Action-Oriented Representations in the Motor Control

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Abstract

Pezzulo (2008, 2011) and Grush (2004) contend for embodied cognitive science but interpret representations of motor behaviors as grounded on predictive internal models; those representations are referring-based. By contrast, the present paper contends that the motor control is ground on both referring-based representation (as manifest in forward models) *and* non-referring-based representation (as manifest in inverse models); the latter is pragmatic representation with the following six characteristics: perspective, changing perspectives, normativity of the goal, planning, coordination, and motor learning by refining inverse models. This is an internal version of the action-oriented representation.

Keywords: inverse internal model; action-oriented representations; forward internal model; motor control; goal.

Introduction

The studies of embodiment and anticipatory behaviors have been over one and a half decades, while the embodied cognitive science is in sharp contrast to cognitivism. However, Pezzulo (2008, 2011) and Grush (2004) regard motor behaviors as anticipatory insofar as their architectures are based on internal models (e.g. emulators, which are (closed-looped) forward models), without which motor behaviors would be `merely adaptive', as they consider. Motor emulators, simulating motor effectors and environmental conditions, can operate on-line or off-line, and consequently are decouplable from the actual environmental conditions (Grush, 2004); because of that simulation, the relation between emulators, on the one hand, and bodily and environmental conditions, on the other, can be put in terms of structural isomorphism (Ramsey, 2007). As internal models operate ahead of the motor effectors, the motor system becomes significantly more efficient, compared to the control based on sensory feedbacks (Grush, 2004; Desmurget and Grafton, 2000).

Apart from that, Pezzulo considers that all cognitive phenomena are grounded on "anticipation of sensorimotor interaction" (Pezzulo, 2011, p. 80). Together, as Pezzulo gathers, cognitive phenomena are embodied, and embodied representations, in turn, are grounded on internal models. What is it, then, that makes such internal models representational? If it is structural isomorphism, then, such a perspective of representation is indeed a foundation of cognitivism, against which the embodied cognitive science aims to challenge. By contrast, if it is not structural isomorphism, then, what indeed is it?

The present paper will inquire into the nature of internal models concerning the motor control, arguing that they are internal in two ways, while each has its pertinent way of representation: the aforementioned structural isomorphism and *effectivity-achieving*, the former being based on *referring-to* (or, standing-in-for) relation, while the latter not, but instead on *goal-fulfillment*. The former way of representation, typically manifest in forward internal models, explains some control functions, including prediction and estimation. Such models are internal on the basis of the mimicking relation. The latter explains some others, including planning and feedback correction. Such models are internal, not based on mimicking, and accordingly the relating representation is non-referring-based.

Section two discusses the representational status of non-referring-based representations, the application of which will be discussed in the following two sections, on mirror neurons, and body schema, respectively. The last section characterizes representations of motor actions.

Two Ways of Representation in Internal Models

The study of motor control is fundamentally concerned with transformation between sensory signals and motor commands, transformation which involves the coupling of two internal models: forward internal models and inverse internal models (Wolpert and Ghahramani, 2000). Forward models simulate how the musculoskeletal system, given certain motor commands, would operate in response to environmental conditions, by *predicting* both the would-be (reafferent) sensory signals of resulting motor movements and consequent errors between those sensory states and the goal-state. Inverse models, by contrast, maintain the opposite way of transformation, from desired motor states (i.e., the goal) to motor commands. Those models are not mimicking-based. Yet, they remain internal because with them the CNS (Central Nervous System) is regarded as modeling the system of sensorimotor transformation (Wolpert and Ghahramani, 2000; Wolpert *et al.*, 1995). What is such a way of modeling based on, if not mimicking?

