

## Continuing Commentary

Commentary on M. Jeannerod (1994). **The representing brain: Neural correlates of motor intention and imagery.** BBS 17:187–245.

**Abstract of the original article:** This paper concerns how motor actions are neurally represented and coded. Action planning and motor preparation can be studied using a specific type of representational activity, motor imagery. A close functional equivalence between motor imagery and motor preparation is suggested by the positive effects of imagining movements on motor learning, the similarity between the neural structures involved, and the similar physiological correlates observed in both imaging and preparing. The content of motor representations can be inferred from motor images at a macroscopic level, based on global aspects of the action (the duration and amount of effort involved) and the motor rules and constraints which predict the spatial path and kinematics of movements. A more microscopic neural account calls for a representation of object-oriented action. Object attributes are processed in different neural pathways depending on the kind of task the subject is performing. During object-oriented action, a pragmatic representation is activated in which object affordances are transformed into specific motor schemas (independently of other tasks such as object recognition). Animal as well as human clinical data implicate the posterior parietal and premotor cortical areas in schema instantiation. A mechanism is proposed that is able to encode the desired goal of the action and is applicable to different levels of representational organization.

### Alternative origins of motor images

Stuart C. Grant and Mark A. Schmuckler

Division of Life Sciences, Scarborough College, University of Toronto,  
Scarborough, Ontario, Canada, M1C 1A4. sgrant@dciem.dnd.ca;  
marksch@scar.utoronto.ca

**Abstract:** Jeannerod (1994) advocates studying motor images to understand the representation of action. We identify an unsettled issue that complicates the use of motor images to study the representation of action and present some evidence for a clear absence of equivalence between motor imagery and movement preparation. We then elaborate and emphasize the relevance of the mental practice literature, which was introduced in the first round of commentary. Finally, we suggest two methods that will allow motor imagery theorists to address these points.

Three aspects of images are relevant to the current discussion. First is the *content* of the images. In this discussion we are concerned with images of motor acts and everyone seems to agree on this point. The second relevant aspect of images is their *form*. This was a key point disputed in the first round of commentary, with many commentators seeking a distinction between visual and motor images. A third aspect of images that has not yet been discussed is their *origin*. They may be produced by the motor system. However, images can also be generated by other systems, such as memory and reasoning. The same information given to the subject to permit the motor system to generate an image is also sufficient to serve as a memory cue or to set up a problem space that is approached rationally. This is cause for concern because only images arising from the motor system would necessarily be informative of the representations used in the motor system. Images arising from reasoning would seem to be bound by the intelligence and creativity of the subject. Images from memory, contrary to the commentaries of Fuster (1994) and Ingvar (1994), would make matters worse, not better. Memory contains many different kinds of information, and subjects can make use of memories that are not purely motor, such as episodic ones. It is therefore important to rule out the other possible sources of images. Unfortunately, this is rather difficult to do.

Decety et al.'s (1989) results can be taken as an example. Interpreted by Jeannerod (1994) as consistent with his general

hypothesis, the results could have been produced by participants reasoning about the effects of the external weight placed on their backs. In this case, subjects might have concluded that carrying a heavy weight, which is hard to carry, over a specified distance, would simply take longer than walking that distance without the weight. Unfortunately, this process is difficult to rule out on the basis of introspective report; such logic need not occur consciously. More generally, many of the results discussed by Jeannerod (1994) could be explained in such a fashion, with participants simply thinking about what it would be like to perform the movements asked of them, and then making inferences as to the possible consequences of this action. Although imagery may be involved in this process, there is no assumption of any motor movement (simulated or otherwise) operating in this situation.

It is also possible that observers in the studies described by Jeannerod (1994) are making use of episodic memories of events during their lives to produce their best guess as to what would happen in the various experimental situations. Accordingly, an alternative to the reasoning process described above for the results of Decety et al. (1989) is that participants, when imagining themselves walking while carrying a weight on their backs, thought about some instance in their lives when they carried a heavy weight for some distance (struggling through the airport toting a heavy suitcase comes quickly to mind), with their subjective impressions of that travel time influencing their answers. Such a process would produce a pattern of inconsistencies and errors similar to the one Jeannerod (1994) assumes is indicative of mental motor performance, but again for dramatically different reasons. More generally, it is difficult to evaluate whether the effects observed in these studies are related to actual mental imagery (in Jeannerod's sense), or to one of the other processes just described.

