

A Biologically Inspired Visuo-Motor Control Model based on a Deflationary Interpretation of Mirror Neurons

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Abstract

We propose a new deflationary interpretation for the functional role of mirror neurons discovered by Rizzolatti and colleagues into the macaque's F5 motor area. Several functional interpretations of the mirror activity have been proposed, emphasizing their role in action understanding and representing, language evolution, or mind-reading abilities. However, according to the interpretation presented here, full understanding of agent goals and intentional action are related to mirror neuron activity only insofar as the process of understanding an intentional action necessarily involves the capability of assigning a "structural description" to the action. In particular, we argue that mirror activity is involved in both recognizing action structural features and associating these features to motor commands. Our functional interpretation includes an *anticipatory* mechanism, enabling one to verify whether the actual, suitably coded visual input, matches an expected visual input computed on the basis of a motor command sequence. This mechanism is involved in both action recognition and action execution control. We believe that this mirror neuron model could fit biological data better than the Oztop and Arbib model. Starting from this interpretation, we propose a biologically inspired visuo-motor control model merging basic elements of the Oztop and Arbib model with an expected perception mechanism. This model has been formalized within an algorithmic stance however actual implementation is in progress.

Keywords: mirror neurons, visuo-motor control, anticipatory mechanism, expected perception.

Mirror System: basic elements

Let us recall basic facts and notions concerning mirror neurons that will be needed to introduce our functional model of mirror neurons and compare it with other interpretations and models. Some macaque's cortical circuits have been found to be strongly involved in controlling arm and hand movements in order to reach and manipulate objects (Luppino G., Rizzolatti G., 2000; Matelli M., Luppino G., 2001; Rizzolatti G., Luppino G., 2001). In particular, these findings concern: a) the VIP \leftrightarrow F4 circuit, transforming object location in appropriate arm movements towards the same object; b) the AIP,PF \leftrightarrow F5 circuit, transforming object features in hand configurations suitable to object manipulation. Area F5 in pre-motor area is functionally interpreted as a "vocabulary of movements",

and the activity of the F5 neurons is selective for both "action goal" (grasping, holding, tearing etc.) and "action modality" (precision grip, whole hand grip, etc) (Rizzolatti G. et al. 1988; Fogassi L. et al. 2001; Gallese et al. 1996).

Moreover, in area F5 a population of neurons was discovered which are "active" (high spike rate) during both the execution of a *Goal Oriented action (executed-GO action)* and the observation of the same action executed by another individual (*observed-GO action*). Because of their characteristic activation, these neurons have been called *mirror neurons* (Fadiga et al. 2000; Gallese et al. 1996; Rizzolatti et al. 1996; Rizzolatti et al. 2001). Hence, the AIP, PF \leftrightarrow F5 circuit is often called Mirror System (MSys). The expression "goal-oriented action" is used to denote a series of prehension movements that relate body parts (effectors like hand or foot) of the subject to a three-dimensional object - e.g. to grasp a food piece by a precision grip is a goal-oriented action.

Canonical neurons form another distinctive family of F5 neurons (Gallese et al. 1996; Rizzolatti et al. 2001). These are active both when the monkey performs a goal-oriented action and when the monkey observes a "graspable object". No data are reported in literature about activation state of canonical neurons when an action is observed. Thus, mirror neurons are indistinguishable from canonical neurons insofar as their spike rates during executed-GO action are concerned, but their behaviours seem to differ insofar as their visual properties are concerned.

Mirror System Interpretations

Several functional interpretations of the MSys activity have been proposed (Arbib M.A. et al. 2000; Arbib M.A. 2003; Fadiga L. et al. 2000; Rizzolatti G. et al. 2001; Makino T. and Aihara K. 2003) which variously emphasize their role in (a) action understanding and representing (Gallese V. 2003; Gallese V. et al. 1996), (b) language evolution (Arbib M. 2004), and (c) evolution of mind-reading abilities (Umiltà M.A. et al. 2001).

In particular, these interpretations of MSys activity often involve a distinction between goal-oriented actions and simple motor events. Gallese (2003), tries to provide a physiological underpinning for goal-oriented action in general, and for the concept of "goal possession" in particular. But the distinction between goal-oriented actions

and simple motor events is mostly assumed on the behavioural grounds that - unlike goal-oriented actions - movements “without goal” do not involve any interaction with objects and do not appear to be deployed for doing anything in particular, except to carry out the movement itself.

