Is Mental Rotation a Motor Act?

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Abstract

We find evidence for a tight coupling between motor action and transformation of visual mental images: in a dual-task experiment involving both *mental* and *manual* rotation, it is found that mental rotation of abstract visual images is faster and less error-prone when accompanied by manual rotation in the same direction, slower and more error-prone when motor rotation is in the opposite direction. Variations in motor speed, on both large and small scales, are accompanied by corresponding variations, in the same direction, in mental rotation speed. We briefly speculate on the mechanisms that could give rise to this interaction.

Introduction

The main finding of the cognitive neuroscience of visual mental imagery has been the identification of perceptual mechanisms in imagery tasks, confirming the intuition that we indeed 'see' our visual mental images. This has been amply demonstrated in studies showing the interaction of visual mental imagery with processes characteristic of visual perception, such as object identification and illusions; in brain activation studies (the activation of occipital cortex in visual mental imagery tasks); and in observations of patients with lesions (see Kosslyn (1994) for a review).

Along with this very important result has come the widespread belief that visual imagery is a *purely* visual function. If we see images of things in our heads, it is because we have seen those things, or their parts, before with our eyes. If we can transform our visual images, it is because we (or our distant ancestors) have watched objects translate, zoom, and rotate. Visual imagery is subserved by the mechanisms responsible for visual perception, object recognition, and the perception of real or apparent motion (Shepard, 1984). According to Shepard's influential view, both the transformation of visual mental images, and mechanisms responsible for apparent visual motion are "*...internalizations* of current or previously prevailing external circumstances" (Shepard, 1984, p. 431), circumstances experienced through (predominantly visual) perception. This empiricist theory of mental imagery is not new, and can be traced back at least to Hume, who was already concerned by one of the main mysteries that currently surround mental imagery, namely why mental images follow continuous trajectories when transformed; his solution is as follows:

> 'Tis... evident, that as the senses, in changing their objects, are necessitated to change them regularly, and take them as they lie *contiguous* to each other, the imagination must by long custom acquire the same method of thinking, and run along the parts of space and time in conceiving its objects. (Hume, 1739/1985, p. 58)

Meanwhile, information has been accumulating on mental imagery in another modality, so-called 'motor imagery'— the first-person imagination of voluntary motor actions (see Jeannerod (1997) for a review). Here, too, it has been found that motor imagery shares mechanisms with the motor system, from premotor cortex, the supplementary motor area and motor cortex (activated during motor imagery tasks), by way of autonomic reactions (similar in motor imagery and motor tasks), all the way down to the muscles (EMG activity during motor imagery)—for a review, see Jeannerod (1997). It has been assumed that motor imagery is distinct from visual mental imagery, as the former is experienced from a first-person perspective, the latter from a third-person point of view.

The peaceful co-existence of, on one hand, visual perception and visual mental imagery, and of motor action and motor imagery on the other, is troubled by a number of borderline cases. What are we to make of, for instance, Parsons's (1994) finding that the mental rotation of images of *hands* (in the service of a typical visual task, object identification) is modulated by the actual orientation of the subject's hands during the task? Or of the result of Wohlschläger & Wohlschläger (1996) that mental rotation is faster when accompanied by motor rotation in the same direction, slower when the motor rotation is in the opposite direction? Or of the finding of Shiffrar & Freyd (1990) that apparent motion, a process that has been closely associated with visual mental imagery, is informed by the kinematics of body parts? Or, indeed, of the existence of a literature (albeit controversial) that suggests that motor constraints are incorporated into the visual system at fairly low levels of *perception* (e.g., Viviani & Stucchi, 1992)? Other, indirect, evidence exists for the interaction between movement (real or imagined) and visual mental imagery, involving, for example, the interaction between real and imagined movement and spatial memory (Johnson, 1982;

Quinn & Ralston, 1986; Finke, 1979); much of this material is ably reviewed by Kosslyn (1994).

In light of this evidence between motor action and visual mental imagery, we put forward the *imagery/motor hypothesis*: the motor system is involved in the voluntary transformations of visual mental images. After all, most *non-mental* image transformations in the environment are directly produced by the subject's manipulation of medium-size objects. Could it be that the motor system guides image transformation, even when the image is not seen, but imagined?

