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Mental and Manual Rotation

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The relation between mental and manual rotation was investigated in 2 experiments. Experiment 1 compared the response times (RTs) of mental rotation about 4 axes in space with the RTs shown in the same task when participants were allowed to reorient the stimuli by means of rotational hand movements. For the 3 Cartesian axes, RT functions were quantitatively indistinguishable. Experiment 2 investigated interference between mental rotation and 4 kinds of simultaneously executed hand movements that did not reorient the stimuli. Interference was observed only when axes of manual and mental rotation coincided in space. Regardless of the hand used, concordant rotational directions facilitated, whereas discordant directions inhibited, mental rotation. The results suggest that mental object rotation and rotatory object manipulation share a common process that is thought to control the dynamics of both imagined and actually performed object reorientation.

The basic task in mental rotation experiments is to decide whether two stimuli differing in orientation are identical or are mirror versions of each other. Angular disparity between stimuli is varied systematically, and response times (RTs) and errors are measured. The typical, most intriguing result found in many mental rotation studies is the almost perfect linear increase of RT with angular stimulus disparity.[1] Together with introspective reports from participants and experimenters, these core findings led to the use of the term *mental rotation* because such rotation resembles the time course of a physical rotation with constant angular velocity. Since the first chronometric studies of mental rotation in the early 1970s by Shepard and his colleagues (see Cooper & Shepard, 1984, for a review), a vast amount of research has been done on this kind of dynamic mental imagery. Mental rotation has been studied for a huge variety of objects, among them hands, feet, and faces (e.g., see Sekiyama, 1982, Parsons, 1987b; and Sergent & Corballis, 1989, respectively), line drawings of natural objects (Jolicoeur, 1985), whole maps (e.g., see Rossano & Warren, 1989), and two-dimensional (2-D) as well as three-dimensional (3-D) nonsense objects. Its relevance for diverse cognitive functions such as naming (e.g., see Jolicoeur, 1985), matching (as in all classical mental rotation studies), and recognizing objects (e.g., see Gibson & Peterson, 1994) has been investigated. Moreover, mental rotation has been studied with the most sophisticated experimental designs including—to mention just a few—under conditions of head tilt (M. C. Corballis, Nagourney, Shetzer, & Stefanatos, 1978) and reaction time pressure (D. Cohen & Kubovy, 1993), after autogenous training (Lison, 1987), and even under microgravity in the Soviet Space Station MIR (Clement, Berthoz, & Lestienne, 1987; Matsakis, Lipshits, Gurfinkel, & Berthoz, 1993).

What is it that made mental rotation a hobbyhorse ridden by cognitive psychologists under such a variety of conditions? One answer is that it constituted a milestone for cognitive psychology and mental imagery research because it demonstrated in a nice, comprehensible way that it was possible to investigate imagery and its properties using RT measurement. Another is that it was the analog nature of the mental rotation process, most impressively demonstrated by Cooper (1976), that piqued psychologists' interest. The resemblance of mental rotation to external physical rotation, however, calls for a mental process that mimics external physical rotation, and one reason for the long-standing so-called "imagery debate" is the failure of imagery proponents to show convincingly how such an analog process is implemented in our brains. Recent electrophysiological studies, however, have measured continuous changes in the activity pattern of cell assemblies in monkeys performing a visuomotor mental rotation task (Georgopoulos, Lurito, Petrides, Schwartz, & Massey, 1989). These studies found that the neuronal population vector—calculated from the cell assemblies' activity pattern—continuously changed its direction prior to the onset of a movement pointing 90° to

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[1] Sometimes curvilinear but still monotonous trends are also observed (e.g., Koriat & Norman, 1985).

the left of a target light. There was no a priori reason for the neuronal population vector to rotate at all, and the fact that it rotated prior to, and not in parallel with, the movement makes it convenient to call it a mental rotation. These results demonstrate how analog operations can be performed by our brains, and perhaps mental object rotation is performed by similar changes in the activity patterns of cell assemblies.

Cognitive psychologists, so far, have mainly tried to explain the analog nature of mental rotation by looking for the relation between mental rotation and the perception of rotary motion. Shepard and Judd (1976) addressed this question by investigating apparent rotational motion and its relation to mental rotation. They showed that the minimum cycle duration required for the apparent rotational movement illusion also increases linearly with the angular difference between the two alternating perspective views of a 3-D object. They found this linear increase to be quantitatively the same for rotations about a vertical axis (y-axis) and rotations in the picture plane (z-axis).[2] The fact that they found a linear relation in their mental rotation experiments too (Shepard & Metzler, 1971), and that the regression lines for picture-plane and depth mental rotations were also similar, led them to the conclusion that the same mechanisms or processes may underlie performance in these different tasks. However, mental rotation speed was about 50–60°/s, whereas the slope of the apparent motion function was calculated as 1,000°/s. Furthermore, Friedman and Harding (1990) showed that mental rotation speed depends on the axis of rotation, whereas the apparent motion illusion does not. Friedman and Harding concluded that mental rotation and apparent motion do not have much in common. In addition, mental rotation is strategic (Just & Carpenter, 1985) compared with the largely automatic processing of apparent motion perception. Hence, the assignment of the perception of real motion as the main explanation for the mental rotation phenomenon is somewhat unsatisfactory. Mental rotation is obviously a much higher level process than the perception of real or apparent motion.

Nevertheless, there have been further, more direct attempts to prove the participation of rotary motion perception in mental rotation. M. C. Corballis and McLaren (1982; see also M. C. Corballis, 1986b) showed that inducing a rotary aftereffect by means of a rotating textured disk influenced the RT of the mental rotation of subsequently presented alphanumeric characters. Compared with RTs in the standard experiment, RTs were increased when the aftereffect was in the direction opposite to that of the presumed mental rotation (discordant[3] condition) and when angular deviation from the upright was large (about 120°). In light of these findings there is good reason to assume that mental rotation and perceived rotation interact to some extent and that a common neural substrate is involved in both processes. One might even be tempted to localize mental rotation at the same early stage of visual information processing at which the motion aftereffect works (Tootell et al., 1995). However, Jolicoeur and Cavanagh (1992) were able to exclude the participation of low-level motion analysis centers in the mental rotation process. They presented rotated characters in different surface media (i.e., the characters were segregated from the background by either luminance, motion, binocular disparity, color, or texture) to determine the level of the visual system at which mental rotation occurs. Though finding slight differences in overall RT level for different surface media, they found no effect of surface medium on mental rotation rate. In a further experiment, a pronounced effect was produced when they rotated the characters about a small angle by means of apparent motion. Concordant rotation of presented characters accelerated the RT of mental rotation, whereas rotations opposite (discordant) to the direction of presumed mental rotation led to delayed responses, compared with a neutral condition. Obviously, figure motion—induced by either apparent motion or by an aftereffect—interacts to some degree with mental rotation.

Summarizing their results, Jolicoeur and Cavanagh (1992) concluded that mental rotation occurs at a relatively high and perhaps abstract level of processing. The higher the level of (supposedly perceptual) processing, however, the more likely it is that processes of action planning are involved (e.g., see Mountcastle, Lynch, Georgopoulos, Sakata, & Acuna, 1975; Taira, Mine, Georgopoulos, Murata, & Sakata, 1990). This is in agreement with a principal difference between motion perception and mental rotation. Whereas motion perception is a rather automatic process, mental rotation is strategic and shares some characteristics with voluntary actions. First, although mental rotation can be relegated to subordinate control (M. C. Corballis, 1986a; Kail, 1991), it does not occur automatically when two objects differing in orientation are presented. Second, mental rotation can be started and stopped voluntarily (Cooper, 1976), and even its speed can be chosen freely (Cooper & Shepard, 1973). In a recent study on apparent motion and mental rotation, P. M. Corballis and Corballis (1993) came to the conclusion that "there is continuity of representation

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[2] Note that Shepard and colleagues produced picture-plane-rotated objects simply by turning the sheets of the perspective drawing of their 3-D stimuli. However, the result of rotating a 3-D object around an axis pointing to depth (z-axis) is not necessarily the same as the result of rotating the object's perspective drawing in the picture plane. The results are identical only if the line of sight is exactly perpendicular to the picture plane and if it intersects that plane exactly in the center of plane rotation—in other words, if the line of sight and the z-axis are identical and perpendicular to the projection surface. As soon as stereographics are used (as in the experiments reported here) it is even impossible to produce the stimuli by rotating the 2-D projection medium, because in stereographics two different lines of sight are used to produce the right- and left-eye stimuli.