Despite their being commonly internal, inverse models and forward models are internal in different ways. Forward models, as aforementioned, simulate how the sensorimotor system and sensory receptors operate under environmental conditions. That simulation maintains predicting activities on grounds of the relation that forward models *refer to* (shortly later) states of the sensorimotor system, given a certain end-state of the sensorimotor system as its goal and certain motor commands readily available for achieving that the goal. The simulation, predication, and the consequent representation, can thereby be regarded as *referring-based*; this is a relation, in turn, based on structural isomorphism between forward models, on the one hand, and environment conditions and the sensorimotor system, including sensory receptors and given goals, on the other. The prediction that forward models make is *anticipation* with reported error signals. Such errors are measured under the referring-based relation through comparison between the resulting state and the goal-state. Errors and the consequent anticipation can be evaluated with the value of truth; consequently, mis-representation is considered with truth-conditions of the anticipation. Because of the involving truth-conditions, forward models consist of *epistemic* representations.

By contrast, inverse models are internal in a different way. Although there may be a sense of internal modeling/representation, in which the CNS provides information of how the sensorimotor system operates, this is not modeling/representation to be measured with the truth-value. As sensorimotor transformation is determined within the CNS (Wolpert and Ghahramani, 2000), that system largely resides in the CNS, apart from processing extended to the peripheral. Given a sensory state as the goal-state, a generated motor command would instead be measured with the value of *satisfaction* (Mandik, 2005), measuring whether the sensorimotor system would effectively achieve the goal; hence, the representation can be regarded as an *effectivity-achieving* relation. Because that satisfaction-value, representations in inverse models are non-referring-based. What is concerned in the effectivity-achieving relation is not the epistemic knowledge, but instead the *pragmatic* knowledge, regarding how *effective* is the *process* of sensorimotor transformation heading toward achievement of the goal.

Representations in inverse models are action-oriented representations as they involve both sensory states *and* motor commands. Despite its being based on a non-referring relation, inverse models remain consisting of representations in good standing, representing in the sense of *directing something toward a goal (directing relation, for short)*; this is a three-position relation among an agent (an acting subject), a goal, and a body part to be directed toward that goal. Such a relation operates in two contexts as its background: the musculoskeletal system and the environment, the former being full of noise and the latter being largely uncertain. Besides, the directing relation presumes primitive (non-detailed) epistemic knowledge of the world/environment, knowledge on which the pragmatic knowledge unfolds. The primitive epistemic knowledge, in the motor control, is typically manifest in the sensory or proprioceptive states of body parts concerning the goal of motor movements, the current state, and the resulting state after a motor movement. The sensory or proprioceptive information, on the one hand, and information for controlling motor movement, on the other, interact in a way that they stand in mutual *coordination*, which is firstly conceived in the thesis of pushmi-pullyou representations (Millikan, 2005). The directing relation is characterized with the following four properties together: perspective, changing perspective, normativity of the goal, and planning.

1. **Perspective**. Inverse models maintain the *sensorimotor transformation*, which generates motor commands that are required for achieving a goal, which is registered with its sensory state. The way in which the sensorimotor transformation operates can be understood with *basis functions* that transform sensory coordinates of the goal-state, undergoing serial changes of a variety of coordinates, into coordinates of the envisaged motor commands (Pouget and Snyder, 2000). Each pair of coordinates, as a note, has an origin at which two coordinates intersect with each other. The origin of a pair coordinates is a standing point on which a body part acts, where body parts may be a hand, an arm, a shoulder, the neck, the head, or an eye. Sensorimotor information in a coordinate system is *perspectival*, like that the sensory information at the retina of an eye is perspectival in the sense of seeing from an eye with egocentric representations. The information of a motor command is also perspectival, in the sense, for example, that the hand sets out to reach an object from the standing point of the original hand-position. Perspective is a characteristic of *cognitive* representations, as opposed to mechanical codes.

2. **Changing perspectives**. Representations in an inverse model are cognitive representations in good standing, as changing coordinates involves changing perspectives, which is remarkable in human thinking, and by no means merely a mechanic transformation.