In our view, however, it is correct to speak of “goal-oriented action” if the agent performing the action actually possesses a goal (Jonas, H. 1953). If we assume this view, behavioural evidence (i.e., the series of movements composing an action) does not suffice to discriminate between goal-oriented actions and actions without a goal. Moreover, we concord with Stamenov (2002) about MSys’ agency blindness: from the analysis of MSys’ activity, during action observation and execution, there is no evidence that this system is able to distinguish agent and observer and then to identify the *self* with one of them. So, if we still want to talk about “goal-oriented actions”, in relation with MSys activity, we have to do it referring only to the *function* of the action, eluding the agent’s goal (his *intention*). In this context the term “*function*” is strictly linked with the *structure* of the action, with “*how it works*”, with “*how it functions*”: the accomplishing of the goal is only the final stage of the functional process of the action.

Action understanding is another notion often involved in MSys’ activity functional interpretations. It is difficult to provide a thoroughly satisfactory account of what it is to understand (recognize, classify, etc.) an intentional action (see for example Giese MA & Poggio T 2003). Nonetheless, at least this much seems to be clear: action understanding necessarily involves the capability of assigning both a *structural description* to the observed behaviour and more subsequent additional interpretive steps. However, we are not concerned with this additional step here, insofar as an empirically adequate functional model of mirror neurons does not require any reference to an interpretive stage.

In the next Section we will give a more precise definition of the meaning of structural description and we will show how to identify a goal-oriented action (only in the sense clarified above) from its structure.

Structural Description and Mirror Neurons

As we are interested in both executed and observed actions, a definition of structural description must be adequate for both executed actions and observed actions.

Let us begin introducing the following two definitions:

- **structural description of executed actions.** Given an agent A (monkey or human experimenter), let us call C_A the internal representation of the finite set of the agent’s own motor commands. We define *structural description* of an A ’s executed action as the correspondent motor command sequence $cs \in C_A^*$ (C_A^* is the set of all strings from C_A , including the empty string).
- **structural description of observed actions.** When the agent A observes an agent B (including the particular case $A=B$), A receives sensory inputs (in the visual modality,

for instance). Let us call $V_{A,B}$ the finite set of all A ’s internal representations of A ’s visual inputs when A observes an action executed by B . We define *structural description* of a B ’s action observed by A as the correspondent A ’s visual input sequence, $vs \in V_{A,B}^*$ ($V_{A,B}^*$ is the set of all strings from $V_{A,B}$, including the empty string).

On the basis of the above definitions we suppose that it possible to identify a GO-action in the following way:

- **structural description of executed-GO actions.** We assume that there is a specific subset of motor command sequences $L_{C_A} \subset C_A^*$ with the following property: if G is an achievable goal of the agent A then there is a sequence $cs_G \in L_{C_A}$ such that the movements corresponding to cs_G make the achievement of goal G possible. *We identify $cs_G \in L_{C_A}$ with the structural description of the executed GO-action.*
- **structural description of observed-GO actions.** We assume that there is a specific subset of visual input sequences $L_{V_{A,B}} \subset V_{A,B}^*$ with the following property: assuming that $vs_G \in V_{A,B}^*$ is the visual input sequence of agent A observing agent B while achieving its own goal G , if $vs_G \in L_{V_{A,B}}$ then there is $cs_G \in L_{C_A}$ such that if cs_G is executed by A then this execution causes the same sequence, vs_G , of A ’s internal representations by visual input. *We identify $vs_G \in L_{V_{A,B}}$ with the structural description of the observed GO-action.*

An account of the capability of providing a structural description of an action does not require one to provide an account of how one understands or performs truly intentional actions. Accordingly, the ensuing interpretation of MSys activity, centred around the idea that mirror neurons recognize and compute structural descriptions of actions, is a deflationary, intentionality-free interpretation

Especially congenial to our proposed interpretation is Gallese’s hypothesis on the possible evolution of MSys from an ancient mechanism devoted to the improvement of action control (Gallese V., Goldman A. 1998). We conceive of the MSys of some agent A as a mechanism devoted to verifying whether a particular sequence of effector’s movements is appropriate, that is,

- verifying whether vs belongs to $L_{V_{A,B}}$
- identifying the corresponding $cs \in L_{C_A}$ if $vs \in L_{V_{A,B}}$