[3] The etymologically more suitable terms *concordant* and *discordant* are used here instead of (and synonymously with) the terms *congruent* and *incongruent*. Note that at the 0° and 180° stimulus disparities there is virtually no meaningful distinction between concordant and discordant. However, if concordant character rotation—induced either by apparent motion or a rotary aftereffect—is capable of facilitating mental rotation, at 180° one would expect a decrease in RTs compared with RTs in a neutral condition in which no character rotation is used. In fact, just such a result was found by Jolicoeur and Cavanagh (1992).

in both apparent motion and mental rotation, and that the same representations may be involved in each. . . . However, the act of mental rotation itself clearly seems to be distinct from that of apparent motion" (p. 465). The processes engaged in motion perception might well be involved in the imagination of rotating objects, but there should be a higher process steering these dynamic imaginations because they are quasi-completely under voluntary control. Considering mental rotation's similarity to voluntary actions, it might be possible that premotor processes (i.e., processes involved in action planning) are involved in mental rotation, a conclusion Kosslyn (1994) drew that was complementary to his earlier work. More precisely, this means that processes engaged in rotatory object manipulation might also be active during mental rotation. In this view, rotating something mentally would be an imagined action rather than the perception-like imagination of an object in rotation.

Evidence for a linkage of mental rotation to action planning is given by several findings. When test persons were asked whether they rotated the right one or the left one of two stimuli, 84% of the right-handed persons rotated the right-hand object exclusively or more frequently than the left-hand object, whereas 66% of the left-handers preferred to rotate the stimulus on the left (Cook, Früh, Mehr, Regard, & Landis, 1994). Although Cook et al. interpreted this result in the sense of a lateralization of mental rotation, they did not consider the fact that only about one third of left-handers are inversely lateralized—that is, that typical right-hemispheric processes are carried out by the left hemisphere, and vice versa (Porac & Coren, 1981). Nevertheless, about two thirds as many left-handers rotated the left-hand object more often, which somewhat contradicts Cook et al.'s lateralization explanation. It seems more plausible to assume that mental rotation consists of more or less concrete action planning that perhaps includes selecting the dominant hand.[4]

One first step in investigating the relation between mental rotation and action more directly was made by Sekiyama (1982, 1983). She presented her participants with line drawings of human left or right hands in five different versions that varied finger position and wrist rotation (Sekiyama, 1982). In addition, each version could appear in any one of eight orientations in the picture plane. Respondents had to decide as quickly and accurately as possible whether a right or a left hand was shown. Results showed that RT depended on the orientation of the presented hand, but not always in the way usually observed in mental rotation experiments. Some hand-shape versions produced RT functions with their maxima at angles different from 180°. When this was the case, RT functions for left- and right-hand versions were mirror reversed. Sekiyama explained her results in terms of "manageable directions": The shapes of the RT functions agreed with the anatomical constraints for the hand movements that would have been necessary to solve the task physically.

To test her hypothesis of a visual-kinesthetic representation of hand movements, Sekiyama (1983) conducted a second experiment in which the participants had to imitate the same hand images and then consecutively rate the physical difficulty involved in the imitative movements. Both rating functions and RT functions showed the same trends, thus confirming that kinesthetic information is preserved in the representations of hand positions. Sekiyama's results were successfully replicated by Parsons, who compared the RT of left–right decisions with the time required to imagine the corresponding spatial transformation of one's body (Parsons, 1987a) or one's hands and feet (Parsons, 1987b). Both RTs and imagination times depended strongly, and in the same way, on the implicit awkwardness of the stimulus orientation, that is, on the extent of anatomical and physiological constraints on a movement to the particular stimulus orientation. Most interesting, however, is that the results of Sekiyama and Parsons demonstrate that a visual task can be solved by an imagined movement of one's own limbs.

Such imaginations could play a significant role in mental object rotation too and perhaps are not restricted to stimuli showing human body parts. Although the relevance of mental rotation to object manipulation in everyday life is obvious, we found no research directly investigating its relation to rotatory object manipulation. Our aim in the experimental work presented here was to start filling this gap. In actually performed object manipulations, the visuospatial representation of an object is changed continuously by actively modifying the input. The question is how in mental rotation a continuous change of that representation (and that is what is generally believed to happen in mental rotation) is achieved. We hypothesize that rotating an object mentally is somehow similar to rotating it physically (e.g., with one's hand) in the sense that there is a common process controlling rotation in both cases. That means there is one common process that in *manual object rotation* controls the rotation of the object via motor commands and that in *mental object rotation* controls the change of the visuospatial representation. This "common-processing" hypothesis implies essentially two things. First, mental rotation should be commensurate with rotary object manipulation: Factors that affect mental rotation should have the same effect on actual rotation. Second, both tasks should be functionally connected, that is, they should depend on each other. This could be investigated by having both tasks executed simulta-

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[4] Another clue for a linkage of mental rotation and motor processes comes from developmental psychology. Snow and Strope (1990) compared the untimed accuracy on a mental rotation test of children between the ages of 6 and 11 years with their performance on several other tasks (graphaesthesia, memory for sentences, auditory blending, visual matching, word fluency, and motor speed). Taking mental rotation as the dependent measure, Snow and Strope found a significant correlation of mental rotation in younger children (6–8 years old) only with graphaesthesia (the recognition of letters and numbers drawn on the back of a blindfolded child's hand). This correlation must be qualified, however, because the younger children performed just above chance level. It is interesting that the older children (9–11 years old) showed a highly significant correlation of mental rotation only with motor speed as measured by the total time needed to perform several cycles of alternate finger–thumb touching, heel–toe tapping, and pronation–supination of both forearms.

neously, that is, by having participants perform mental rotation while making rotational hand movements.

The commensurability of the two tasks can be tested by comparing the mental rotation RT with the RT required to solve the same task when—instead of in imagination—the stimuli are reoriented by hand movements (called *manual object rotation* here). Factors that influence RT in one task should have the same effect in the other task. The well-known effect of stimulus orientation on mental rotation RT should similarly be found in manual object rotation. Demonstrating such a similarity for different levels of difficulty would corroborate the commensurability of the two processes. However, showing similarity does not allow one to draw any conclusions regarding the underlying processes. Mental and manual object rotation might be controlled by two independent processes that result in the same RT functions. Nevertheless, demonstrating the similarity of both tasks is a prerequisite for investigating their functional connection. Should both tasks yield dissimilar RT functions, it would be more realistic to think of them as reflecting independent processes, and one would be spared further investigations.

Experiment 1

Experiment 1 was designed to test whether rotary object manipulation is commensurate with mental rotation. This was tested by comparing the mental rotation RT function with the RT that would be required in the same task, if the object could be manipulated physically. We expected that the difference between the two functions would be negligible. Further corroboration of commensurability would be provided by a demonstration of negligible differences in these functions for different levels of difficulty. Stimulus conditions that slow down mental rotation should also increase the operation times of manual object rotation. We used rotation about different axes in space, which are known to elicit different speeds of mental rotation (Parsons, 1987c), to provide these various levels of difficulty.