3. **Normativity of the goal**. An end-state of a motor movement is considered to be a *goal-state*, including velocity or position as its parameters. A goal-state is a target state for the ending condition of the motor control. Furthermore, a goal-state is also an end-state for comparison between a current state and the goal-state, with the resulting error signals to be reduced by setting up a new motor command that brings about a new motor state. Because it is recognized as a goal-state, an end-state is assigned a *normative* significance for directing motor movements toward that goal-state. To put it metaphorically, a goal is set-up cognitively as a ‘desired’ target for further pursuit. Because of that normative significance, an end-state of motor movements becomes a goal-to-be achieved for *pragmatic* representations, as opposed to epistemic ones. The goal-state is regarded as a reference point, in comparison with which currents states of hands and limbs are evaluated and the discrepancy is to be reduced. This is the process of feedback correction, with which the motor control heads toward the reference point. In the nutshell, the goal-state is taken normatively as a target to be achieved with the motor control.

4. **Planning**. Inverse models operate in the course of *planning*, which manages reverse engineering when given a sensory goal-state and expecting to generate a motor command that can be used to achieve that goal-state (Wolpert and Ghahramani, 2000). The reverse engineering maintained by inverse models cannot be a biomechanically causal process, because the course of planning operates purely internally (in the CNS) without being executed in the

way of driving muscles,[1] and because the management of *reverse* engineering aims to 'reverse' the causal chain from motor commands to the goal-state and consequently does not fall in that causal chain. More importantly, it is because the determination of a motor command for achieving a goal basically can be managed in many different ways. A motor command is *selected* with the optimal control, control which operates with a number of principles, such as minimizing energy used by muscles, smoothness with minimum-jerk, and minimum variance (Todorov, 2004). In inverse models, selection with principles is a matter of computation, as Wolpert and Ghahramani (2000) conceive. The optimal control starts with a *cost* that defines the task goal (Todorov, 2004), cost which evaluates how far it is away from the goal, evaluating for the relating computation. We can accordingly grant codes of inverse models the status of representation for their being the vehicle of computation.

As is worth noting, although inverse models are internal models, the optimal control cannot run as decouplable models with perfect accuracy. According to Todorov (2004), open-loop optimalization preconceives "what the control schemes the sensorimotor system might use" and consequently approximate the average behavior of motor movements (pp. 910-1). By contrast, only closed-loop optimalization can incorporate sensory and motor noise in the biomechanical model and receive feedbacks from the environment. That is, it is the closed-loop optimization that manages the *on-line* sensorimotor transformation, which responds to *real* information of the motor system in its immediate environment. Thus, inverse models are embodied and situated because of the on-line computation of the sensorimotor transformation managed by the inverse models.

Above, when inquiring into vehicle of inverse models, we see four characteristics of the motor representation in the sense of directing toward goal-achievement. It is contrasted to referring-based representation in forward models.

A system of the directing relation is representational in the action-oriented sense. The control of actions has goal-states. Motor control, for example, is the determination of actions in order to achieve a goal-state. Commands in the motor control can be considered in the context of *action-oriented representations*: action-oriented representations are those that "include in their contents commands for certain behaviors (Mandik, 2005, p. 285)." In addition, action-oriented representations are "representations that simultaneously *describe* aspects of the world and *prescribe* possible actions, and are poised between pure control structures and passive representations of external reality (Clark, 1997, p. 49; emphasis added)." Millikan's (1995, 2005) thesis of pushmi-pullyou representations, an early version of action-oriented representations thesis, explains the representational status of association between description and prescription. Such an association is representational because of its function of *coordination* between various aspects of living experiences, coordinating between what is sensed and what is to be done. Such coordination ranges from animal behaviors (e.g. a food call of hens), Gibsonian affordances (e.g. environmental layouts for opportunities of action; e.g. grasping the handle of a cup), to common norm (e.g. driving on the right) and social role (e.g. waiting in orderly queues). It is representational, as Millikan argues, because of its proper function that contributes to survival, for example, eye-brink has the proper function of preventing foreign matter entering the eye.

Mirror Neurons

Motor actions are anticipatory, not simply because motor control is for achieving goals but intrinsically because motor acts are implicitly embedded in goal-oriented actions. This is indicated in Rozzi *et al.*'s (2012) research on mirror neurons.