In addition to these alternative sources of images concerning motor acts, there are experimental data that question the functional equivalence of images of motor acts and motor preparation. Rieser et al. (1986) looked at the influence on spatial orientation of the proprioceptive information associated with movement through the world. They compared the pointing accuracy of subjects who viewed a set of target locations from one position in a room with accuracy pointing to these same targets following three transformations. In one condition, observers were led blindfolded

to a new position in the room. In a second condition, observers imagined themselves moving to this new position in the room. Finally, in a third condition, observers imagined themselves walking to this new position while simultaneously walking in a circle. It is interesting to note that Rieser et al. (1986) found that pointing was only accurate in the condition in which observers actually walked to the new point of observation, with pointing accuracy in the two imagined conditions greatly diminished. This study accordingly suggests that the motor imagery of moving to a new location in space is not equivalent to the actual movement in terms of spatial orientation.

Finally, in their commentary, Chua and Weeks (1994) raise an important point that deserves elaboration. They mention that the beneficial effects of mental practice may be obtained because imagery benefits the cognitive components of the task rather than the motor components. Recent meta-analyses (Driskell et al. 1993; Feltz & Landers 1983) support this idea. Both sets of authors note that motor tasks are composed of motor as well as cognitive components, with most tasks scalable according to the relative importance of these factors. Given this distinction, it is important that any effect on motor behavior resulting from motor imagery have its primary impact on the motor component; if motor imagery affects the cognitive component of a task, while leaving the motor aspect unchanged, this weakens the idea of a functional equivalence between motor imagery and preparation. One way of thinking about this effect is that tasks with a primary component of motor performance should be affected more by motor imagery than tasks that are primarily cognitive. Unfortunately, although both sets of metaanalyses found that mental practice facilitated motor performance, this influence was strongest for, and sometimes restricted to, tasks in which the primary component was cognitive, as opposed to motor. By way of explanation, it is assumed that the mental practice of a task gives one the chance to rehearse the sequences of movements as symbolic components, affording a performer the chance to think about what types of actions might be performed, the consequences of such actions, and so on. Unfortunately for Jeannerod's hypothesis, this finding is antithetical to the idea that motor imagery is a simulation of motor movements thereby influencing the motor component of a given task and raises the possibility that if the task were rid entirely of the cognitive component, the effect of mental practice might disappear altogether.

When Chua and Weeks originally raised this point, Jeannerod responded by questioning the validity of the distinction between motor and cognitive aspects of a task, and suggested that "it could well be that what has been attributed to 'cognitive' factors is precisely what pertains either to the early stages of motor preparation or to imagery" (p. 237). This denial of different, cognitive representations seems to run counter to the target article, which contrasts pragmatic representations with semantic representations.

A way of examining the possibility that a particular image of motor activity may originate from memory or reasoning rather than the motor system is related to a point made in the original commentary by Dufour et al. (1994). One could ask observers to perform tasks that seem reasonable on the surface, but are in truth impossible due to internal anatomical constraints or external constraints imposed on one's body. Obviously, episodic memories of previously performed actions are of no use, given that this is a novel movement. Moreover, if observers are actually simulating the activity involved in these movements with the motor system (as suggested by Jeannerod), then the resulting images should reveal the impossibility of the act. In contrast, if observers are simply reasoning about how the task might be done, then the impossibility of this task will not necessarily be readily apparent. As such, reports of successful performance would indicate some reasoning process other than mental simulation in the motor system.

Another way to substantiate the functional equivalence of motor imagery and motor performance would be to create situations in which motor imagery mimics the effects of motor performance,

thereby producing well-known motor phenomena. For example, one common finding in the motor domain is that learning a new skill follows a power function; this finding is so ubiquitous that some consider it to be a general law of learning (Newell & Rosenbloom 1981). If, in fact, motor imagery is functionally equivalent to motor performance, then motor performance of a novel task after varying amounts of mental practice should produce similar power-law learning curves; such a study has not, to our knowledge, been conducted. It should be noted, however, that such a successful demonstration would be a necessary, but not sufficient, step in the validation of motor imagery. Success would show that *something* in mental practice was producing the power law, although again, the origin of that something would be debatable. Failure would weigh against the validity proposition of functional equivalence.