Mirror System Models

Many computational models inspired by mirror neuron findings have been proposed (Marom Y. et al. 2002; Billard A. & Matari’c M.J. 2001; Oztop E. & Arbib M.A. 2002; Tetsunari Inamura, Yoshihiko Nakamura and Moriaki Shimozaki 2002; Miall RC. 2003; Demiris Y & Johnson M 2003). Some such models, for example those of Marom Y.

et al. (2002) and Billard A. & Matarić M.J. (2001), suppose that mirror activity is directly linked to motor activity, i.e. mirror activity causes the correct activity in motor area. However, these models are unable to account for the fact that an inactivation of mirror neurons is known to cause only a slowdown of motor activity, since the correct action is eventually performed when mirror neurons are inactivated (Fogassi L. et al. 2001). Hence, in contrast with the account provided by these models, it seems reasonable to hypothesize that mirror activity facilitates motor activity without being strictly necessary to it. This view also differs from a hypothesis embodied into one of the more interesting and detailed mirror neuron models, that is, the Oztop and Arbib model (OA model) (Oztop E. & Arbib M.A. 2002), for the OA model assumes that mirror neuron activity does not influence motor activity.

The OA model is represented as a system of interacting schemas (functional units). Distinguishing features of the OA model include:

- On the basis of object features (affordances) oriented to perform an action, it is computed a hand-program controlling hand movements. This computation step models the activity of canonical neurons.
- Hand state hypothesis. Visual input is coded into a vector of observer-independent features. Under this hypothesis, the moving hand can be another agent's or the observer's own hand.
- The functional role of mirror neuron activity is modelled by means of a recognition module classifying the correct action on the basis of object affordances – hand state associations. This module is implemented using a multi-layered feed-forward neural network which is trained on the basis of affordances – hand state association sequences and the corresponding hand-program. In this connection, the authors remark: "... output is a signal expressing confidence that the observed trajectory will extrapolate to match the observed target object using the grasp encoded by that mirror neuron" (Oztop E. & Arbib M.A. 2002).

According to the OA model, a visual input sequence is transformed into a sequence of hand states, vs , and is classified by the action recognition module. This process is similar to the process of verifying whether vs belongs to some specific subset of "visual input sequences". Thus, in the OA model mirror neurons are basically assigned the role of classifying arm+hand movements with respect to "structural features" of the movement concerning object features and hand shapes during the action. Evidently, the OA model is an intentionality-free model too, and its focus is the ability to classify actions on the basis of structural features. One has to notice, however, that this model does not account for some crucial biological data, notably the fact that mirror neuron inactivation causes motor slowing (Fogassi L. et al. 2001).

MEP Model

We propose now an alternative visual-motor control model for goal-oriented actions, which is centred on the following interpretation of mirror neurons:

- Mirror neurons code an expected perception;
- Mirror neurons compare the expected perception representation with the actual perception.

As we will argue below, this interpretation enables one to account for the following biological data:

- mirror neuron are active in the same way during both executed-GO actions and observed-GO actions. (This is accounted for by the OA model too.)
- an inactivation of mirror neurons causes a motor slowing, but the correct action is still performed. This means that mirror activity facilitates without being a necessary condition for the correct activity of the motor area. (This is unaccounted for by the OA model.)

Some novel qualitative predictions can also be made on the basis of this interpretation. Notably, one should observe a decrement in neural activity if an unexpected event occurs during a GO action, for instance, if the graspable object is taken away. At the moment, no data relevant to assess this conjecture are reported in the literature.

Our model and the OA model share the following similarities:

- Visual input is coded in a vector of observer-independent features.
- An initial sequence of subtasks or commands, the plan, is computed from both task and/or object features oriented to perform an action.

A distinctive feature of our model is its anticipatory mechanism, significantly related to the expected perception model proposed in Datteri E. et al. (2003).

Accordingly, let us call this model Mirror Expected Perception model (MEP, see Figure 1), and let us proceed to a description of its interacting functional parts.

If an agent A performs a GO-action:

1. Object location (relative to A 's hand), object features (relative to A 's hand intrinsic features), arm coding (A 's arm shape and A 's arm motion relative to the object) and hand coding (A 's hand shape and A 's hand motion relative to the object) are computed, in an observer-independent internal representation, from somatosensory and visual information (actual perception): v_j . This step captures the functional interpretation of AIP and VIP neurons.
2. Both an arm plan and a hand plan are computed from task assignment and v_j . One can represent these plans as a sequence of subtasks or commands coded as an internal representation $cs \equiv c_1 c_2 \dots c_k$. This step captures the functional interpretation of F4 neurons and F5 canonical neurons.

