The body schema: neural simulation for covert and overt actions of embodied cognitive agents

Pietro Morasso[1*] and Vishwanathan Mohan[2]

[1] Department of Robotics, Brain and Cognitive Sciences, Istituto Italiano di Tecnologia,
Via Enrico Melen 83, 16152, Genoa, Italy
pietro.morasso@iit.it

[2] School of Computer Science and Electronic Engineering, University of Essex
Wivenhoe Park, CO34SQ, UK
vishwanathan.mohan@essex.ac.uk

[*] Corresponding author

E-mail address: pietro.morasso@iit.it

Full postal address: Department of Robotics, Brain and Cognitive Sciences
Istituto Italiano di Tecnologia
Via Enrico Melen 83, 16152, Genoa, Italy

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Abstract

This brief commentary on the general topic of "body schema" is focused on its computational role, as an internal model that integrates proprioceptive information, for allowing embodied cognitive agents to carry out the neural simulation of covert and overt actions in a unitary manner. The discussion takes inspiration from the vintage but still valid seminal observation by Marr and Poggio that, in order to understand cognitive agents, both human and artificial, we should consider them as Generalized Information Processing Systems, to be analyzed along three levels: computational, algorithmic, and implementation. Accordingly, the body schema concept is briefly analyzed along this line, with the purpose of outlining a cognitive architecture that links embodied cognition with motor control through the body schema.

Introduction: the body schema as a generalized information processing system

The hypothesis that human purposive behavior requires some form of body representation, based on proprioceptive information, has been around for more than a century [1], supported by clinical observations that also suggested a multiplicity of representations [2-4]: *Body Schema* proper*, Body Image,* and *Superficial Schema.* Although such descriptive multiplicity is associated with a variety of clinical findings, we suggest that it highlights the multiple facets of a complex but unitary computational process: a somatotopically organized, extended body schema model, whose main function is the neural simulation of both real (overt) or imagined (covert) actions [5]. In this framework, such an extended body schema concept plays the crucial role of a bridge between embodied cognition [6] and motor control, enabling goal-directed actions guided by prospection [7,8].

In general, cognitive agents — human or artificial — are characterized by the persistent need to link purposive actions to the prediction of their outcomes [9], a feature that was originally captured by Norbert Wiener with the invention of Cybernetics [10]. Such legacy was unfolded over the years and is still running through the contemporary developments of robotics and artificial intelligence, on one side, and neuroscience/cognitive science, on the other. In both cases, we can take inspiration from a seminal observation by Marr and Poggio [11] that, in order to understand cognitive agents, we should regard them as *Generalized Information Processing Systems.* This means, in particular, to articulate our investigation into three nearly independent but complementary levels of analysis, avoiding a widespread tendency to mix them: 1) the *computational level* that should clarify **what** needs to be computed and **why**; 2) the *algorithmic level*, focused on **how** the computation is carried out, in terms of the used representations and the processes employed to build and manipulate the representations; 3) the *implementational/physical level*, related to the selection and activation of the specific neural hardware used to carry out the computation. Although this epistemic approach was applied mostly to vision, there is ground to believe that the view of David Marr included motor cognition as well, considering his early work on theories of cerebellum, hippocampus, and neocortex: probably, he simply did not have time to do it for his premature death.

The computational level

A computational theory of the body schema may stem from the fact that a cognitive agent is continually involved in prospectively-guided, goal-directed actions and thus is faced by the challenge of choosing an action course on the basis of the predictable outcome. The literature on motor imagery, with particular emphasis on the studies related to the body schema [12-14], has clearly shown that *overt* actions are just the tip of an iceberg because, ‘under the surface’, is hidden a vast territory of *covert* counterparts, i.e. actions ‘without movement’. The purpose of covert actions is to predict the likely outcome of a course of action, for understanding and deciding: for example, to restrain from acting, if the predicted result is dangerous and/or clearly leading to failure, or to analyze the anticipated failure for obtaining hints about a change of plan, and so on [15]. Consequently, the body schema should not be conceived as a passive and static representation of the body but as an active and dynamic mechanism, including the plastic extension to the skilled usage of tools [16] recruited and animated in a task-oriented manner. At this level of analysis, it is also necessary to consider the vexing question about the high-degree of redundancy of the human body that forces the cognitive/control system to choose action synergies among an infinite number of solutions: consider, in particular, Bernstein’s *Degrees of Freedom problem* [17] and Lashley’s *Principle of Motor equivalence* [18].

Shortly, what needs to be computed by the body schema, as a generalized information processing system driven by proprioceptive information, is a detailed prediction of the possible outcome of whole-body actions, generated according to a combination of goals and task constraints. Such predictions, while being fundamental for the skilled behavior of cognitive agents, also play a role in anticipating others' actions/goals, a capability that is crucial for imitation and skill transfer.