To make mental and manual object rotation conditions as similar as possible, for manual object rotation we gave individuals the opportunity to turn the stimuli on the display by means of a knob. This was the only difference between the two conditions. Because mental rotation performance is sensitive to practice (Kail, 1986; Kail & Park, 1990; Leone, Taine, & Droulez, 1993; Tarr & Pinker, 1989), each individual took part in only one experimental condition; that is, for each individual, the object was rotated about only one axis and the task had to be solved either mentally or with the aid of rotational hand movements.

Method

Participants. The 92 right-handed participants were psychology students at the Universität Konstanz or at the Ruhr-Universität Bochum. All students had normal or corrected-to-normal stereoscopic vision. Students at the Universität Konstanz took part to fulfill course requirements. Most of the students at the Ruhr-Universität Bochum received credit they needed in order to register for their preliminary exam. During holidays, they were also paid 5 deutsche marks (DM). The few who did not need such credit were paid 10 DM. Two thirds of the students were women. Care was taken to distribute men and women equally over the experimental conditions. We suspected that 10 of the 40 participants in the mental rotation condition solved the task by guessing for at least one stimulus, which we concluded by calculating the binomial probability of attaining the respective number of correct answers by chance ($\alpha = .05$). This was also the case for 4 of the 52 participants in the manual object rotation condition. The data of these participants were excluded from analysis. In addition, in the manual object rotation condition, 3 participants turned the knob (see *Apparatus* section below) in fewer than 10% of the trials, and another 9 participants turned the knob almost exclusively (more than 90% of the trials) in one direction. Again, these participants' data were not analyzed. Thus, the final sample consisted of 66 individuals, 30 in the mental rotation condition and 36 in the manual object rotation condition. The proportion of dropped participants (28%) corresponds to that in other mental rotation studies (e.g., Yuille & Steiger, 1982: 23–44%).

Stimuli. A more natural version of one of the cube array objects applied by Shepard and Metzler (1971) was used to generate the stimuli. The object consisted of 10 cubes, and each cube had an apparent edge length of 1 cm. The surfaces were shaded gray as if there were a punctiform light-source 250 cm above, 10 cm in front of, and 30 cm to the left of the object and a background/light-source illumination ratio of 5:9. Stimuli were presented stereoscopically (see *Apparatus* section). Stimuli for the right eye were constructed using a central perspective that simulated a cyclopean observer 60 cm away from, 25 cm above, and 20 cm to the right of the object. Stimuli for the left eye were constructed similarly but an eye-to-eye distance of 6 cm was assumed. For each experimental condition, we created 12 test stimuli by rotating the object and its mirror counterpart in 60° steps around an axis that went through the object's center of mass, which we calculated by assuming homogeneous mass distribution. Four axes were chosen for the construction of the stimuli: the horizontal x-axis, the vertical y-axis, an axis pointing to depth (z-axis), and a bisector (b-axis) between the y-axis and the z-axis that ran upward and away from the observer. The Cartesian rotational axes (x, y, and z) were parallel to the figural axes of the object at 0° orientation. Each individual saw only stimuli generated by a rotation about one of the four axes. In the manual object rotation condition, the orientation of the test stimuli on the screen could be changed by means of a knob. Turning the knob caused a change of the stimulus orientation in real time with an angular resolution of 3°.

Apparatus. Stimuli were presented on an AMIGA 2000B computer using a special stereoscope (55 cm long) mounted to the computer monitor. The stereoscope was used to provide approximately equivalent depth information (Sollenberger & Milgram, 1993) in the mental rotation condition and the manual object rotation condition because the latter condition offered the opportunity to obtain depth through rotary motion. Each stereoscopic channel ended in a 9.5 × 18.0 cm rectangular opening in contact with the monitor surface. Participants had to look through small circular apertures (diameter = 4.5 cm) equipped with lenses (+2 diopter), which thus made a chinrest unnecessary. A participant started each trial by pressing the middle button of the response keypad. Responses were given by pressing either the left or the right button of the same keypad (see Figure 1A). In the manual object rotation conditions the participants could also turn the stimulus on the display by means of a knob. The rotational axis of the knob was fixed parallel to one of the Cartesian axes or parallel to the oblique B-axis. Regardless of which position was chosen, the center of the knob was always in the same spatial position, below and somewhat to the right of the stereoscope and 23 cm above the

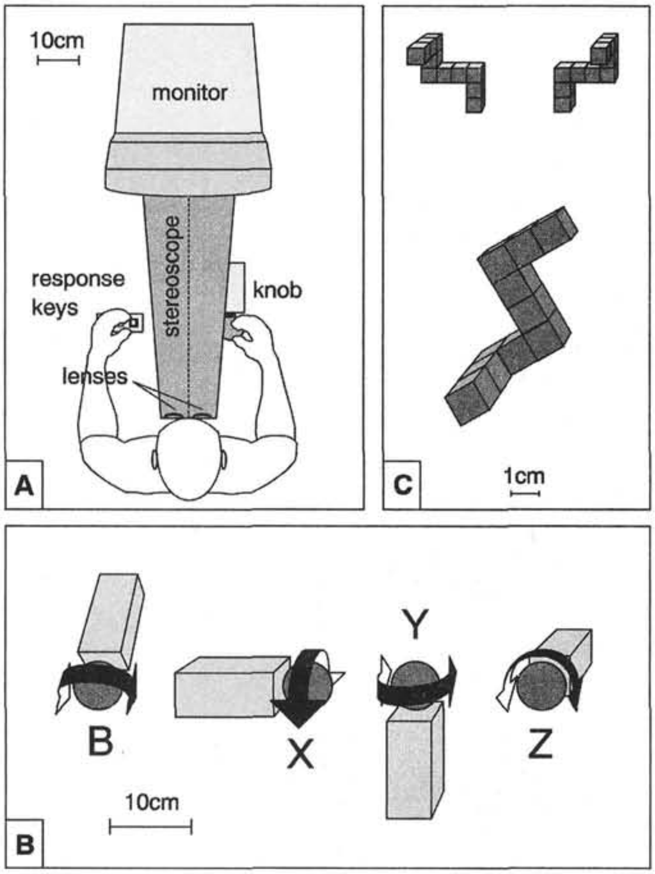

Figure 1. Apparatus and presentation of stimuli.

tabletop (see Figure 1B). The angular position of the knob was measured during the vertical blank (i.e., every 20 ms) with an angular resolution of 1°, and the stimulus orientation was matched immediately (i.e., in the next frame) to the knob position with a resolution of 3°.

Design. A matching-to-sample design was used with the probe stimulus at the center of the display. The two comparison stimuli consisted of the two isomers at the 0° orientation. They were reduced to half the size of the probe stimulus and were presented at the upper left and upper right of the display (see Figure 1C). These sample stimuli remained on screen throughout the session. The relative position of the standard and the mirror-image sample stimuli (i.e., standard stimulus at left or at right) was balanced across participants. Each session consisted of 16 blocks of 12 trials, which resulted in a total of 192 trials. Each block contained the standard and the mirror-image versions of the object at six orientations, which resulted in 12 different stimuli. Trials within each block were randomized by the computer, which used the actual system time as random seed. The first block served as a warm-up and was excluded from data analysis.

Each individual was assigned randomly to one of eight experimental groups; that is, she or he was in either the mental or the manual object rotation condition and saw only stimuli generated by a rotation about one of the four axes.

Procedure. Participants sat on a height-adjustable chair. They were asked to adjust the height of the chair to a position that allowed them to look agreeably through the small aperture of the stereoscope. They were instructed interactively during the first three trials of the first block. They were told to respond as quickly as possible without making errors. The remaining nine trials of the first block were practice trials. The experimenter stayed in the room with the participant for some of the practice trials to survey whether the instructions had been fully understood and to clarify eventual further questions. The left hand was used for responding, and in the manual object rotation condition, the right hand was used to turn the knob. A gray square in the center of the lower two thirds of the initial screen indicated that a trial could be started. As soon as the center key of the microswitch was pushed, the test stimulus replaced the square. Students now had to decide, as quickly and accurately as possible, which one of the two sample stimuli matched the test stimulus by pressing the corresponding key (left or right). When the response was given, the test stimulus was immediately replaced by another square, which indicated that the next trial could be started. Also, if no response was given within 12 s after stimulus presentation, the square replaced the test stimulus and the dependent measures of those unanswered trials were qualified as missing. No feedback was given concerning the accuracy of the response.