Despite these concerns, however, Jeannerod's (1994) explorations of motor imagery represent an intriguing approach to theories of motor performance, bringing together findings from perceptual, motor behavior, and neuropsychological domains. Clearly innovative, this approach raises interesting conceptual and empirical questions concerning the nature of motor representations. Further investigation of these issues is bound to be of interest to investigators of motor behavior and mental representation.

## Response intention and imagery processes: Locus, interaction, and contribution to motor learning

Robert M. Kohl<sup>a</sup> and Sebastiano A. Fisicaro<sup>b</sup>

<sup>a</sup>Division of Health, Physical Education, and Recreation and <sup>b</sup>Department of Psychology, Wayne State University, Detroit, MI 48202.

**Abstract:** By way of commentary on Jeannerod (1994), we propose that (1) intention, response imagery, and actual response processes carry equal weight in inferring from one process to another, (2) memory networks control intention, which interacts with imagery-based processing to control response imagery, and (3) response imagery will demonstrate learning effects better when imagery reconstruction and elaboration are emphasized and neutral retention tests are utilized.

**Locus.** In his target article, Jeannerod (1994) emphasized the common locus of processes responsible for controlling intention to respond and response imagery. Focusing on shared mechanisms between intentional and imagery processes may promote the unlikely hypothesis that these processes do not involve mechanisms unique to each. The relationship between intention to respond and response control, on the one hand, and the relationship between intention to image a response and controlling response imagery, on the other, may be similar. For example, as in demonstrations with response control (Henry & Rogers 1960), Ito (1990) obtained greater reaction times prior to the initiation of an image of a complex response than prior to the initiation of an image of a simple response, suggesting that processes responsible for controlling the intention to image a response and processes responsible for controlling response imagery have some independence.<sup>1</sup> Hence, as in response control, although intention and imagery control share some common mechanisms, there may be mechanisms unique to each.

Jeannerod also focused on shared mechanisms between processes responsible for response control and imagery control of a response, even to the extent of shared peripheral mechanisms. However, Kohl et al. (1993) demonstrated perfect transfer from imagery to actual responses on the same task in different muscle groups. Peripheral activity accompanying imagery cannot account for these transfer effects.

Jeannerod also reported that perception theorists have proposed that actual and imaged events activate common mechanisms high in the central nervous system (CNS) (e.g., Kosslyn

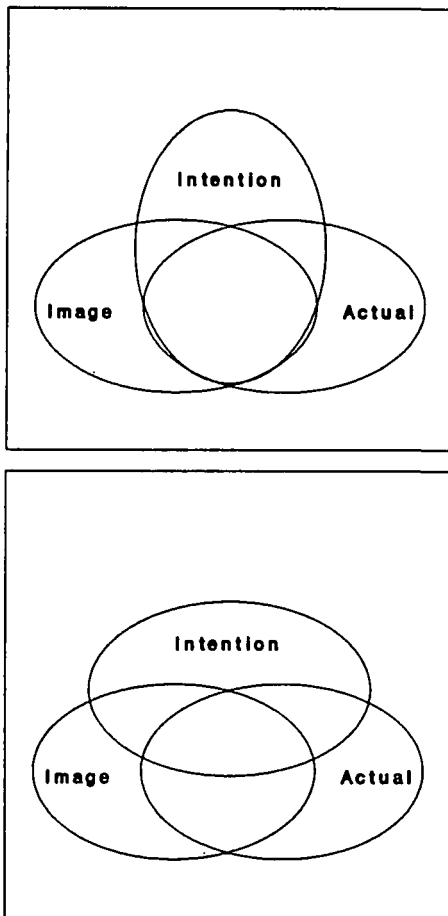


Figure 1 (Kohl & Fiscaro). Hypothesized relationships among intention, imagery, and response control.

1988). However, these theorists also specify imagery mechanisms that control image generation and transformation that are not activated by actual events.

