 16.50-17.10 | **Kinematic synergies enable robust balance control in humanoid robots**<br>**Wolfgang Maass** (Technical University of Graz, Germany) |
| 17.10-17.40 | **Discussion** |
| 17.40-18.10 | *Coffee / tea break* |
| **18.10-19.40** | **Design of adaptable and versatile robot controllers** |
| 18.10-18.30 | **A control theory approach to biological motion primitives**<br>**Francesco Nori** (IIT, Genoa, Italy) |
| 18.30-18.50 | **Distributed learning of locomotion in modular robots**<br>**David Johan Christensen** (SDU, Odense, Denmark) |
| 18.50-19.10 | **Control of movements in articulated robots using discrete and rhythmic movement primitives**<br>**Auke Ijspeert** (EPFL, Lausanne, Switzerland) |
| 19.10-19.40 | **Discussion** |
| 20.00 | *Dinner* |

## Friday 10 April 2009

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| 7.30-8.30 | *Breakfast* |
| **08.30-10.30** | **Open questions on functional role and neural implementation of a modular controller** |
| 08.30-08.50 | **Introduction**<br>**Hans Scherberger** & **Andrea d'Avella** |
| 8.50-10.30 | **Discussion** |
| 10.30-11.00 | *Coffee / Tea Break* |
| **11.00-13.00** | **Open questions on learning in modular control architectures** |
| 11.00-11.20 | **Introduction**<br>**Wolfgang Maass** & **Etienne Burdet** |
| 11.20-13.00 | **Discussion** |
| 13.00-14.30 | *Lunch* |
| **14.30-17.30** | **From neuroscience to robotics and back. Can modularity help building versatile and adaptive robot controllers? Can robotics inspire new approaches for testing modularity in biological control systems?** |
| 14.30-14.50 | **Introduction**<br>**Jochen Steil, Martin Giese** & **Auke Ijspeert** |
| 14.50-17.30 | **Discussion** |
| 20.00 | *Dinner in Florence* |

## Saturday 11 April 2009

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|---|---|
| 7.30-8.30 | *Breakfast* |
| **08.30-10.30** | **Future collaborative activities** |
| 08.30-10.30 | **Report on active collaborations among the participants** |
| 10.30-11.00 | *Coffee / Tea Break* |
| 10.30-12.30 | **Discussion on possible proposals and teams** |
| 12.30-14.00 | *Farewell lunch* |
| Afternoon | *Departure* |

# Statistical information on participants

Not including the ESF representative.

**Country of origin**

| | |
|---|---|
| Italy | 4 |
| Germany | 3 |
| United Kingdom | 3 |
| Switzerland | 2 |
| Austria | 1 |
| Denmark | 1 |
| Canada | 1 |
| United States | 1 |

**Age structure**

| | |
|---|---|
| < 40 | 4 |
| 41 – 50 | 10 |
| 51 – 60 | 2 |
| > 60 | 0 |

**Gender**

| | |
|---|---|
| Male | 16 |
| Female | 0 |

# Final list of participants

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