Participants in the manual object rotation condition were additionally asked to position their right arms so they could operate the knob comfortably. If necessary, their right elbows were supported by a Styrofoam pillow. Participants were encouraged to make use of the knob even though it was not always necessary to turn it in order to align the stimuli. They were asked to respond as soon as they were able to make a decision, and for that purpose it was probably not necessary to bring the stimulus exactly into the upright position. As in the mental rotation condition, each trial could be started with the middle button of the microswitch. As soon as the stimulus appeared, it could be rotated on screen by turning the knob with the right hand. As in the mental rotation condition, students had to push the response buttons of the microswitch as quickly and accurately as possible. They were allowed to give responses while turning the knob.[5] As before, as soon as a response was given, the stimulus was replaced with the gray square, which indicated that the next trial could be started.

Results

Besides the practice trials, a total of 32 unanswered trials (0.56%) and 7 trials with RTs lower than 500 ms (0.12%) were discarded prior to statistical analysis. Mean correct RTs and error rates for each stimulus angle were computed for each participant. Means of these means are shown in Figure 2 and Table 1, respectively. In addition, the amount of the rotational hand movements exerted on the knob and the direction of manual object rotation were recorded.

Response times. Participants' mean correct RTs were submitted to an analysis of variance (ANOVA) with the within-subject factor of stimulus orientation (SO) and the between-subjects factors of axis of rotation (AX) and rotation condition (RC; manual vs. mental object rotation). As expected with mental rotation experiments, a strong overall effect of SO was found, $F(5, 290) = 112.37$, $p <$

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[5] In fact, they never did, as was indicated by an inspection of the time elapsed between the end of the movement and the pressing of the response button.

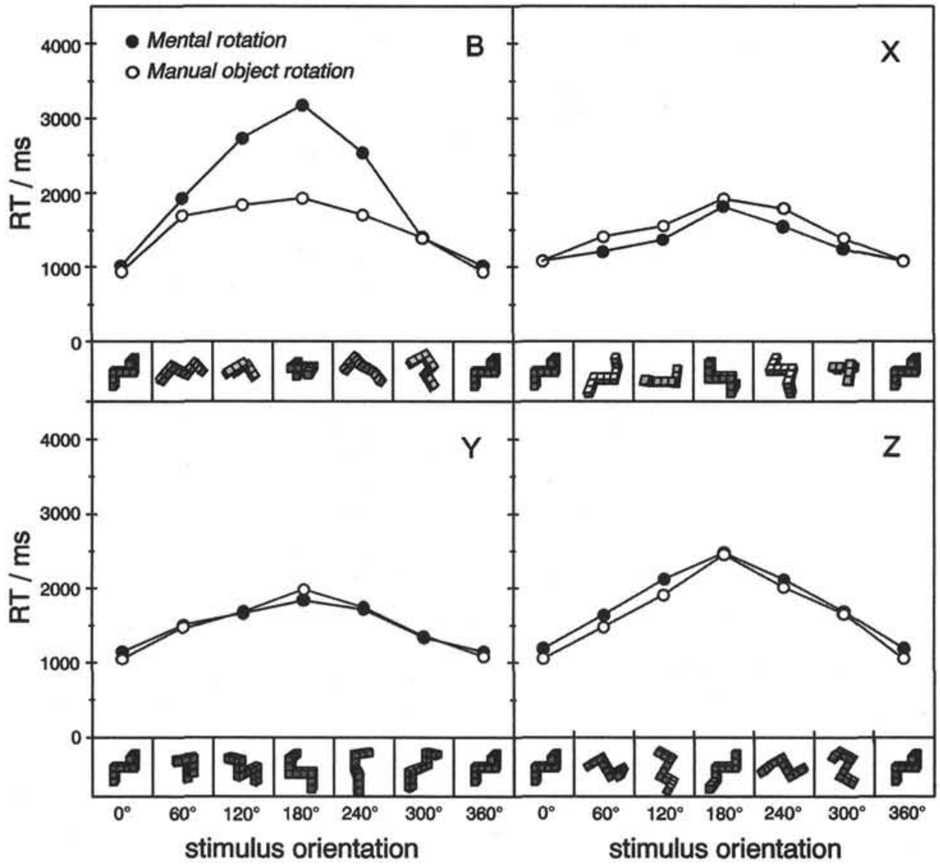

Figure 2. Experiment 1: Mental and manual object rotation response time (RT) functions for different axes of rotation (indicated in the upper right of each panel). Open circles show mean RT for manual object rotation; filled circles show mean RT for mental rotation. Underneath each panel the standard right-eye version of the stimulus is shown rotated about the respective axis to the orientations indicated on the abscissa. Note that for aesthetic reasons, means for the 0° stimulus orientation are repeated at the right for the 360° orientation.

.001.[6] Figure 2 shows that RT increased with angle. This increase, that is, the rotation speed, was significantly different for different axes of rotation, $F(15, 290) = 5.41$, $p < .001$, but it did not differ for the two rotation conditions, $F(5, 290) = 2.20$, $p = .08$. Overall level of RT, however, depended neither on AX, $F(3, 58) = 2.28$, $p = .09$, nor on RC, $F < 1$, nor on the AX × RC interaction, $F(3, 58) = 1.23$, $p = .31$. The three-way interaction reached significance, $F(15, 290) = 2.60$, $p < .01$, indicating that the axial differences in rotation speed depended on RC.

Pairwise contrasts revealed that only the rotation speeds for the x-axis and the y-axis were similar, $F(5, 290) = 1.07$, $p = .37$. All other comparisons showed significant differences ($df = 5, 290$ for all contrasts): b vs. x, $F = 10.98$, $p < .001$; b vs. y, $F = 8.20$, $p < .001$; b vs. z, $F = 4.75$, $p < .01$; x vs. z, $F = 4.62$, $p < .01$; and y vs. z, $F = 4.58$, $p < .01$.

As already mentioned, these axial differences in rotational speed depended on the RC. The above ANOVA model, however, does not allow an estimation of the respective contrasts of the three-way interaction. Hence, a second ANOVA was computed that combined the two between-subjects factors of AX and RC into one eight-level factor that still distinguished the eight experimental groups. Provided that only group means are compared, the second ANOVA is equivalent to the first. As suggested by the results shown in Figure 2, the only significant difference in rotation speed between the manual and mental object rotation conditions was found for the oblique b-axis, $F(5, 290) = 7.56$, $p < .001$. All other comparisons revealed no speed difference ($F < 1$ in all cases).

Errors. Errors were submitted to the same type of ANOVA that we used to analyze RT. Errors significantly increased toward SOs of higher angular disparity, $F(5, 290) = 3.49$, $p < .01$, but depended neither on AX, $F(3, 58) =$

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[6] In general, if Mauchly's (1940) sphericity test showed a significant ($\alpha = .05$) deviance from equicorrelation for a repeated factor or for a combination of factors including at least one repeated factor, we corrected p values using Greenhouse and Geisser's (1959) ϵ.