The algorithmic level

For the algorithmic level of analysis of the body schema, we suggest to focus on the simulation and emulation theories for the representation of prospectively-guided, goal-directed actions. Emulation theory [19,20] assumes that an abstract representation of movement kinematics is maintained internally over short periods of time, in such a way to support motor imagery, both self-initiated or externally triggered: an emulator typically receives input from motor planning and outputs the sensory consequences as though the movement has been executed. Simulation theory [5,21] postulates that imagined actions rely on the same set of neural mechanisms as the real actions, hence encapsulating in this mechanism the goal, the motor plan and sensory consequences. For example, observing someone "drinking a cup of coffee" or paying attention to the sentence "she drinks a cup of coffee" entails a simulation recruiting brain structures that overlap with the structures involved when one actually" drinks a cup of coffee" [22].

Internal emulation or simulation mechanisms, that were also advocated in cognitive robotics [23], may be interpreted as dynamic processes that animate the body schema. However, what still needs to be clarified is how the internal simulation may actually be organized and carried out. One possibility is that the animation of covert actions is carried out by using an internal model separate and independent of the model used for overt actions [24-26]. The alternative approach is based on the idea that the internal simulation of covert actions is performed by the same neural mechanism normally involved in overt actions, but relying on endogenous rather than exogenous sensorimotor signals [15,27,28]. The latter approach is certainly more parsimonious than the former one and is supported by a large body of direct and indirect evidence; moreover, it is linked to the still influential tradition underlying the ideomotor theories of the 19th century [29,30], namely the concept that the 'idea' of an action, i.e. the predicted/desired sensory consequences of a covert action, applies as well to goal-directed overt actions.

The question is then to figure out an algorithmic formulation of the 'idea' of the ideomotor theory that can tackle the redundancy of the motor system, without being stuck by the need to directly solve the inverse kinematic problem, i.e. choosing one among the infinite number of joint rotation patterns that are compatible with a desired trajectory of the end-effector. The proposed solution is a generalization of the Equilibrium-Point Hypothesis (EPH), introduced in the 1960's and debated ever since [31-33]. The rationale of the EPH is that the central nervous system generates overt actions as a shift of the equilibrium posture for both single- and multi-joint movements, exploiting the spring-like properties of the neuromuscular system. The generalization of EPH, for including both covert and overt actions, was carried out by defining the Passive Motion Paradigm (PMP) [34-35]. The basic idea, along with Jeannerod's simulation theory, is that overt and covert actions are both generated by a simulation process that "animates" the neural body schema. The novelty of PMP is to explain how the animation may be carried out: in simple terms, this neural process can be assimilated to the animation of a 'passive' marionette (*the body schema*) by means of a few wires (*the virtual forces*), pulled by the puppeteer, according to a storyboard (*the task plan*). Remarkably, this force-based mechanism solves the "Degrees of Freedom problem" in an implicit manner, without explicit kinematic inversion, and it naturally allows to combine multiple goals by superimposing the corresponding force fields. It is worth pointing at the analogy between PMP and Active Inference [36-37]: in both cases, there is no need to have distinct sensory and motor representations, because the 'proprioceptive predictions' of the intended action, generated by the simulation process, are sufficient to allow the motor controller to produce the basic motor synergies. Such predictions encode beliefs about the state of the world, including both proprioceptive and exteroceptive components. The standard causality between sensory and motor representations is somehow inverted: motor commands are not necessarily intended to cause desired movements – but desired movements may cause motor commands (in the form of the predicted consequences of movement). Moreover, the body schema framework also allows an agent to address the imitation game with a master, by providing the machinery for simulating the exemplary actions of the master and anticipate his intentions.

Considering that the *algorithmic level* is supposed to focus on **how** the computation is carried out, we may summarize the discussion above by saying that whole-body, goal-oriented synergies, for both overt or covert actions, may be generated by an animation process of the body schema, based on the PMP.

The implementation/physical level

The algorithmic hypothesis, that the same body schema is involved in the generation of overt and covert actions, can lead to different implementation strategies for transforming a selected covert action into the corresponding overt counterpart. One possibility is that the proprioceptive predictions of a planned action are used as reference signals by simple feedback control mechanisms, one for each DoF: such servomechanisms would attempt to minimize the difference between the proprioceptive predictions and the measured sensory feedback signals. This is an implementation strategy that is frequently used in robotics, relying on the fact that robotic technologies allow to provide sensory feedback signals that are virtually noiseless and delay-less. In human physiology this is certainly not the case and the real-time control of overt actions is implemented by a combination of different control strategies (feedforward, feedback, and stiffness control), tailored to specific task and environmental conditions and aimed at compensating noise and delay of sensory signals.