The F5 neurons in the brain are subdivided into groups for various motor acts, such as grasping, holding, tearing, and manipulating, which are anticipatory behaviors. Experiments with monkeys show the existence of mirror neurons. Such neurons fire differently while executing the grasping act, depending on different final goals of the action, e.g. grasping the food to eat, or grasping it and placing it into a container. In an experiment that requires grasping with pliers as a tool, a monkey is trained to get an object with normal pliers. The pliers are open and should be closed in order to get an object. When the monkey is given 'reverse' pliers, the pliers are in a condition of closure; to get an object, the hand should open pliers. The result is that most F5 neurons fire depending on the completion of the final goal-state, that is, holding the given object, but independent of the hand movement itself (opening or closing) (Umiltà *et al.*, 2008). The lesson is that a motor act is represented as a *goal*-oriented action. As Rozzi *et al.* (2012) put it, "the neuronal selectivity for the action goal during grasping observation represents a prediction of the action outcome (p. 182)." A movement of motor movement, say, hand opening with the tool of 'reverse' pliers, is incomplete without incorporating a final state of *goal*-achievement, namely, getting the given object firmly. Mirror neurons "predict the action goal with contextual cues" (ibid.). Putting in terms of action-oriented representations, prescription of action is incomplete without incorporating description of the goal-state. The motor movement is integrated with goals, in a way that coordination appears between prescriptive and descriptive information. Representation of motor action is indicated in characterization of a goal and the prescription of motor actions, which is goal-oriented and non-referring-based.

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[1] The ideomotor action is initiated with an idea or imagery (Koch *et al.*, 2004), which specifically initiates the generation of motor commands for being further executed in driving muscles. The inverse models for generating those motor commands are *internal* models, not in the sense that they *mimic* motor activities, but that they manage *planning* that provide the motor commands needed for achieving the goal at stake.

Prescription (of actions) is connected to description (of states) in another sense: the body representation is used for generating actions, as discussed in the theme of body schema.

Body Schema

The *body schema* is the information of visual and bodily sensations tightly coupled with information available for generating motor actions. It can be considered in the context of action-oriented representations, with the focus on description-prescription association, as discussed below. The manipulation of actions, which is anticipatory, requires spatial knowledge of bodily parts, which is knowledge poised for use in processes of motor control from the controller's point of view, as opposed to the observers'. That knowledge is the body schema, as discussed by Christensen (2012). That would likely be knowledge, generally speaking, put in an egocentric spatial framework, which is put in a way that can be immediately taken into account in determination of motor commands. That egocentric spatial framework is highly detailed with various reciprocal relations, as indicated by Christensen as follows. A bodily part thus encoded in space is, at least, one that is posited in relation to external objects and simultaneously one in relation to other bodily parts. For example, when I grasp a cup in front of me around a desktop computer, the arm is positioned in relation to the keyboard and the cup that I intend to reach, and the arm is positioned in a further relation to the hand and other limbs connecting to it. The egocentric spatial framework includes somatosensory information (the sensation of touch, signals received from the skin) and proprioceptive information (sensory information received from muscles, tendons and joints, information concerning the stretch and load of muscles).

In Christensen's (2012) research, the body schema is contrasted with the body image in the following three respects; in general, the description-prescription connection is manifest in the use of body schema for controlling actions. Firstly, body schema is body representations for use in actions, while body image is body representations available in perception. Secondly, the body schema is unconscious knowledge, while the body image is information available for generating consciousness. Thirdly, the body schema is changeable along with the time when an action proceeds, while the body image is comparatively "more static" (ibid. 285). The body schema is more complicated, as we can understand, because various sensations are made available for use and consequently is constrained in use, as manifest in the following two properties of the body schema.