Table 1
Mean Error Rates (%) for Axes, Rotation Conditions, and Orientations in Experiment 1

	Orientation					
Axis	0°	60°	120°	180°	240°	300°
			Mental rotation			
b	1.0	4.2	7.3	4.4	8.4	1.0
x	0.5	1.6	3.1	4.2	3.2	1.6
y	1.6	1.9	2.2	3.4	2.6	1.9
z	2.6	2.0	5.5	4.6	4.6	3.5
			Manual rotation			
b	1.0	2.1	2.4	2.1	2.3	3.0
x	1.4	0.5	0.3	1.2	0.9	1.9
y	0.0	1.1	1.1	1.6	1.7	2.9
z	2.0	2.5	1.7	5.1	2.6	0.4

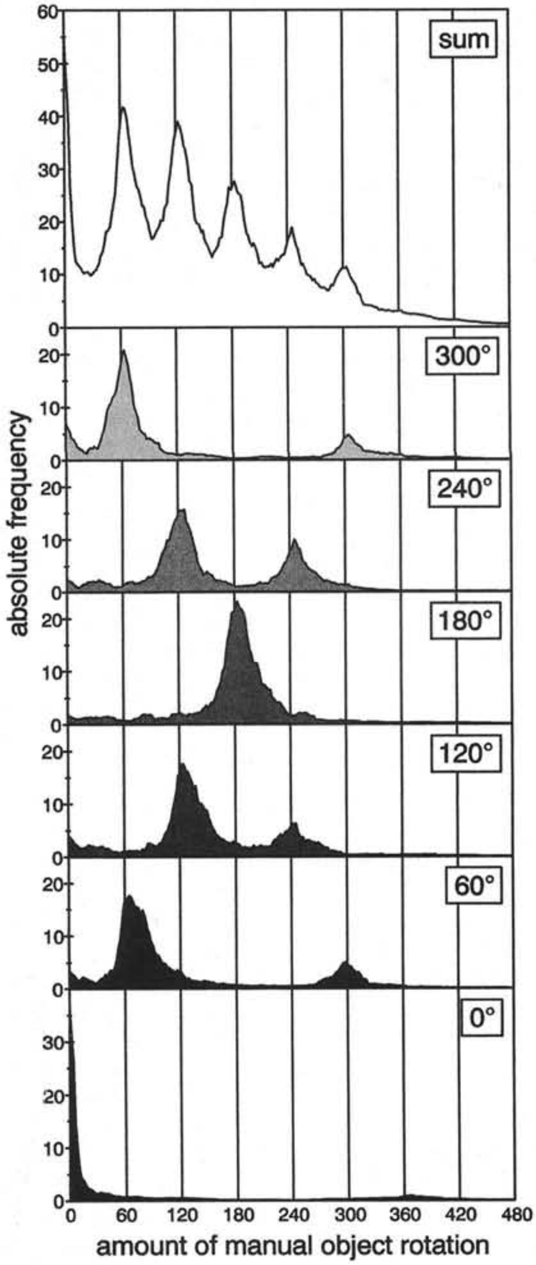

Figure 3. Experiment 1: Distribution of the amount of manual object rotation for each stimulus orientation. Distributions were smoothed by moving average (bin width = 9).

1.10, $p = .36$, nor on RC, $F(1, 58) = 1.37$, $p = .25$. There were no interactions between any of these factors: RC × AX and SO × AX, $F < 1$; SO × RC, $F(5, 290) = 1.03$, $p = .39$; and SO × RC × AX, $F(15, 290) = 1.40$, $p = .16$.

Amount of manual object rotation. The amount of manual object rotation (AMOR) exerted on the knob ranged from 0° to 736°. Forty trials (0.74%) with an AMOR higher than 400° were discarded because we assumed that participants were just playing around in these cases. The distribution of AMOR was investigated for each SO (see Figure 3). Clearly, the peaks of the distributions depended on SO and corresponded almost exactly to the stimulus disparity. It is interesting, however, that distributions for the 0°, 60°, 120°, 240°, and 300° SOs were bimodal. In each case, a second lower peak was found at opposite angles, that is, at angles that corresponded to the longer way around the circle.

Distributions were also rising toward very small angles, that is, those close to 0°. Especially for SOs of 0°, these small AMORs were produced by accidental small movements, because participants' right hands tended to keep in touch with the knob during the whole experimental session. With SOs different from 0°, these trials with small AMORs probably indicate that participants sometimes solved the task by mental rotation or by retrieving the response from memory (this is due to practice; see Tarr & Pinker, 1989). Because the latter case cannot be excluded for the mental rotation condition either, these trials (5.7%) were not excluded from the above analysis of RT.

The unexpected finding that participants sometimes turned the stimulus in the "wrong" (i.e., longer) direction made a closer analysis of the direction of manual object rotation (DMOR) necessary. For this analysis, accidental rotations of the knob had to be excluded. The indent at 29° of the overall distribution of AMOR (see Figure 3, upper panel) was defined as the cutoff. Thus, all trials with an AMOR less than 29° (5.7%), as well as those with an SO of 0°, were excluded from the analysis of DMOR. For each participant and each SO, the relative frequency of counterclockwise (CCW) rotations was computed. Next, the relative frequencies of CCW rotations were treated as *p* scores, and by analogy to classical psychophysics, the point of subjective equality (PSE) and the difference threshold (DL) were calculated. PSE here corresponds to the fold point, probably close to 180°, where rotations in CCW and clockwise (CW) directions are equally probable. DL gives a measure of how precisely participants were able to determine the shortest direction. Thus, next the *p* scores were converted to *z* scores, and a regression analysis with the factors of SO and AX was performed to obtain the linear threshold function for each axis. There was a strong linear relationship between the *z* scores and SO, $F(1, 168) = 287.75$, $p < .001$. Threshold functions depended on AX, $F(3, 168) = 13.95$, $p < .001$, which indicates that there were different fold points (PSE), and on the AX × SO interaction, $F(3, 168) = 11.50$, $p < .001$, which implies a dependence of DL on the axis. Pairwise contrasts for PSE and DL revealed that the *b*-axis was substantially different from all other axes ($p < .001$ and $df = 1, 168$ for all comparisons): for PSE, *b* vs. *x*, $F = 33.84$; *b* vs. *y*, $F = 18.29$; and *b* vs. *z*, $F = 24.08$; for DL, *b* vs. *x*, $F = 21.54$; *b* vs. *y*, $F = 20.54$; and *b* vs. *z*, $F = 22.47$. The other axes had identical threshold functions: PSE, $F(1, 168) < 1$, and DL, $F(1, 168) < 1$, in all cases. Parameter estimates were used to calculate the fold points (PSE) and DLs for each axis. The PSEs were 162°, 204°, 188°, and 188° for the *b*, *x*, *y*, and *z* axes, respectively. The DLs were 120°, 47°, 48°, and 43° for the *b*, *x*, *y*, and *z* axes, respectively. *T* tests of the *z* scores for the SOs of 60°, 120°, 240°, and 300° showed that for the *b*-axis, the *z* scores for 120° and 240° were not significantly different from 0: for 120°, $t(9) = 0.43$, $p = .67$; for 240°, $t(9) = 1.66$, $p = .13$. That is, the *p* scores for these angles were not different from 0.5, and thus in these cases, statistically the participants turned the knob in either direction with equal frequency.

Discussion

Similar to the case in standard mental rotation experiments, in manual object rotation RT increased with the amount of angular disparity between stimuli. Speed of manual rotation as well as speed of mental rotation depended on AX. Errors did not differ between axes or RCs, which thus excludes speed–accuracy trade-offs. Manual and mental object rotation functions matched each other, with the exception of that for the oblique *b*-axis. Because the *b*-axis differed from the Cartesian axes in two other aspects, we discuss its results later. When both RCs are compared, the speeds of manual and mental object rotation were not different for any of the three Cartesian axes. The same rank order of speeds among these axes was found as was found in Parsons's (1987c) experiment, and it was identical for the manual and mental object rotation conditions. Intercepts were also identical. Thus, it can be concluded that, at least for Cartesian axes, mental and manual object rotation are similar processes in a phenomenal sense.