There are at least two ways in which the imagery/motor hypothesis may be true. First, motor information may be statically, structurally incorporated into the visual system, so that, for instance, it may be difficult to (visually) imagine trajectories that violate constraints on body movement (such as the $R^{1/3}$ law, that Viviani & Stucchi (1992) suggest may be structurally incorporated into visual perception). Second, the motor system may play a dynamic, 'on-line' role in guiding visual imagery transformations; this version would account for Parsons's (1994) data.

The following experiment was carried out to test the hypothesis of *dynamic* interaction between visual imagery transformation and the motor system. It combines the classic mental rotation task of Cooper & Shepard (1974) with a motor task, in which the subject performs a simultaneous *manual* rotation. (The manual rotation was active, but its speed was nevertheless controlled—see description below for how this was managed). The null hypothesis predicts a simple dual-task effect, undifferentiated according to the details of the imagery or motor tasks. The imagery/motor hypothesis, on the other hand, predicts that the motor system is involved in transformations of mental images, such as mental rotation. If the motor system is occupied with a *manual* rotation task, involving rotation with a given speed and direction, the concurrent *mental* rotation task should be impeded to the extent that *its* speed and direction clash with those of the motor task.

Experiment

What follows is a summary of the experimental procedure. For full details, see Wexler, Kosslyn & Berthoz (1997).

Method

The experimental apparatus consisted of a computer screen (at subject's eye level, seen through a visual tunnel) for the presentation of visual stimuli; a joystick that was free to turn in a small circle in a plane parallel to the computer screen (located below the screen, at the level of the subject's abdomen); and two foot-switches, on which the subject's feet rested.

Each trial consisted of two tasks, the *imagery* task and the *motor* task.

Imagery Task. Very similar to the Shepard & Cooper (1973) two-dimensional mental rotation task. It consisted of three phases: (1) on the computer screen, the subject saw one of the figures (illustrated in Figure 1) in its canonical orientation, centered at the top of the screen (5 sec), along with an arrow that pointed from the center of the screen to the figure (5 sec); (2) the figure and arrow disappear, and a new arrow reappears, pointing from the center of the screen to a different location, differing by an angle θ from the previous upright arrow (1.5 sec); (3) the figure reappears (either the original, or its mirror image) translated to the location indicated by the arrow as well as rotated by angle θ (like numerals on some clock faces). The subject's task was to determine, as quickly as possible, whether this last figure was a the same as the first (except for a rotation), or whether it was also mirror-reflected; the response was given by pressing one of two pedals. The time between the onset of the third stimulus and the pressing of a pedal will be referred to as the response time (RT). The subject was encouraged to begin the process of mental rotation at the onset of phase 2.

Figure 1: Stimuli in imagery task, in their canonical orientations

Motor task. The simultaneous motor task consisted in rotating the joystick handle in a previously specified direction (i.e., clockwise or counterclockwise) and at a specified angular speed, ω (either 45°/sec or 90°/sec). In preliminary training, the subject learned to rotate the joystick at the required speed within a given tolerance (45%). The subject could see neither his hand nor the joystick, due to the presence of the visual tunnel.

Before the beginning of each block of 16 trials, the subject was given (verbally) the direction in which he was to turn the joystick, and was required to produce manual rotations until the angular speed for two successive rotations was within the tolerance range around the target angular speed ω. The motor task was synchronized with the imagery task: the joystick remained fixed at the 12 o'clock position (0°) during phase 1 of the imagery task; the subject began turning the joystick at the onset of phase 2 of the imagery task, and was to keep turning at the constant speed ω until a response was given in the imagery task.

Experimental Design. The experiment was a 2 (ω=45, 90°/sec) × 2 (counter-, clockwise manual rotation) × 8 (values of angle θ in imagery task, evenly spaced by 45°) × 4 (initial stimuli) × 2 (response conditions: mirror-reflected or not) design. The subjects came for two sessions, each of which consisted of 8 blocks of 16 trials. Trials with errors (either giving the wrong answer in the imagery task, or failing to turn within the tolerance range of the target motor speed, ω) were repeated at the end of each session. In addition, immediately following the second session, subjects repeated the task, but without the motor rotation (4 blocks of 16 trials each), the 'no-motor' condition.

The subjects were divided into two groups; one group had motor speed ω=45°/sec in the first session and ω=90°/sec in the second session (the 45-90 group), and vice versa for the 90-45 group. Within each session, the direction of motor rotation alternated from block to block. The remaining order of trials was random.