First of all, stimuli of sensation are coded in a spatial reference frame that is basically used for representing the external world, yet representations of actions and the goal are involved. When I feel itching on one foot, I remain in a position to scratch it accurately in the correct foot. Even when I cross my legs, it remains the case, yet the processing time needs to be longer, indicating that things are getting more complicated concerning any further action pointing to a specific position. The lesson, as can be interpreted, is that sensations in the body schema arise in an egocentric space that is not independent from the actual motor processes, but instead using the egocentric space in the *actual management* of motor processes. The way in which motor processes proceed, in other words, would affect the sensations in the body schema. The body schema consists of sensations that are tightly involving in, rather than independent from, processes of motor actions. More important, such sensations arise in the egocentric space that intrinsically takes shape with the management of motor *actions*. As arguably, representations of such sensations involve the aforementioned directing relation, which is action-oriented with non-referring-based characters such as changing perspectives, planning and normativity of the goal for action.

Secondly, the body schema is put in modular representations, modular in both perspectives of sensation and action. As signified in the modularity, fingers are part of the hand, and in turn part of the arm. For representations in a module are independent from those outside it, apraxia patients may have difficulties in grasping a spoon, while they can reach the food with the spoon easily (by moving the arm without using the hand). That is, the damage in processes of controlling the hand, because of modularity, does not affect those of controlling the arm (Sirigu *et al.*, 1995; cited from Christensen, 2012, p. 285). When sensations are modularized, their relating processes for action are modularized in a concordant way, which manifests a way of description-prescription connection.

The above discussions concern how sensations of motor actions are organized, which are actually organized in relation to processes of motor actions. A further question regarding body schema concerns its cause. Namely, what is it that initiates sensations of movement: Is it motor commands of the movement in the central neural system (CNS), or muscular structures that carry out the motor movement? The answer is muscular structures; such an answer indicates the tight coupling between sensations and motor actions, which takes place not at the level of motor commands at the CNS but down at the level of muscular structures.

Ellaway *et al.* (2004) organize an experiment that elicits finger movements, twitches, happen nearly simultaneously at the left and the right hands, and further identifies which movement is sensed earlier. Specificially, the twitch at the left hand fingers is elicited with electrical stimulation of forearm muscles, while that at the right is initiated with transcranial magnetic stimulation (TMS) functioning in the human motor cortex. The TMS stimulation, as is suspected, brings about an efferent copy of the motor command, a copy which initiates sensations of the twitch at the right hand fingers. If this is true, then the right hand twitch would be sensed earlier, as the route of signal transduction in the brain is certainly shorter than a sensory feedback from the peripheral. Yet, it is not the case; the sense of twitch at the right, elicited with the TMS, is actually later that sensed at the left, with electrical stimulation. As Ellaway *et al.* (2004)

discuss, there is no evidence that TMS takes an early efferent copy. The early sensations are directly initiated by synchronous volleys of action potentials in muscular afferents. Eventually, those volleys at the left are sensed earlier than the afferent responses to the muscle twitch at the right. In the nutshell, those muscular volleys arise at the onset of the left twitch, while sensory feedback of muscular twitch at the right turns up at the end of the twitch.

The body schema as discussed above, to conclude this subsection, can be considered in the context of action-oriented representations. During the course of a motor action, first of all, locations of bodily parts should be represented in a way that is readily available for use in that action. As discussed above, the body schema is information of sensations that are tightly coupled with information for generating motor actions. Such sensations are action-oriented as they are structured in egocentric spatial framework and objects and bodily parts in that framework are mutually related responding to a way that is easy for use.

Cognitive Representations

In the motor control discussed above, motor systems are qualified as representational manly in three senses together: directing relation, coordination, and the *basis* for developing/learning new motor skills through practice. Firstly, the relation of directing something toward the goal, as previously discussed, manifest a novel sense of representation—non-referring-based representation—in inverse models of the motor control. Secondly, the coordination between various factors involving in connections between sensory information and motor commands makes the motor actions readily approaching to the goal-state, thus showing the description-prescription connection of action-oriented representations. The sensorimotor transformation stands at the core of inverse models, which presumes this description-prescription connection.