Figure 1 illustrates two ways to conceptualize the relations among intention, imagery control, and response control (overlap represents shared mechanisms). These relationships conflict with Jeannerod's main theme that imagery could be uniquely used to make inferences about intention. The relations among intention, imagery, and response control processes in Figure 1 illustrate that all three processes carry equal weight in inferring from one process to another.

**Interaction.** Perhaps because Jeannerod emphasized the com-

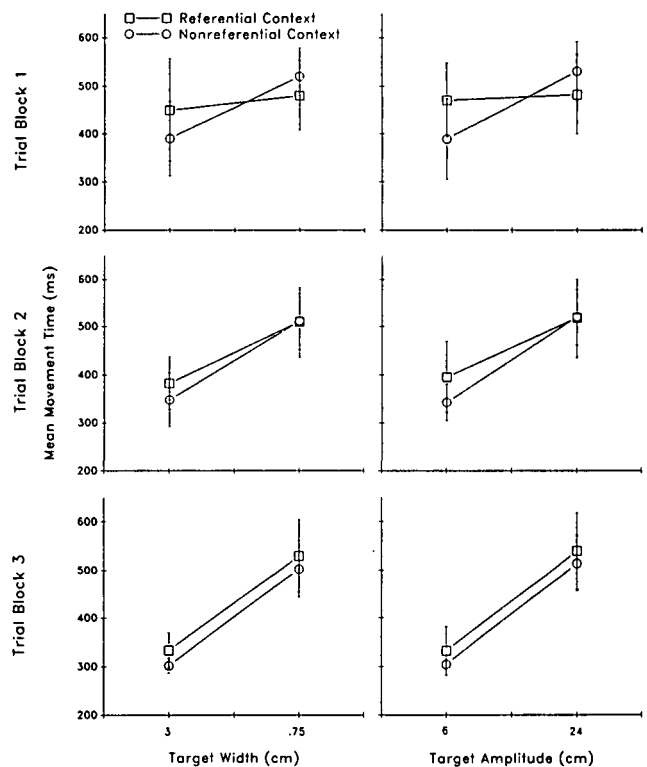


Figure 3 (Kohl & Fiscaro). Reported MT data (in ms) as a function of context, trial block, and bias [target width (left panels) and target amplitude (right panels)] from Kohl and Fiscaro (1995).

monality of intentional and imagery processes, his discussion failed to mention the manner in which these separate processes might interact to control response imagery. Kohl and Fiscaro (1995) demonstrated one example of this interaction. Reported movement times (MT) were obtained from subjects' imagery of Fitts tapping tasks. Subjects reported imaged target hits from one Fitts task while holding target displays of two Fitts tasks in imagery. The displays were imaged in either referential (different tasks) or nonreferential (identical tasks) context. In a second session, subjects repeated the procedure, but reported from the other task.

Index of difficulty (ID) was held constant for the tasks (see Fig. 2), and preperformance biases were created by indicating to subjects that MT only increased with decreases in target width or only increased with increases in amplitude. Figure 3 illustrates the

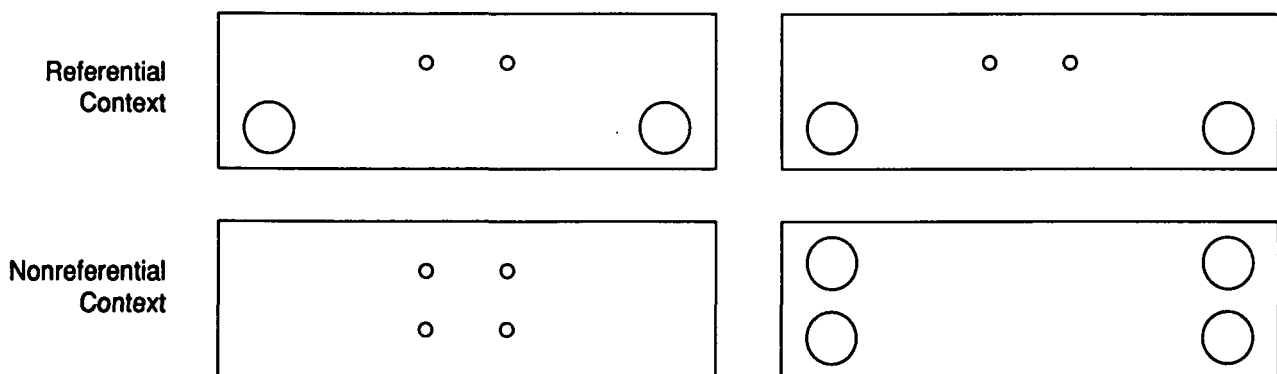


Figure 2 (Kohl & Fiscaro). Referential context (top panels) and nonreferential context (bottom panels) target displays for two counterbalanced experimental sessions (left and right panels) from Kohl and Fiscaro (1995).