The crucial point is that synergy formation (of covert actions) and motor control (of overt actions), although interrelated and deeply complementary, are logically independent processes, with different computational mechanisms, different constraints, and different timelines. Synergy formation prescribes the recruitment of different groups of joints and muscles and the basic timing, reflected in the spatio-temporal invariances of biological motion [38], but is not and cannot be concerned with the biomechanics of the body, the dynamics of the environment, or haptic interaction; moreover, a great part of the covert actions remain unnoticed, inside the virtual domain of mental simulations.

Consider, for example, the act of whole-body reaching while standing [39,40]: this an example of a dual task, with a 'focal subtask' (*reach the designated target with the hand*) and a 'postural subtask' (*keep the projection of the center of mass – CoM - inside the basis of support - BoS*). For simplicity, let us focus on a planar paradigm, related to reaching movements in the sagittal plane: the task is bidimensional, with a constraint about the horizontal position of the CoM, and there are 6 available DoFs (ankle, knee, hip, shoulder, elbow, wrist). Thus, this is a redundant task, with infinite solutions and a potential interference between the two subtasks: focusing only on the former may cause the latter to be violated. The interference problem can be avoided by a task manager by applying the PMP to the body schema with two virtual force fields: a force applied to the hand that pulls it to the target and a force applied to the CoM for pushing the CoM projection away from the border of the

BoS. By learning and remembering how to tune the two force fields, the task manager may induce the body schema to generate a stable whole-body reaching synergy, in the form of a 6-dimensional proprioceptive prediction; the crucial point is that, although such a multi-joint synergy may be statically stable, it is likely to be insufficient to activate all the involved muscles in such a way to provide dynamic stability of the body, i.e. avoiding a fall. This goal is outside the competence of the synergy formation mechanism and can be achieved by the motor controller by combining three control strategies and recruiting them simultaneously: 1) A *feedforward strategy,* namely a bias of the antigravity muscles, driven by the proprioceptive prediction above; 2) A *stiffness strategy,* consisting of the coactivation of antagonist muscles for achieving joint stiffness values sufficient to compensate for unaccounted internal and external disturbances; 3) A *feedback strategy,* driven by delayed sensory information of body sway, for consolidating the overall dynamic stability of the action.

The first control action provides the basic skeleton of muscle recruitment and activation, satisfying the static criterion of stability. The second one is simple and functional for most joints of the kinematic chain, but is certainly ineffective for the ankle joint, which is critical for the dynamic stability of the standing body: measured values of ankle stiffness are indeed smaller than the crucial rate of growth of the gravity toppling torque due to body sway [41]. As a consequence, the third control action, limited to the ankle joint, is crucial. The main problem to be faced is that the feedback signal about the ongoing sway is delayed by an amount that is comparable to the natural falling time constant of the body 'inverted pendulum': the risk is that a continuous delayed feedback control could enhance rather than eliminate the danger of falling. The solution adopted by the motor controller is an intermittent control policy that alternates off-phases and on-phases during postural oscillations [42-44]: active feedback control is switched on if the state of the inverted pendulum (tilt angle and angular velocity) is departing from the equilibrium condition, whereas it is switched off in the opposite case. In this manner, dynamic stability of the standing body is not a rigid equilibrium point but a robust, persistent postural oscillation (sway).

We would like to stress the separation but also the deep complementarity between body-schema driven synergy formation, on one side, and the body-environment interaction, including the specific control action, on the other [45]: for example, intermittency characterizes the latter but not the former computational process. Synergy formation, that operates on the body schema distributing the action to the redundant set of degrees of freedom of the body, incorporates the constraint of static equilibrium in the spatio-temporal patterns of proprioceptive predictions; however, the actual dynamic stabilization of the initial and final postures is carried out by a hybrid combination of different mechanisms that exploit muscle stiffness and intermittent feedback control.

In summary, the implementation/physical level of analysis of the body schema concept is mainly concerned with the recruitment and tuning of different control mechanisms, that may allow the detailed proprioceptive predictions to meet the challenge of the interaction of the body with the physics of the real world.