Data Analysis

Because of its complexity, only the main results of the analysis will be given here; for details, the reader is referred to Wexler, Kosslyn & Berthoz (1997).

Twelve paid volunteers participated as subjects (6 men and 6 women). Subjects had no prior laboratory experience with mental imagery. They were divided randomly into the 45-90 and 90-45 groups (3 men and 3 women in each).

Imagery task. Data was collapsed across the 4 × 2 stimulus and reflection conditions, and across subjects. Figure 2 shows an example of the RT curves for the different motor conditions, in the first session for the 45-90 group.

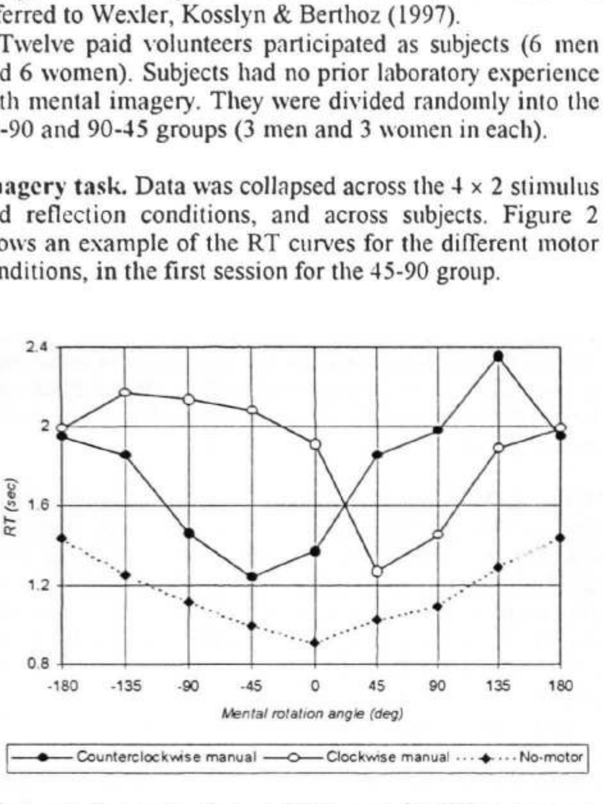

Figure 2: Example of mental RT curve for different motor conditions: CW manual rotation, CCW manual rotation, and no manual rotation. Clockwise angles are positive.

As can be seen from Figure 2, concurrent manual rotation had a strong *selective* effect on the mental rotation. When subjects were performing clockwise *manual* rotation, for example, *mental* rotation was faster clockwise than counterclockwise, and vice versa for counterclockwise manual rotation. The effect was strong enough to shift the minimum of the RT curve. In ordinary mental rotation experiments, the minimal RT is at $\theta=0°$, as it is in our no-motor condition (the dotted curve); it is easiest to compare two successive stimuli when they are at the same orientation. This is not so when the mental rotation is accompanied by motor rotation. When subjects perform a motor rotation, they find it easiest to compare the two stimuli when the second stimulus is rotated by 45° with respect to the first, in the direction of the motor rotation!

Similar results were obtained for the 90-45 group in the first session (except that the RT minima were not shifted from 0°). In the second session, however, the effect all but disappears. In order to study this imagery/motor interaction effect quantitatively, we performed an ANOVA, categorizing trials as *compatible* if the mental rotation is in the same direction as the manual rotation, and *incompatible* otherwise. On session 1 data alone, the ANOVA yields a significant effect of compatibility ($F(1,10)=9.49$, $p=.01$), but not on session 2 ($F(1,10)=.69$, n.s.).

In the analysis of errors, a similar effect of imagery/motor compatibility was obtained. In the first session, errors are higher in the incompatible case (36% of trials) than in the compatible case (28%), giving $F(1,10)=4.43$, $p=.06$. By the second session, the effect disappears (15% and 16%, respectively, $F(1,10)=.02$).

Is there any relation between the speed of mental rotation and the motor speed? The imagery/motor hypothesis predicts that, all else being equal, higher motor speed ω would speed up mental rotation, and lower ω would slow it down. This can be checked by comparing the average mental rotation speeds of the two groups of subjects (the 45-90 and the 90-45 groups) in the two sessions. This effect must be distinguished from two uninteresting effects, a possible inter-group difference in mental rotation speed (caused by individual differences among the subjects who happen to be in each group), and an overall speeding up of mental rotation with practice. Define the mental rotation speed as $|\theta|/RT$. Averaging by group and session, we obtain the results in Figure 3.