results (target bias, left; amplitude bias, right). Under both bias conditions, MT reflected (1) Fitts's law during early trials for referential imagery and (2) the biases for nonreferential imagery and at later trials for referential imagery. The biases may not have affected reports during early trials in the referential condition because imagery was constrained by the invariant relativity of stimuli. Here, since identical IDs create similar processing demands, early trial reports may have reflected imagery-based feedback or feedforward processing. However, since MT did not match subjects' stored intention (biases), the interaction between imagery and perceptual-motor mechanisms may have been transformed over trials to create a match between what subjects were imaging and their intention. In the nonreferential condition, subjects were not constrained by the relativity of stimuli and could more easily transform imagery to match intention. Hence, response imagery control may involve memory networks that control intention, which in turn influences imagery-based information processing.

**Motor learning.** The motor learning experiments reported by Jeannerod did not distinguish between imagery aftereffects and retention effects. Typically, researchers have reported that actual practice was better than imagery practice, and that both were better than a baseline control on retention tests. However, retention tests typically used in response imagery experiments more closely resemble the actual practice conditions. When more neutral retention tests are used, retention differences between actual and imagery practice are reduced (Kohl et al. 1992).

Finally, based on constructs such as memory reconstruction and elaboration, researchers have emphasized nonlinear motor learning (Shea & Kohl 1991). Because imagery has generation and transformation requirements, it may be uniquely suited to reconstruct and elaborate motor responses to facilitate motor learning. Hence, when researchers begin to use neutral retention tests and emphasize such notions as response imagery reconstruction and elaboration, the benefits to motor learning from imagery may exceed current expectations.

#### NOTE

1. Jeannerod referred to reaction time in imagery experiments as the time difference between stimulus onset and response initiation. However, this measure better reflects imagery response time, which is defined as imagery reaction time (time difference between stimulus onset and response imagery initiation) plus imagery movement time (the time difference between response imagery initiation and completion).

## In search of nonvisual motor images

Yves Rossetti<sup>a</sup> and Gilles Rode<sup>b</sup>

<sup>a</sup>*Vision et Motricité, I.N.S.E.R.M. U. 94, F-69500 Bron, France.*  
*rossetti@lyon151.inserm.fr;* <sup>b</sup>*Pav. Delore, Hopital Henry Gabrielle,*  
*F-69565 Saint Genis Laval Cedex, France.*

**Abstract:** Jeannerod's target article and a number of commentators stressed the necessity of distinguishing between motor representation and perceptual images. A patient with a lesion of the central somatosensory pathways allowed us to test for this distinction. The outcome suggests that motor images may not be visual and that the "pragmatic" framework proposed by Jeannerod for vision can apply to other sensory modalities.

In his target article, Jeannerod (1994) proposed that viewing an object can give rise to two distinct types of representation. He distinguishes between the direct motor use of visual affordances (pragmatic representation) and a more complex identification of the object (semantic representation): "actions are driven by an internally represented goal rather than directly by the external world" (p. 187). Several questions arose in the commentaries

about how to distinguish between motor and visual images (e.g., Elliott & Maraj 1994; Klatzky 1994; Mitchell 1994; Prinz 1994; Rizzolatti 1994; Strong 1994; Van der Heijden & Bridgeman 1994). It has been proposed that there may be different reference systems for motor and visual images (Prinz 1994; Strong 1994). In his Response, Jeannerod (1994) noted that "separating motor and perceptual images is a recurrent concern" (R.4, p. 232), but that "it is difficult to think of an experiment . . . where a visual 'pragmatic' image could be generated without being associated with a visual 'iconic' image" (R.4, p. 233). An example of pure pragmatic processing is presented later in the Response (R.7): Patients with a lesion in V1 can preshape their hand according to visual object shape or orientation without being aware of these objects (Perenin & Rossetti 1993; 1996). It remains difficult, however, to infer from this result that the pragmatic motor representation is nonvisual. Were such an observation replicated with other sensory modalities, this would be a positive demonstration that motor representation may not be visual. Indeed such a demonstration may be available in the tactile domain.