Conclusion

This commentary analyzed the body schema as a Generalized Information Processing System, highlighting the fact that it is at the center of a cognitive architecture that supervises and coordinates overt and covert actions for skilled behavior. Figure 1 summarizes the separation but deep complementarity between the two main blocks of the cognitive architecture, namely the block that carries out muscle-less synergy formation, mainly in charge of covert actions, and the motor controller, responsible of the actual generation of muscle synergies. What flows from the cognitive to the control block is a continuous pattern of sensory predictions, while a pattern of corresponding sensory feedback signals flows in the opposite direction. Both patterns are multimodal, including in particular proprioceptive, tactile, and visual components [47-50], with a predominance of the proprioceptive component. Although the main function of this bidirectional flow of sensory information is related to the control-cognitive framework, another critical function, from the implementation point of view, is related to the need of calibrating and maintaining/updating the calibration of the body schema. This problem is central in the robotic field because multisensory calibration is essential for effective performance of cognitive robots [51,53]. Finally, we need to contrast this view of the body schema, as an information processing system for embodied cognition, to radically different formulations like the Smart Vehicles of Valentino Braitenberg [54], the refusal of neural representations by Rodney Brooks [55] or the reduction of cognition to agent-environmental dynamics by Anthony P. Chermero [56]. In particular, let us briefly focus on the criticism of Brooks, who advocates a totally bottom-up architecture that is supposed to achieve "intelligence without representation": this architecture is organized in layers, decomposing complicated intelligent behaviors into many "simple" behavioral modules, which in turn are organized into layers of simpler behaviors, down to reflex-like reactive mechanisms. Generally, the main problem of layered bottom-up architectures is that they scale-up badly when one attempts to deal with complex bodies and complex behaviors in a complex environment. Moreover, intelligence without representation may capture smart skills but is completely unable of prospective behavior that is based on the systematic and cumulatively use of action memory in its different forms: working, procedural, and episodic [9,57].

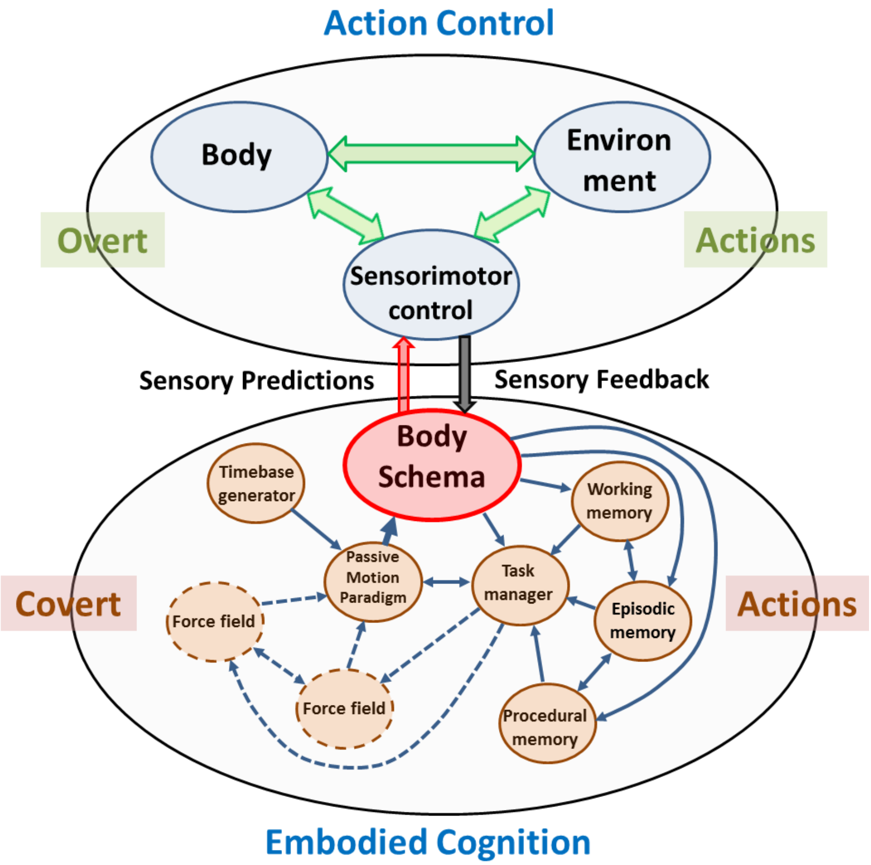

Figure 1. Schematic diagram of a cognitive architecture built around the body schema model as a Generalized Information Processing System. The body schema is a somatotopic structure, holding a proprioceptive image of the body, that is animated by the Passive Motion Paradigm (PMP), thus generating a flow of sensory predictions related to goal-oriented covert actions. Most of them remain hidden, thus carrying out the fundamental prospective function of an embodied cognitive system, namely foresight and anticipation of future consequences of an action, including assessment and re-planning. The selected action plans are transformed by the sensorimotor control system, combining the appropriate control strategies, as a function of biomechanics and physics of the environment. The animation of the PMP is organized by the Task Manager that instantiates task-related Force Fields, recalling and exploiting memory traces of previous experiences accumulated during training and practice.

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Competing interests statement

The authors declare that they have no competing interests to declare.

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