Representations in the above two senses together are different from those in perception, declarative language and memory. Each of the latter representations is basically a matter of factuality and consequently is to be evaluated with truth-value. By contrast, the motor control concern both factuality and effectivity, and consequently need to be evaluated with the value of accuracy. In the maintenance of anticipation, evaluation of motor actions can be made in terms of accuracy; for example, reaching without missing the target, grasping a cup firmly, walking ahead in balance, are movements that fulfill the goal-states accurately. Whether a goal-state is achieved can be evaluated, regarding the degree of error when a current-state is compared to the goal-state; in this way, conditions of misrepresentation are clearly defined. Thus, representations of the motor action differ from those of perception, memory and declarative language, in a way that the category of accuracy is different from that of truth. This is a distinctive reason why the bases of motor actions—coordination and non-referring-based anticipation, as aforementioned—are not put in the categories of structural isomorphism (as Ramsey (2007) characterizes), 1-1 correspondence or mirroring, on which representations of perception, memory and declarative language are based.

The third sense of representation—the basis for development of novel skills through refining inverse models—must be addressed for responding to the problem of characterizing cognitive representations in terms of necessary and sufficient conditions, which attempts to find a clear-cut boundary (with a set of properties) between the mental and the physical. Yet, coordination and the non-referring-based anticipation not only appear in behaviors but also turns up in biological structures (e.g. homeostasis), even in physical phenomena (see various examples of anticipatory coupling in Stepp and Turvey (2010)). By contrast, that motor actions are cognitive is distinguishingly manifest in the characteristic that individuals may develop (as opposed to changing in the phylogeny) various dexterities through practice. Motor actions are bases for further development (through practice) of motor skills. The development of motor skills implicates that structures and phenomena of motor actions continue and are enhanced in those skills. The continuation is unlike further constructions on materials, e.g. building up a house with sand and stone, and constructing a bridge with steel. Rather, the development of motor new skills is like a young manager being supported (and consequently `enhanced') by experienced advisors. The motor dexterity is developed out of motor actions, which provide primitive structures and shapes for further transformation into various motor dexterities. The continuation from motor actions to motor dexterities is made possible with practice, especially that through perseverance. Furthermore, learning of motor skills is achieved by adapting internal inverse models (Wolpert and Ghahramani, 2000), which are non-referring-based models, as aforementioned. Hence, the motor learning is achieved on grounds of adapting non-referring-based models. To summerize, insofar as motor dexterities are cognitive performances, those three characteristics of the motor control—non-referring-based anticipation, coordination, and the basis for development of dexterities through practice—make representations of the motor control be consisted of not only truth-based representations but effectivity-based representations.

Concluding Remarks

Pezzulo (2008, 2011) and Grush (2004) contend for embodied cognitive science but interpret representations of motor behaviors as grounded on internal models, apart from this, motor control would be ‘merely adaptive’. Pezzulo argues that motor control is representational because of predictive models; similarly, Grush argues it because of the prediction made in forward models. As prediction made in forward models is ground on the referring-based representation, their arguments are amount to the claim that the motor control is representational because of the referring-based relation. Against this claim, as the present paper contends, inverse models disclose that motor control may be representational in a different sense—directing relation (directing something toward a goal)—a non-referring-based sense of representation. This new sense of representation has four characteristics: perspective, changing perspectives, normativity of the goal, and planning.

Apart from those four characteristics, the cognitive representation of the motor control has two more characteristics: coordination, and the basis for motor learning by refining inverse models. As for coordination, motor behaviors are characterized with action-oriented representations, in which sensory states are directly connected with motor information, and in turn descriptive information is tightly connected with indicative information, which results in coordination of relating elements in the regarded phenomena.

The property of decouplability is seen as a pivotal characteristic of referring-based representation, and is used to challenge the notion of action-oriented representation manifest in embodied cognitive science. The reason is that without decouplability even biological phenomena, such as homeostasis, would be representational. In order to meet this challenge, the present paper raises the third characteristic of motor behaviors—the basis for development into dexterity through practice—motor representations are bases that can be extended to ground the development of motor dexterities. Such a continuation to dexterity manifests the cognitive nature of motor representations, as aforementioned, and consequently distinguishes motor behaviors from biological ones.