Given the commensurability of the two processes, it is possible to transfer the findings from the manual object rotation condition to mental rotation. We observed that manual object rotation did not always follow the shortest path. On some trials, the participants rotated the longer way around the circle. The frequency of turning the knob in the "wrong" direction was higher on SOs close to 180° (i.e., at 120° and 240°) than on those close to 0° (60° and 300°). On average, this frequency was 9.5%, which is consistent with observations by Hinton and Parsons (1988). Applying psychophysical methods, we could establish a threshold function for rotating in the CCW direction. The DL, identical for the three Cartesian axes, was about 46°. Given the similarity of the RT functions, it is quite probable that mental rotation also sometimes runs in the "wrong" direction. Otherwise, the RT in the manual object rotation condition would have been somewhat higher than the RT in the mental rotation condition, specifically at 60°, 120°, 240°, and 300°, but not at 180°, where there is no shortest direction. This was not the case. If we assume that manual and mental object rotation are comparable processes, then one of the basic assumptions of mental rotation—namely, the shortest-direction hypothesis—should be qualified. It seems that rotation mainly, but not always, follows the shorter one of the two possible angles. A demonstration that this is, in principle, possible was already given by Metzler and Shepard (1974). In a long series of stimuli in which the presumed mental rotation direction was held constant, Metzler and Shepard inserted trials on which stimuli had to be rotated in the opposite direction in order to follow the shortest path. Distributions of RT on those trials were bimodal and indicated that individuals sometimes were misled by the direction of preceding trials.

What about the oblique *b*-axis? It differed in two aspects from the three Cartesian axes. First, manual object rotation speed for the oblique *b*-axis was about twice as fast as mental rotation speed. Second, the threshold function for the direction of rotation was substantially different. DL was 120°, which was almost three times higher than DL for the Cartesian axes. The longer angle was chosen in 32.3% of the trials (compared with 9.5% of the trials with Cartesian axes). For trials with SOs from 120° through 240°, students even rotated in either direction with equal frequency. Obviously, individuals in the *b*-axis condition often could not figure out the shortest direction. This was probably due to a general inability to conceive the position of the axis and the angle of the shortest path of rotation between two orientations of an object when there was no coincidence among the object's principal axes, the rotation axis, and the viewer axis (Parsons, 1995). Thus, individuals might have changed their strategy to just turning the knob in a randomly chosen direction until the orientations of the probe and sample stimuli matched. No doubt, after some fumbling one can always align a pair of real objects, whatever their relative orientations, but probably, rather than using the shortest path of rotation, participants achieve this alignment by successive rotations about different axes or by a rotation about an axis that instantaneously changes its orientation. Using 13 different rotation axes, Parsons (1987c) showed that the latter kind of reorientation—also called spin-precession—explains his RT data just as well as (if not slightly better than) shortest-path rotation.[7] The results of Experiment 1 show that in mental rotation, shortest-path rotation is not used in the case of the oblique *b*-axis. Otherwise the participants in the manual object rotation condition should have been able to figure out the shortest direction of rotation more accurately.

Regarding the correspondence of manual and mental object rotation observed with the Cartesian axes, there is good reason to expect correspondence for oblique axes too

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[7] In the case of the Cartesian axes, shortest-path rotation and spin-precession lead to identical rotation paths.

when a device is used that does not force participants to use single-axis/shortest-path rotations in the manual object rotation condition. Given that then the correspondence would also be shown for oblique axes, it would be possible to infer from the observed movements which kind of mental transformation was used to align objects in this more general case.

However, first, alternative explanations for the observed correspondence of mental and manual object rotation must be excluded. It is possible that participants solved the task by mental rotation in both conditions and that the observed hand movements in the manual object rotation condition were just mimicking the mental rotation process in an epiphenomenal sense. Second, mental and manual object rotation might be driven by two distinct processes that result in the same RT functions but are otherwise independent of each other. Of course, because the similarity of the RT functions in the two conditions was observed only with the Cartesian axes, these alternative explanations are also restricted to the Cartesian axes.

Experiment 2

To exclude these alternative explanations, we must additionally show that both manual and mental object rotation are structurally connected. If either task falls back on the same structure, the tasks should interfere with each other when executed simultaneously. Our basic idea in Experiment 2 was to investigate the influence of rotational hand movements on the performance of mental rotation. Note that rotational hand movements are only a part (although an essential one) of the processes going on in manual object rotation, which is a perceptual-motor task rather than a pure motor task. We used the fact that an object is predominantly rotated in the direction of the shortest angular path to investigate potential interference effects. Rotating a knob in a certain direction should lead to an inhibition of mental rotation on trials in which the direction of the shortest angle is in opposition to that direction (discordant trials). On the other hand, facilitation should occur if the directions of mental rotation and rotational hand movements are identical (concordant trials). The experimental condition was termed z-right, because the knob had to be turned about the z-axis with the right hand. Only the z-axis stimuli of Experiment 1 were used in Experiment 2.

In Experiment 2 we included four different control conditions, which were designed to identify the level of motor processing at which hand movements interfere with mental rotation. To follow the logic of the control conditions, consider first the features of the experimental condition termed z-right: (a) the *presentation of an arrow*—an arrow pointing either CW or CCW was shown prior to each trial; (b) the *execution of a directed movement*—a movement had to be executed in the direction indicated by the arrow; (c) *the movement was rotary;* (d) *the movement axis and mental rotation axis were parallel*—the rotary movement was performed about the z-axis, that is, an axis that was parallel to the axis used to generate the stimuli; and (e) *the dominant right hand was used.*

The four control conditions of Experiment 2 were designed to find out which of the above features was a necessary condition for eliciting an interference effect. Thus the five conditions can be arranged logically in the following way:

1. *No movement.* In order to show that the mere presentation of an arrow is not sufficient to yield interference with mental rotation, a no-movement condition was established in which an arrow simply pointing either left or right was shown prior to each trial. If the execution of a directed movement is a necessary condition for the interference effect, then the no-movement condition should fail to cause interference. On the other hand, if the mere presentation of an arrow suffices to elicit interference, then the effect should be found in this condition and in all the conditions below.

2. *Translation.* In the translation condition, the participant had to move his or her right hand to the right or the left (according to the arrow direction) in a linear way. If translating the directional information of the arrow into any directed movement is necessary to elicit interference with mental rotation, then the interference effect should occur in this condition and in all the conditions below.

3. *Y-right.* However, if it is necessary that the directed movement be rotary for interference to occur, then any rotary movement should evoke interference with mental rotation. Rotation about a vertical axis with the right hand (the y-right condition) was used to test this. Note that the mental rotation axis is perpendicular to the rotation axis of the movement in this condition. If the rotary characteristic of the movement is sufficient to evoke interference, then the y-right condition and all the conditions below should lead to an interference with mental rotation.

4. *Z-right.* This is the experimental condition. Should it be necessary for the interference effect that mental rotation and rotary hand movements be executed about parallel axes, then interference should occur only in this and in the following condition.

5. *Z-left.* Should it be crucial that the movement be performed with the dominant right hand, the z-left condition should fail to elicit an interference effect. The z-left condition was identical to the z-right condition, except that the rotary movement about the z-axis was executed with the left hand.

By following this sequence of conditions it should be possible (a) to determine the necessary features that cause interference and thus (b) to specify the level of motor processing at which interference occurs. Having determined the level of motor processing, we thought it would be interesting to show the reverse interference, that is, an interference of mental rotation with motor performance. We therefore recorded the movements exerted on the knob or the trackball for further analyses. If mental and manual object rotation processing share a common process, interference should also be observed in this reverse sense.

Method

Participants. Fifty-nine right-handed psychology students at the Universität Osnabrück and students from different fields at the Ludwig Maximilians Universität München (LMU) participated in this experiment. For their participation, students at the Universität Osnabrück received an attestation that they needed in order to register for their preliminary exam, and students at the LMU were paid 12 DM. Eleven students (18.6%) were suspected to have solved a substantial part of the task by guessing because they made fewer than 75% correct responses.[8] Forty-eight individuals remained for data analysis and were distributed over the five experimental conditions in the following way: 10 participants in each of the no-movement, z-left, and y-right conditions and 9 participants in both the translation and z-right conditions.