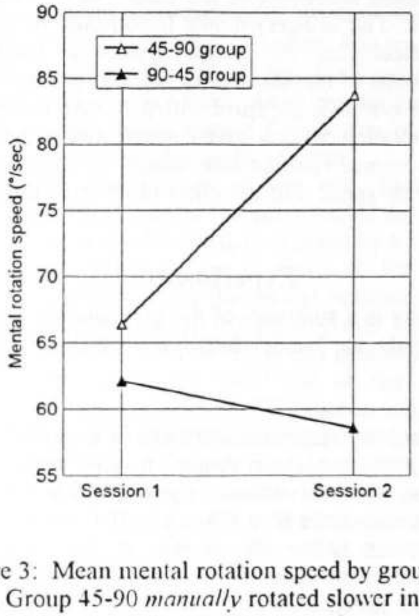

Figure 3: Mean mental rotation speed by group and session. Group 45-90 *manually* rotated slower in the first session, faster in the second; vice versa for group 90-45.

Both of the uninteresting effects mentioned above are present in the data: group 90-45 is somewhat slower at mental rotation than group 45-90 (not surprising given the size of the groups and the large variations in the population), and there is an overall trend for higher speed in the session 2. Superimposed on these, however, is a very large and interesting inter-group difference: group 45-90 (which manually rotated faster in session 2) becomes much faster at mental rotation in session 2, whereas group 90-45 (which manually rotated slower in session 2) actually has somewhat slower mental rotation in session 2. This effect is highly significant statistically, $F(1,10)=21.49$, $p<.001$ for the group × session interaction. This is strong support for the motor-imagery hypothesis; all else being equal, mental rotation is faster in the presence of fast motor rotation, and slower in the presence of slow motor rotation. We will see more evidence for the relation between mental and motor speeds below.

Motor and imagery tasks. Although we have already seen from the analysis of RTs and errors that there is very specific interference between the motor and mental rotation tasks, to get to the heart of the relationship between mental and motor rotations we must examine the subjects' motor trajectories in more detail.

We first analyzed the relationship between the angle θ – the angle between the two stimuli in the imagery task – and what we will call the *motor angle*, θ_m, the angle through which the subject had rotated the joystick handle at time of response to the imagery task. If mental rotation follows the motor rotation, there should be a positive correlation between the absolute values of the angles $|\theta|$ and $|\theta_m|$. But this is not a very good test, because even if the two rotations were entirely unrelated we still would expect a positive correlation, given that mental rotation takes more time for larger $|\theta|$ and so does motor rotation for $|\theta_m|$. If the two rotations in fact proceed together, the correlation between the angles should be much weaker when the rotations are incompatible (i.e., in opposite directions) than when they are compatible: having one's mental image at orientation θ_m as a result of the motor rotation would not do the subject much good if the test stimulus is at the opposite orientation, $-\theta_m$.

The correlation analysis was carried out individually for each subject. All non-error trials with $\theta \neq 0$, 180° (in order to allow analysis of the compatibility factor) and $|\theta_m| < 360°$ were classified by subject, session and compatibility; in each set the coefficient of correlation between $|\theta|$ and $|\theta_m|$, r, was calculated. The mean correlations by compatibility and session are summarized in Table 1. Each of the numbers in Table 1 is an average over the individual coefficients of correlation; for example, for session 1 compatibility, the r's ranged between −.05 and .81. The correlations are consistently positive, and thus all mean values of r, except the low value for session 1 incompatible, are significantly positive at $p<.01$ (two-tailed t test). In session 1, the result is as predicted: there is a significant correlation between the angles in the compatible trials, and essentially no correlation ($t(11)=1.07$, $p=.3$) in the incompatible case. Moreover, the relation r(compat.) > r(incomp.) holds individually for 11 out of 12 subjects in session 1, and a t test for the compatibility yields $t(11)=2.48$, $p=.02$ (two-tailed). As in the results for the RTs and errors, this effect, although robust in the first session, seems to wash out by the second session (the t test for the compatibility effect gives $t(11)=.09$, n.s.).