Dissociation between conscious perception ("identification") and motor response ("localization") toward a tactile stimulus has been reported in a patient with a cortical parietal lesion (Paillard et al. 1983). We recently had the opportunity to study a patient (J. A.) with a similar symptomatology (Rossetti et al. 1995). This patient presented with a subcortical haemorrhage in the left parietal lobe with lesion of the posterior thalamus; J. A. was fully anesthetized for all somesthetic modalities on the right side of the body. Parietal and frontal somesthetic evoked potentials were absent. J. A. was unable to report whether any tactile, thermal, or noxious stimulus was applied to his arm. By contrast, when asked to point toward the locus of the stimulus with the left index, he performed with an accuracy well above chance. In addition, the use of a dichotomous forced-choice paradigm (e.g., touching hand vs. arm) did not reveal any significant stimulus detection, demonstrating that a dichotomy between conscious and unconscious processing was not appropriate to describe the case. Like Paillard et al.'s patient, he wondered himself about this ability. At this point, we described our patient as being able to localize but unable to identify the stimuli, that is, as a tactile equivalent of blindsight.

The next step in the experiment was to investigate whether there was a visual representation underlying J. A.'s ability. He was asked to point to the locus of the stimulus on a picture of his arm (scale 1), placed adjacent to the unseen stimulated arm. In this condition, he again performed at chance level, demonstrating that only the movements performed toward the actual stimulus could be performed accurately. This result suggests that stimulus location was represented in motor coordinates and could not be translated into visual coordinates. It should be emphasized that such a dissociation supports a "where versus how" dichotomy, parallel to the classical "what versus how" distinction.

A major implication of the present results concerns the non-visual nature of motor representation argued for by Jeannerod. If the pragmatic use of somesthetic information can be confirmed in other case studies, this would positively demonstrate that motor representations used by the pragmatic system are not visual, and would answer some of the questions raised in the commentaries.

Another interesting aspect of our studies with J. A. concerns the time constant of the representation used to produce the significant motor responses. We investigated J. A.'s pointing to his anesthetized arm when a delay was introduced between the end of stimulus application and the "go" signal. Significantly above-chance performance was obtained for delays up to 1 second, but random pointings were observed for longer delays (2 and 4 sec). Along the same lines, pointing movements made by healthy subjects toward immediate proprioceptive targets and memorized targets were shown to exhibit different spatial distributions, which suggests that they depend on two distinct representations (Rossetti & Régnier 1995). Other recent examples of this kind can be found in the literature (review: Rossetti 1997). These results

would be compatible with Jeannerod's idea that "motor representations are not objects of contemplation" (p. 187).

Implicit processing of visual and somesthetic information shows that lesions of the primary sensory areas prevent conscious identification of the stimulus but allow the production of a movement aimed at it. This residual processing not only depends upon the motor rather than the verbal mode of response, but it appears to be specific to the direct and immediate motor use of the ongoing stimulus. According to this analysis, there is considerable similarity between the implicit processing of visual and somesthetic information. The pragmatic function of behavior outlined by Jeannerod for visually defined goals may then also apply to sensory modalities such as touch and proprioception, thereby broadening its scope of applicability.

#### ACKNOWLEDGMENT

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## Author's Response

### Motor representations: One or many?

M. Jeannerod

Vision et Motricité, INSERM U94, 69500 Bron, France.  
jeannerod@lyon151.inserm.fr

**Abstract:** Two issues have been raised. The first concerns whether consciousness is attached to a given type of action. It is argued that purposive actions are represented before being executed and that motor representations can either remain implicit or become explicit according to the task. The second issue concerns whether or not mental imagery of action is independent from action. Recent evidence showing the commonality of neural mechanisms for motor imagery and action, respectively, goes against the idea of independent processes.