Stimuli and apparatus. Five different objects,[9] adapted from those used by Parsons (1987c), were used to generate the stimuli of Experiment 2 through rotation of each object and its mirror shape about the z-axis in 60° steps (see Experiment 1 for the construction and presentation of stimuli). An arched arrow pointing in either the CW or the CCW direction was used to indicate the direction in which the rotational movements had to be made. In the translation condition, CW indicated a rightward, and CCW a leftward, horizontal translational movement. The same apparatus was used as in Experiment 1. In the z-right and y-right conditions, the position of the knob was identical to that in the z-axis and y-axis conditions, respectively, of the manual object rotation condition of Experiment 1. In the translation condition, the knob was replaced by a trackball. In the z-left condition, the positions of the knob and the response keys were exchanged. For the no-movement condition, the knob was removed.

Design. The design was similar to that used in Experiment 1. Half of the trials were preceded by a CW arrow; the other half, by a CCW arrow. The direction of the arrow was randomized across trials but balanced over stimuli. Each session consisted of two blocks of 120 trials each, which resulted in a total of 240 trials. Each block contained the standard and the mirror-image versions of each object at six orientations; this resulted in 60 different stimuli, each of which was preceded once by a CW arrow and once by a CCW arrow. Trials were randomized within each block by the computer. The first 30 trials of the whole session served as a warm-up and were not analyzed. After the participant pushed the start button (see *Procedure* section), a pair of sample stimuli consisting of the expected probe stimulus and its mirror image, both at 0°, appeared in the upper third of the screen (for details see the Experiment 1 *Method* section). Each individual took part in only one of the five movement conditions.

Procedure. The procedure was basically the same as that used in Experiment 1. A gray square on the screen indicated to the participant that a trial could be started by pushing the center key of the response keypad. After that start button was pushed, an arrow pointing in either the CW or CCW direction replaced the square. In the movement conditions, the requested movement had to be made in the direction indicated by the arrow for 400 ms in order to bring up the probe stimulus, which replaced the arrow. Participants had to continue executing the movement to keep the probe stimulus on screen. Pausing from the movement for more than 100 ms or a reversal of its direction caused the probe stimulus to disappear immediately. It reappeared as soon as the desired movement was resumed. In the no-movement condition, the arrow stayed on screen for 400 ms until the probe stimulus replaced it.

All rotational movements—that is, z-right, z-left, and y-right—had to be exerted on the knob as described in Experiment 1. The translational movement had to be exerted on the trackball with the palm of the right hand. Responses had to be given with the left hand, except in the z-left condition, where the response keys were operated with the right hand and the knob with the left. Responses were accepted, and hence initiated the next trial, only if the probe stimulus was on the screen. Thus it was guaranteed that the desired movement was exhibited throughout the duration of a trial.

Results

Besides the practice trials, a total of 9 unanswered trials (0.09%) and 5 trials with RTs lower than 500 ms (0.05%) were discarded prior to statistical analysis. Mean correct RTs and error rates for each stimulus angle and arrow direction were computed for each participant. Means of these means are shown in Figure 4 and Table 2, respectively. In addition, to obtain a measure of motor performance, we recorded the movements of the knob (or trackball). For correct trials, the average speed and—as a measure of smoothness—the number of transient reversals of the movement direction (which resulted in sudden disappearance of the stimulus) were calculated for each participant, SO, and arrow direction. Means of the average speed and means of the number of directional reversals are shown in Table 3.

Response times. Subjects' mean correct RTs were submitted to an ANOVA with the within-subject factors of arrow direction (AD) and SO and the between-subjects factor of experimental condition (EC), which had five levels (no movement, z-left, z-right, translation, and y-right). As expected with mental rotation experiments, a strong overall effect of SO was found, $F(5, 215) = 207.99$, $p < .001$, which was identical for all ECs, $F(20, 215) = 1.17$, $p = .31$. The overall RT level was identical for all ECs, $F(4, 43) = 1.81$, $p = .14$, and was independent of AD, $F(1, 43) < 1$, in each EC, $F(4, 43) < 1$. There was a significant AD × SO interaction, $F(5, 215) = 3.91$, $p < .01$, which depended on the EC, $F(20, 215) = 1.96$, $p < .05$. The latter three-way interaction made separate analyses for each experimental condition necessary (Keselman & Keselman, 1993).

In all conditions, SO had a strong effect on RT. AD did not influence overall RT level in any condition. The AD × SO interaction was significant only in the z-left and z-right conditions. See Table 4 for the statistics.

To test for the interference effect directly, we calculated planned interaction contrasts[10] for each EC, using the respective error terms of the above ANOVAs. The interference effect was highly significant in the two z conditions: z-left, $F(1, 45) = 15.81$, $p < .001$; z-right, $F(1, 40) = 29.49$,

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[8] This criterion had to be changed because each stimulus now was shown only four times. Applying the criterion of Experiment 1 would have required the participants to solve the whole task without errors. None of the participants was this accurate.

[9] We used five different stimuli rather than only one in this experiment because we wanted to allow for a broader generalization of an interference effect that was found in a preliminary experiment that used only one object (Wohlschläger, 1996, Experiment 2).

[10] The contrast weights were 0, 1, 1, 0, −1, and −1 for the 0°, 60°, 120°, 180°, 240°, and 300° SOs, respectively. The contrast weights were +1 and −1 for the CW and CCW arrow directions, respectively. We calculated interaction contrast weights by multiplying the contrast weights of the main factors (Rosenthal & Rosnow, 1985). In addition, the overall $\alpha = .05$ significance level was adjusted according to the Bonferroni approach.