Table 1: Correlations between motor and imagery task angles, by session and compatibility conditions

	Session 1	Session 2
Compatible	.385	.257
Incompatible	.083	.264

Finally, we compare the speeds of the mental and motor rotations. In each session, the subject had a target speed for motor rotation, ω, equal to either 45 or 90°/s. We have already seen that the speed of mental rotation roughly followed the motor speed; when the motor speed decreased in the session 2 the mental speed also decreased, and vice versa. However, within each session there were spontaneous variations in the actual motor speed, because the subject never precisely achieved the goal ω, and was allowed a margin of error of 45%. We now ask whether these spontaneous variations of motor speed around ω are also positively correlated with variations in the mental rotation speed.

In each trial, define the *motor speed* as the mean angular speed of motor rotation during the test phase of the trial (i.e., Phase 3), and the *mental speed* as before (i.e., the angle θ divided by the RT). For each subject and each session, we perform a quantile analysis of motor versus mental speed with four levels. Namely, we sort the trials (for each subject, session, angle (45°, 90°, and 135°) and compatibility condition, which makes 32 trials) by motor speed, in ascending order. We then group trials together by 25-percentile blocks (i.e., trials whose motor speed falls in the lowest 25% are grouped together ("first quantile"), then trials whose motor speed falls between 25% and 50% ("second quantile"), and so on, making a total of four levels). We then analyze the *mental* speed as a function of quantile, session and compatibility, averaging over subjects and angles.

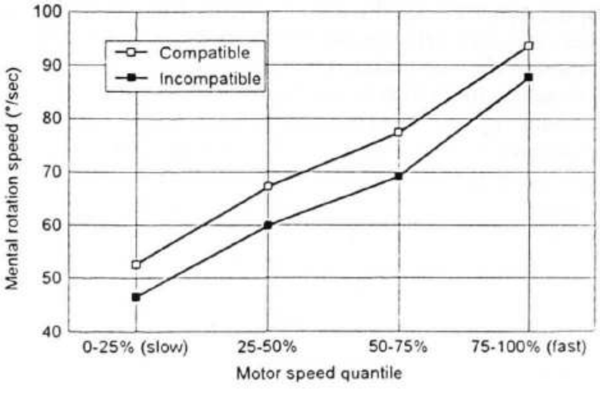

Figure 4: Dependence of mental rotation speed on motor speed (the latter expressed as a quantile).

Figure 4 shows mean mental speed as a function of the motor speed quantile, for compatible and incompatible trials averaged over both sessions. As is evident, there is a strong positive correlation between the mental and motor speeds: mental rotation was slower on trials where motor rotation was slower, and vice versa. There is a lawful relationship between the two speeds: the curves in Figure 4 have mental speed steadily and monotonically increasing with motor speed quantile: roughly speaking, for every increase in the motor speed there is an increase in the mental speed. The effect of quantile is highly significant, $F(3,30)=136.90$, $p<.0001$, for both sessions together. This effect remains significant if the first and second sessions are analyzed separately, with $F(3,30)=103.41$ in the first session and $F(4,36)=92.76$ in the second (both give $p<.0001$). In addition, we note an effect of compatibility, that remains significant in the second session. The effects of the motor rotation on the mental rotation speed are highly specific (mental rotation speed increases steadily with motor speed, and is mental rotation is faster when its direction is compatible with the motor rotation); they prove to be, moreover, more robust to the effect of practice than the simple RTs and errors as analyzed in the previous section, as they remain highly significant in the second session.

Another way to assess the significance of the effect of motor speed on mental rotation speed is to repeat the quantile analysis for only two levels; that is, to group together trials according to whether the motor speed was above or below the median (for that particular subject and session). Here we find that for *all* 12 subjects, mental speed in the slow-motor trials is below mental speed in the fast-motor trials; moreover, this is the case for both the first and the second sessions. Thus, we have found that both large-scale variations (from one session to another) and small-scale variations (spontaneous variations within each session) in motor speed lead to corresponding variations in the mental rotation speed.

Discussion

Briefly, our main results are as follows. Mental rotation is faster and less error-prone when accompanied by motor rotation in the same direction, slower and more error-prone when motor rotation is in the opposite direction. Variations in motor speed, on both large and small scales, are accompanied by corresponding variations, in the same direction, in mental rotation speed. The first of these results confirms that of Wohlschläger & Wohlschläger (1996). The second result is new, and is important in that it shows the detail of the interaction between the motor system and mental image transformation.

The results strongly support the imagery/motor hypothesis, in its dynamic form: the subject's motor action has a clear effect on the concurrent mental rotation, to such an extent that the mental rotation, in both its direction and speed, can almost be said to be mimicking the motor action.