**R1. Rossetti & Rode** raise an important question, but fail to answer it. They start with the correct idea that there are two (or perhaps more) ways of triggering an action. One way, the action can be driven by an external stimulus; in the other, it can be triggered endogenously, by an "intention." This does not imply, however, that stimulus-driven actions rely on a "direct" transformation of sensory input into motor commands. In the target article (Jeannerod 1994a), my point was that these "automatic" actions are indeed centrally represented (the model of an activation of a set of "schemas" was proposed, but there are other possibilities as well). They rely on a complex visuomotor transformation that specifies the goal in terms of a program for the action. The need for an intermediate structure between sensory input and motor execution is illustrated by one of the essential features of this type of action, motor equivalence. In monkey experiments, premotor neurons, for example, may encode an action without specifying which hand has to be used (e.g., Rizzolatti et al. 1988): this property requires a level of organization which cannot be present in a purely responding system. In the target article, I referred to this point in stating that object-oriented actions are driven by "implicit knowledge of object attributes" (p. 199) and that they are coded in

terms of the "desired" state of the effector system. The terminology of "direct" action is thus misleading, because it implies that motor representations are epiphenomenal and are devoid of causal properties.

What **Rossetti & Rode** do not seem to appreciate is the fact that motor representations can be implicit, nonconscious. It is not because a movement is automatic and executed without a clear awareness of the goal that it is generated "directly," without being represented at some level of the system. The issue of consciousness is thus orthogonal to that of the generation of actions. Consciousness does not pertain to a particular pathway: its presence or absence labels a situation or a task, irrespective of which pathway is used. As stated by Frith (1995), "consciousness is for other people," and it is required when one has to report the explicit content of an experience. This requirement does not exist when actions are automatized as parts of a continuous behavioral stream. Neuropsychological cases (e.g., blindsight or nonconscious detection of tactile stimuli) showing that patients can generate appropriate responses to objects or stimuli of which they are not aware, therefore do not contradict this point.

A possible way to disentangle the types of representations used for different types of action would be to measure their "life time." **Rossetti & Rode** were apparently able to get an estimate of this duration by asking their patient to wait before giving the motor response: accuracy degraded after one second or so. Hence the idea that a delayed response selects a "perceptual" rather than a "motor" mechanism. In fact, the introduction of a delay before the response is given does not always discriminate between types of responses. Gentilucci and Negrotti (1994) showed that pointing by hand to the *remembered* location of a target (a delayed visuomotor response), or reproducing its location by moving a laser beam (a perceptual response) yielded different types of errors despite the fact that the two types of response were delayed: target distance was underestimated when the subjects pointed, but it was overestimated when they matched its location with the beam.

**R2. Kohl & Físicaro** consider the hypothesis (put forward in the target article) that the mechanisms for controlling intention to respond and response imagery share the same structural basis is unlikely. They believe instead that the process for intending to respond and controlling the response is distinct from that for intending to image and controlling the image response. In other words, intention to move and intention to image to move would be separate processes, hence response control and imagery control of a response should be different.

It could also be argued, according to **Kohl & Físicaro's** Figure 1, that the same intention is common to both imagery control and response control. In this case, the prediction would be that image and response share the same mechanisms at the intentional level, but diverge when they come to "execution." Examining the content of a motor image would thus give the same information about the intention than looking at the motor response itself, because both would originate from the same source. This hypothesis seems to be supported by experimental data. Consider for example the neurons described by the Rizzolatti group in monkey premotor cortex. A given neuron will fire when the monkey grasps a piece of food (a rapid, automatic, stimulus-driven action) and when the monkey watches another

monkey doing the same action (a motor image) (see Rizzolatti et al. 1996). In man, we also showed that motor imagery and motor execution activate similar cortical networks (Decety et al. 1994; see also Stephan et al. 1995). The main difference between intending/executing and intending/imagery was that the motor cortex was not found to be activated in the second case.

The present view is even more radical: the primary motor pathway is now found to be activated during motor imagery as well, as shown by recent experiments using functional resonance magnetic imaging (Leonardo et al. 1995; Roth et al. 1996). This forces one to reevaluate the theory, and to consider motor imagery as an action which is carried down to the level of execution, with an additional, parallel command for blocking the output.