3. Starting from $i=1$, we have the following loop (Mirror loop: steps 3.2 and 3.3 capture our interpretation of F5 mirror neurons):
 - 3.1. c_i is sent to a controller which transforms c_i in an arm motor program and a hand motor program which control the motor apparatus.
 - 3.2. At the same time, from c_i an expected perception ev_i is computed.
 - 3.3. ev_i is compared with the new actual perception v_{i+1} . If $ev_i = v_{i+1}$ then the step 3.1 is carried out on the next subtask c_{i+1} else the process returns to step 1 to compute a new plan.

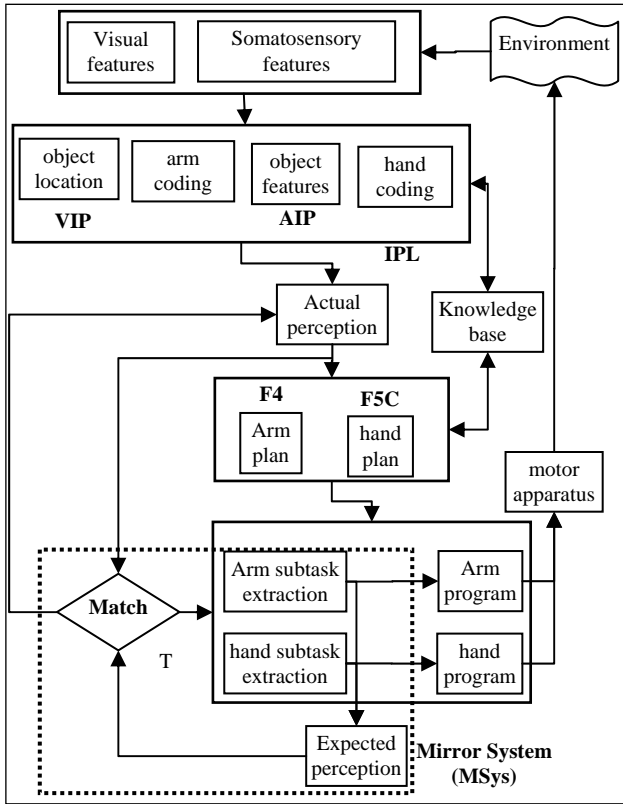


Figure 1: Architecture of the MEP model. For more details see the text.

Notice that steps 3.2 and 3.3 express salient aspects of our new interpretation of F5 mirror neurons, i.e. an expected perception is computed and the expected perception is compared with actual perception. We observe that inactivation of mirror neurons corresponds to “expected perception does not match actual perception” in our model. Therefore, in this case, the plan is continuously rebuilt, but the first step of the plan is always carried out. This means that the action is correctly executed, even though in a slowed down fashion. And this slowing down is exactly what happens in the biological case, i.e., when mirror neurons are inactivated.

If an agent A observes an agent B carrying out a GO-action, the same process is carried out by A , except for the motor program sending step:

1. object location (relative to B 's arm), object features (relative to A 's hand intrinsic features), arm coding (B 's arm shape and B 's arm motion relative to the object) and hand coding (B 's hand shape and B 's hand motion relative to the object) are computed, in an observer-independent internal representation, from visual information (actual perception): v'_1 .
2. From v'_1 a potential arm and hand plan $cs' \equiv c'_1 c'_2 \dots c'_k$ is computed (but it is not sent to the motor apparatus).
3. Starting from $i=1$ we have the following loop (Mirror loop: the following steps capture our interpretation of F5 mirror neurons):
 - 3.1. an expected perception ev'_i is computed from c'_i
 - 3.2. ev'_i is compared with the new actual perception v'_{i+1} . If $ev'_i = v'_{i+1}$ then the process continues from step 3.1 with the next subtask c'_{i+1} otherwise the process returns to step 1 for computing a new plan.

Notice that the same sequence of expected perceptions occurs when the same GO-action is observed or executed by agent A , i.e. if $cs' = cs$ and $v'_1 = v_1$ then $ev'_1 v'_2 \dots ev'_k = ev_1 ev_2 \dots ev_k$. This is what happens also for the mirror neuron's activity in the biological case.

Notice, moreover, that a fundamental hypothesis is the observer independence in the coding of hand-arm information..