Another important finding is the practice effect. The subjects' performance on both the imagery and the motor tasks improved in the course of the two experimental sessions, which is unremarkable; what is more interesting is that on some measures (the RT and error ANOVAs, and angle correlations), but not on others (mental vs. motor speed correlations), the interaction between the two tasks went from a strong effect in session 1 to virtually nil by the end of session 2.

There are at least two plausible explanations for the effect of practice, neither of which is in conflict with the imagery/motor hypothesis. First, from the imagery side, mental rotation has been found to be extremely sensitive to practice (see, for example, Tarr and Pinker, 1989), and the overall trend for increasing RTs found in this study is no exception. There is certainly more than one way to compare two images at different orientations, and effortful, voluntary mental rotation (the only kind of mental image transformation relevant to the imagery/motor hypothesis) is only one of them. Indeed, a number of subjects spontaneously reported that over the course of the experiment they shifted from mental rotation—a strategy they were instructed to use—to landmark- or memory-based strategies. Some of these may involve mental mechanisms that are less coupled, or not coupled at all, to motor mechanisms.

Another possible reason for the decrease in coupling between the mental and motor rotations in the second session would be a change in the subjects' organization of the motor task. Namely, the task of turning the joystick handle at a fixed speed was at first difficult for most subjects, and required much deliberate planning. By the end of the experiment, however, the task was to a large extent automated, as evidenced by a decreasing rate of motor error. In a recent study, Seitz and Roland (1992) have found that the activation of the supplementary motor area (SMA) was modified during the learning and automation of a motor task: SMA activation was highest at the beginning of the learning phase, and decreased as the performance of the task became automatic. As it is precisely the motor planning areas such as the SMA that are expected to be responsible for the interaction with mental image transformation (see discussion below), a similar automation of the motor task in our experiment could account for the partial decrease of the motor-imagery interaction in the second session. The practice effect that we have observed thus provides indirect evidence that it is the higher motor areas, such as the SMA and premotor cortex, and whose activation decreases with practice, that are responsible for the motor/imagery interaction.

In another PET study, Deiber et al. (1991) showed that premotor cortex and the SMA are more strongly activated in endogenous movement. One way to test the foregoing explanation of the effect of practice, as well as the involvement of motor planning mechanisms in the imagery/motor interaction, would therefore be to repeat the present study with a condition in which the subject randomly chooses the direction of rotation on each trial. In light of the results of Deiber et al., the motor-imagery interaction should be even stronger in such a procedure than that seen in the present study, and should decrease slower with practice.

What can be the nature of the imagery/motor interaction? We propose that it has to do with *anticipation*. In planning motor action, the brain routinely anticipates the sensory consequences of the action. For example, Duhamel, Colby & Goldberg (1992) found neurons in the parietal cortex of the monkey that modify their retinotopic receptive fields immediately before an eye movement, by the same amount as the intended saccade. Georgopoulos et al. (1989) have found a type of mental rotation in the motor cortex that may anticipate the results of object manipulation.

Now, even in the absence of overt movements (which are often costly and irreversible), anticipatory mechanisms could furnish a visual mental image of the results of a putative action (Kosslyn, 1994). The action would be planned (which would involve such frontal motor planning areas as the supplementary motor area and premotor cortex—see Deiber et al., 1991), but not overtly executed. For instance, if you have a visual mental image of an object, and you imagine rotating the corresponding object (that is, you have a *motor* image, which certainly mobilizes the motor planning centers of the cortex), the motor anticipatory mechanisms would furnish a visual image of the rotating object. On this view, the motor system would guide the transformation of mental imagery, not only of one's body, but of abstract objects as well. Our experimental results do not directly confirm this admittedly speculative model ("visual mental image transformation as visual-motor anticipation"), but they do provide evidence of rather tight coupling between motor action and visual image transformation. More directs test of this hypothesis are in progress.

The view presented here, the importance of motor action in the guidance of mental image transformation, goes somewhat against the grain of thinking in cognitive science, which typically assigns to action the role of mere output—rather than participant—of higher cognitive processes, among which we may include visual mental imagery. The role of action has recently been re-evaluated, in such diverse fields as linguistics (Lakoff, 1987) and robotics (Brooks & Stein, 1993). Kirsh (1995), for instance, has discovered situations where *overt* action plays an important part in spatial reasoning. It may well turn out that motor mechanisms, through either overt or covert channels, play a constructive role in cognition.

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