This is the reason imagining an action can be so efficient in learning and rehearsing motor skills (Vogt 1995). What **Kohl & Fiscaro** report on the interaction between "intending" and "imaging" in a Fitts's law task is not contradictory with this view. Their idea of having the subjects doing the two things at the same time is a good one, in principle. It must be quite difficult, however, to control what subjects actually do during such tasks, an uncertainty which is reflected by the double mechanism postulated by these commentators. They conjecture that subjects would first use an imagery-based strategy and then would progressively move over trials to a strategy in conformity with their (intentional) bias. More simply, it could have been the case that the image was progressively transformed under the influence of the physiological constraints met by mentally "executing" movements which violate Fitts's law.

A new experiment (Decety & Jeannerod 1996) stresses the validity of Fitts's law in purely mental processes. Normal subjects were instructed to walk mentally through gates of different widths positioned at different distances. The gates were presented to the subject with a 3-D visual display (a virtual reality helmet) which involved no calibration with external cues and no possibility for the subject to refer to a known environment. Subjects had to indicate the time they started walking and the time they "passed through" the gate. Mental walking time was found to increase with increasing apparent gate distance and decreasing apparent gate width. Thus, it took longer for the subjects to walk mentally through a narrow gate than to walk through a larger gate placed at the same distance. (For another demonstration of Fitts's law in mentally simulated actions, see Sirigu et al. 1995.) Note that in the Decety and Jeannerod experiment, the subjects never experienced actually walking through the gates; nor did they ever see physical gates. Their mental time estimates could not be derived from prior experience. These results strongly indicate that intending, imaging, and executing are based on the same representational grounds (Jeannerod 1996).

**R3. Grant & Schmuckler** address the same point of the postulated equivalence between motor imagery and movement. One of their arguments is that motor images can arise from different origins, including nonmotor ones, and that "only images arising from the motor system would necessarily be informative of the representations used in the motor system." Images arising from other sources, like reasoning or memory, would not. Because Grant & Schmuckler suspect that many of the motor images used in behavioral experiments (including those by Decety et al. 1989, for

example) arise from simply thinking about "what it would be like to perform the movements," they cannot be considered as expressing the activity of the motor system.

The problem I see here is that one cannot oppose a cognitive stage and a motor stage in motor representations. The logic of stages which implies that some aspects of a representation are based on psychological (symbolic) processes whereas others are based on physiological processes, is a fallacious one. The two "stages" are the two sides of the same phenomenon, with the cognitive aspect being the content and the motor aspect being the vehicle. One cannot conceive images arising directly from the motor system: mental images are formed from a cognitive store and are channeled through whichever system (e.g., motor, visual) is required by the task or the situation.

The study of biological correlates of these images may help us understand the continuum between the two sides. Indeed, activation of brain areas related to motor control is found not only during mental simulation of simple movements like grasping objects or moving a joystick (e.g., Decety et al. 1994), but also during more cognitive motor images such as generating action words (Martin et al. 1995). The same is true for less explicit forms of motor representations like watching somebody's action or inspecting tools (Martin et al. 1996). Accordingly, one should expect that the beneficial effects of mental practice on subsequent motor performance will be obtained by rehearsing the more explicit aspect (the content) or the less explicit aspect (the vehicle) of the motor image because both will result in activating the motor system.

The possibility raised by **Grant & Schmuckler** (and also by Dufour et al. 1994 in the initial commentary) that subjects could be able to image impossible movements, would obviously run against the present framework of equivalence of different forms of motor representations. This possibility, however, seems quite unlikely: instead, several experiments suggest that mentally simulated movements respect biomechanical limitations. Parsons (1994), for example, showed that subjects mentally rotate their hands (in order to match a target hand position) at a rate that corresponds to biologically plausible trajectories, not to trajectories that would violate biomechanics.

These data indicating that motor images (and motor representations in general) are compatible with the rules of functioning of the motor system should prompt new experiments. One of these experiments, as suggested by **Grant & Schmuckler**, should investigate whether motor learning based on motor images, and perhaps also on observation of action, follows the same general power function observed in other forms of learning. A positive result would constitute another firm basis for the theory.

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Letters "a" and "r" appearing before the authors' initials refer to target article and response, respectively.

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