On the basis of the formalism introduced in Section *Structural Description and Mirror Neurons* we state that if the mirror loop is executed without interruptions then the visual sequence $vs' \equiv v'_1 v'_2 \dots v'_{k+1}$ belongs to $L_{V_{A,B}}$ and the corresponding command sequence belonging to L_{C_A} is $cs' \equiv c'_1 c'_2 \dots c'_{k+1}$.

Observe that, in our interpretation, the *understanding of an action* is the capability to associate to the visual sequence $v'_1 v'_2 \dots v'_{k+1}$ the potential plan $cs' = c'_1 c'_2 \dots c'_k$ such that if cs' is carried out by A then A should be able to perform the same task of B . Thus, according to MEP, the role of F5 Mirror neurons is to control whether some plan is correct on the basis of visual and/or somatosensory information. During a executed GO-action this ability enables one to continue on in plan execution or else to restart a new plan in such a way that an agent is able to control unexpected events. During the observation of an action this ability enables one to associate sequences of visual information to potential plans.

From an algorithmic point of view, the main blocks of this overall process can be schematized as the algorithm in the table 1.

Concluding remarks and future work

We have introduced the biologically inspired, visuo-motor control mode, MEP, based on a new deflationary,

intentionality-free interpretation of mirror neurons, and differing in significant ways from the Oztop and Arbib functional model. We have argued that mirror activity is involved in both recognizing action structural features and associating these features to motor abilities. To achieve this functionality, mirror neurons take part into an anticipatory mechanism which verifies whether the actual visual input, matches a predicted visual input computed on the basis of a motor command sequence. We have emphasized that our mirror neuron interpretation could fit biological data better than one of the more interesting and detailed mirror models, that is, the Oztop and Arbib model. Notably, it was pointed out that the MEP model accounts for experimental data collected during inactivation of mirror neurons, i.e., for the fact that action is slowed down and yet correctly executed in these situations. Moreover, on the basis of MEP one predicts a decrement of mirror neuron activity if an unexpected event takes place during some goal oriented action .

One should carefully note, however, that the MEP model does not fit all available experimental data on mirror neurons. For instance, it was showed in Umiltà M.A. et al. (2001) that a subset of mirror neurons becomes active during action presentation, and also when the final part of

the action, which is crucial for triggering the response in full vision, is hidden. In this case, our interpretation fails because expected perception does not match actual perception. In order to fit these experimental data we might introduce a “weaker” definition of match between expected perception and actual perception; for example, one may suppose that an expected perception matches an actual perception when the actual perception *does not contradict* the expected perception.

Note, finally, that we have not addressed here various central questions: How is the right plan computed? How is the actual perception computed in an observer-independent representation? We have merely supposed that it is possible to perform these subtasks because we were chiefly concerned here with the problem of including a mirror neuron functional model into a visuo-motor control model. All implementation details have been ignored so far, but the next step of our research program is to implement this model in a simulated environment. subsequently, we intend to probe MEP by embodying the proposed visuo-motor control model into a real robotic platform interacting with another robot in a real environment.

Table 1: The MEP algorithm.

<pre> A l g o r i t h m : M E P Input: task: Agent Task, executeGoAction: Boolean Global variables: environment visuallInput ← read(environment) handObjectFeatures ← AIPComputation(visuallInput, task) objectLoacation ← where(visuallInput) v ← coding(handObjectFeatures, objectLoacation) plan ← canonicalComputation(v, task) c ← pop(plan) IF (executedGoAction is TRUE) THEN WHILE c is not NIL DO environment ← perform(c) ev ← EPGenerator(v,c) visuallInput ← read(environment) handObjectFeatures ← AIPComputation(visuallInput, task) objectLoacation ← where(visuallInput) v ← coding(handObjectFeatures, objectLoacation) match ← mirrorComputation(v,ev) IF (match is FALSE) THEN plan ← canonicalComputation(v, task) c ← pop(plan) ENDWHILE ELSE WHILE c is not NIL DO ev ← EPGenerator(v,c) visuallInput ← read(environment) handObjectFeatures ← AIPComputation(visuallInput, task) objectLoacation ← where(visuallInput) v ← coding(handObjectFeatures, objectLoacation) match ← mirrorComputation(v,ev) IF (match is FALSE) THEN plan ← canonicalComputation(v, task) c ← pop(plan) ENDWHILE ENDIF </pre>
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