In the nutshell, the motor control is ground on both referring-based representation (as manifest in forward models) and non-referring-based representation (as manifest in inverse models); the latter representation has six characteristics: perspective, changing perspectives, normativity of the goal, planning, coordination, and motor learning by refining inverse models. Clark's and Mandik's notion of action-oriented representations is largely limited to reactive actions (though not necessarily reflexes); its internal version can be found in internal inverse models of the motor control.

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References

Christensen, M. S. (2012). Body schema, illusions of movement and body perception, in Gollhofer *et al.* (eds.).

Clark, A. (1997). *Being There*: *Putting Brain, Body and World Together Again*. Cambridge, MA: MIT Press.

Ellaway, P H, Prochazka, A., Chan, M., Gauthier, M. J. (2004). The sense of movement elicited by transcranial magnetic stimulation in humans is due to sensory feedback, *Journal of Physiology*, 15, 556(pt 2): 651–660.

Gollhofer, A., Taube, W., and Nielsen, J. B. (eds.) (2012). *Routledge Handbook of Motor Control and Motor Learning*, London, UK: Routledge.

Grush, R. (2004). The emulation theory of representation: motor control, imagery, and perception. *Behavioral and Brain Sciences* 27: 377-442.

Koch, I., Keller, P. E., & Prinz, W. (2004). The ideomotor approach to action control: Implications for skilled performance, *International Journal of Sport and Exercise Psychology*, v.2, pp. 362-375.

Mandik , P. (2005). Action-oriented representation. In Kathleen Akins and Adrew Brook (eds.) Cognition and the Brain: The Philosophy and Neuroscience Movement. Cambridge: Cambridge University Press.

Mandik, P. (2003). Varieties of Representation in Evolved and Embodied Neural Networks, *Biology and Philosophy*, 18: 95–130, 2003.

Millikan, P. (2005). Pushmi-pullyou representations, in Language: A Biological Model, Oxford University Press.

Pezzulo, G. (2011). Grounding procedural and declarative knowledge in sensorimotor anticipation. *Mind and Language*, 26(1):78–114.

Pezzulo, G. (2008). Coordinating with the Future: the Anticipatory Nature of Representation. *Minds and Machines, 18,* 179-225.

Pouget, A., and Snyder, L. H. (2000) Computational approaches to sensorimotor transformations, *Nature Neuroscience* supplement, v.3, pp. 1192-1198.

Ramsey, W. M. (2007). Representation Reconsidered. Cambridge University Press. Cambridge: UK.

Rowat and Selverston (1997). Oscillatory mechanisms in pairs of neurons connected with fast inhibitory synapses , *Journal of Computational Neurophysiology,* 4(2):103-27.,

Rowat and Selverston (1993). Modeling the gastric mill central pattern generator of the lobster with a relaxation-oscillator network, *Journal of Computational Neurophysiology*, 70(3): 1030-53.

Rozzi, S., Buccino, G., Ferrari, P. F. (2012). Mirror neurons and imitation, in Gollhofer *et al.* (eds).

Schwartz, A., and Koller, D. (1986). Diurnal phototropism in solar tracking leaves of *Lavatera cretica*. *Plant Physiology*, 80: 778-781.

Stepp, N., and Turvey, M. T. (2010). On strong anticipation, Cognitive Systems Research, v.11 (2): 148–164.

Todorov, E. (2004). Optimality principles in sensorimotor control, *Nature Neuroscience*, 7(9): 907-915.

Umiltà, A., Escola, L., Intskirveli, I., Grammont, I., Rochat, M., Caruana, F., Jezzini, A., Gallese, V., and Rizzolatti, G. (2008). When pliers become fingers in the monkey motor system, *Proceedings of the National Academy of Sciences of the United States of America.* 105(6): 2209-2213.

Wolpert, D. M., and Ghahramani, Z. (2000). Computational principles of movement neuroscience, *Nature Neuroscience* supplement, v.3, pp. 1211-1217.

Wolpert, D. M., Ghahramani, Z., and Jordan, M. I. (1995). An internal model for sensorimotor integration, *Science*, v. 269, pp. 1880-1882.