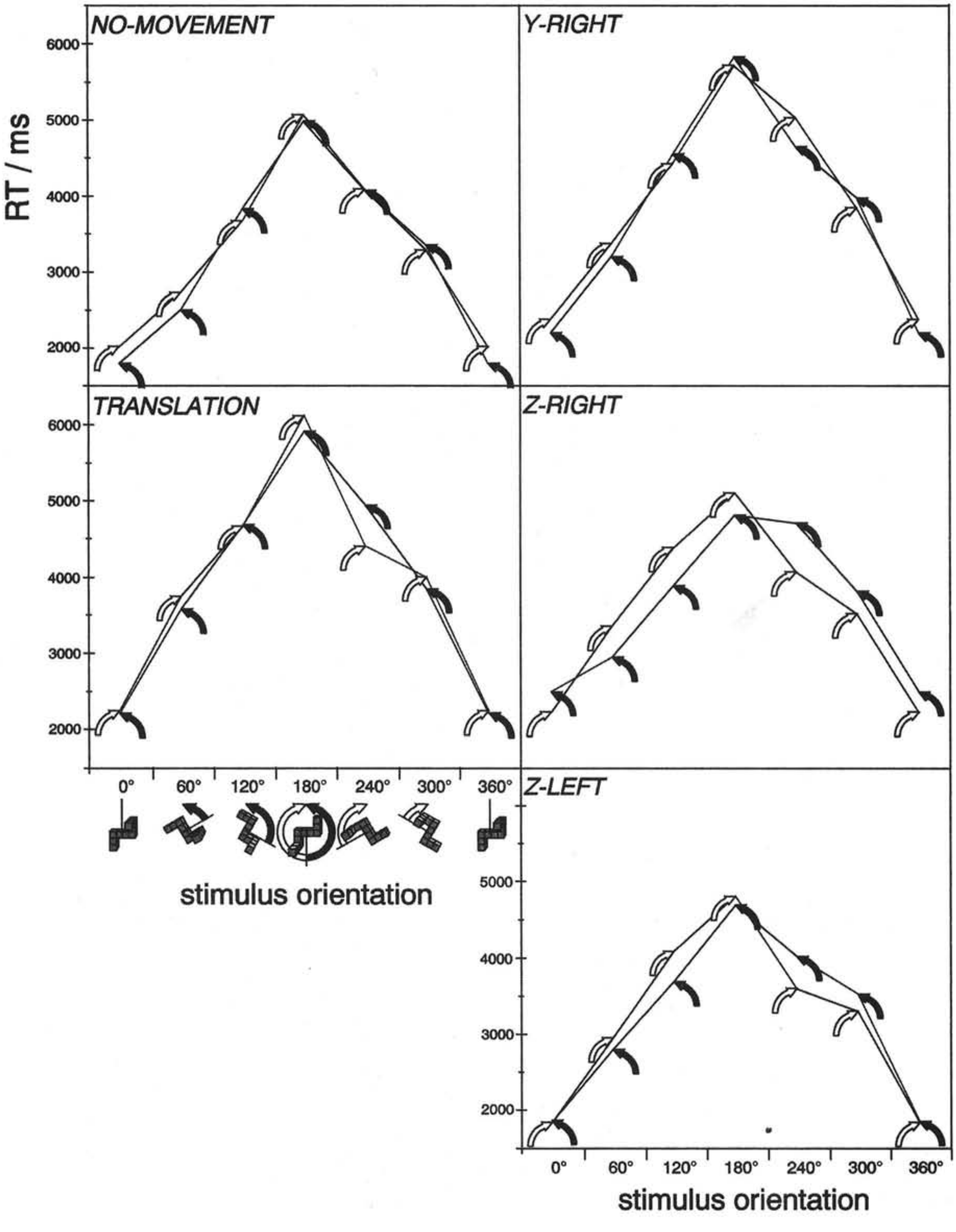

Figure 4. Experiment 2: Mental rotation response time (RT) as a function of stimulus orientation and direction of various simultaneously performed hand movements. The movement condition is indicated in the upper left of each panel. Arrows along curves indicate the direction in which the hand movement was made (clockwise vs. counterclockwise in the rotational conditions *y*-right, *z*-right, and *z*-left and rightward vs. leftward in the translation condition; note that in the no-movement condition, prior to each trial the same arrows were shown as were shown in all other conditions, but no movement was required). Arrows shown with sample stimuli indicate the direction of the shortest mental rotation. Note that the shortest path is ambiguous at 180° and that no mental rotation is required at 0°.

Table 2

Mean Error Rates (%) for Experimental Conditions, Arrow Directions, and Orientations in Experiment 2

Movement condition and arrow direction	Orientation 0°	60°	120°	180°	240°	300°
No movement						
CW	4.7	3.5	8.6	14.1	9.1	10.8
CCW	2.9	2.8	11.4	19.9	13.9	11.4
z-left						
CW	5.1	5.7	19.0	24.2	17.4	11.5
CCW	5.1	4.1	16.3	24.6	10.6	12.1
z-right						
CW	5.5	13.2	14.3	17.3	13.9	9.0
CCW	5.0	11.9	16.3	13.5	11.8	10.1
Translation						
CW	11.5	10.0	20.4	23.3	19.1	12.3
CCW	8.2	9.3	9.6	28.0	13.4	12.8
y-right						
CW	3.4	7.0	20.1	19.9	15.8	14.4
CCW	1.7	12.6	19.0	21.8	18.4	13.1

Note. CW = clockwise; CCW = counterclockwise.

Table 4

Summary of the Five Separate Analyses of Variance of Response Time in Experiment 2

Experimental condition	AD		SO		AD × SO	
	F	df	F	df	F	df
No movement	0.52	1, 9	45.46**	5, 45	1.01	5, 45
z-left	0.00	1, 9	41.31**	5, 45	2.62*	5, 45
z-right	0.00	1, 8	38.41**	5, 40	5.82**	5, 40
Translation	0.00	1, 8	36.53**	5, 40	1.32	5, 40
y-right	0.66	1, 9	51.86**	5, 45	1.14	5, 45

Note. AD = arrow direction; SO = stimulus orientation.
$^{*}p < .05$. $^{**}p < .001$.

$p < .001$. However, it was not significant in any of the three other conditions: no movement and y-right, $F(1, 45) < 1$; translation, $F(1, 40) = 1.62, p = .21$.

Motor performance. Movement patterns were quite different between subjects but consistent within subjects. Most participants turned the knob using only their index fingers (50%, 67%, and 70% in the z-left, z-right, and y-right conditions, respectively). Others used their whole hands and thus had to release the knob from time to time in order to put their hands back without causing a disappearance of the stimulus (40%, 22%, and 30% in the z-left, z-right, and y-right conditions, respectively). One participant each in the z-left and z-right conditions made very slow rotational movements (average speeds of 8°/s and 25°/s, respectively). They did not have to put their hands back. In the translation condition we basically observed two movement patterns. Two participants moved the trackball very fast (average speed of the trackball = 518 mm/s). They, of course, had to move their hands back frequently. The remaining participants operated the trackball by slowly driving the trackball with their palms (average speed = 34 mm/s) or by spreading their fingers (average speed = 121 mm/s) and driving the trackball from the tip of the little finger, crossing the palm to the thumb, and continuing to the tip of the thumb, or the other way round, if they had to make a leftward movement. The latter two groups of participants only rarely had to put their hands back.

Table 3

Mean Movement Speed and Mean Number of Directional Reversals for Concordant, Discordant, and Neutral Trials for the Four Experimental Movement Conditions

Movement condition	Concordant trials	Discordant trials	Neutral[a] trials
z-left			
Speed (deg/s)	304	305	301
No. of reversals[b]	.325	.625	.550
z-right			
Speed (deg/s)	514	494	509
No. of reversals	.389	.972	.694
Translation			
Speed (mm/s)	189	183	198
No. of reversals	4.61	4.67	3.58
y-right			
Speed (deg/s)	536	541	542
No. of reversals	1.75	1.60	1.78

[a] Neutral means all trials with 0° and 180° stimulus orientations irrespective of movement direction. [b] Mean number of reversals per participant (i.e., per 70 trials in each condition). Note that not all participants showed directional reversals for every condition. Therefore, the average number of reversals is often less than 1.

Concerning the speed and smoothness of the movements there were no a priori hypotheses about their dependence on SO or movement condition. Thus, instead of an ANOVA involving these factors, we tested the interference hypothesis directly by means of the same interaction contrasts used for RT, but we used unique error terms constructed by crossing the contrasts with the subject effects (Rosenthal & Rosnow, 1985). In the z-right condition, the trend of the movement speed tested by that contrast—lowest speed with discordant trials, intermediate speed with neutral trials, and highest speed with concordant trials—was significant (see Table 3 for mean speeds), $F(1, 8) = 7.66, p < .05$. No such trend was found in any of the other conditions: z-left, $F(1, 9) < 1$; translation, $F(1, 8) < 1$; and y-right, $F(1, 9) = 1.21, p = .30$.

The number of transient reversals of the movement direction was significantly higher on the concordant trials than on the discordant trials (see Table 4 for the mean number of such reversals) in both the z-left, $F(1, 9) = 5.20$, $p < .05$, and the z-right conditions, $F(1, 8) = 11.45, p < .01$. The other conditions revealed no interference effect of mental rotation on the smoothness of the movement: translation, $F(1, 8) < 1$; y-right, $F(1, 9) < 1$.

Errors. Errors were submitted to the same type of ANOVA that we used to analyze RT. The overall error level depended neither on AD, $F(1, 43) < 1$, nor on EC,

$F(4, 43) = 1.31, p = .28$, nor on the AD × EC interaction, $F(4, 43) = 2.00, p = .11$. Errors significantly increased with SO, $F(5, 215) = 28.88, p < .001$, but this increase was independent of EC, $F(20, 215) = 1.40, p = .16$, AD, $F(5, 215) = 1.05, p = .39$, and the AD × EC interaction, $F(20, 215) = 1.20, p = .26$.

Discussion

The standard findings of mental rotation experiments were replicated in Experiment 2. RT as well as errors increased with angular disparity. Errors depended solely on angular disparity, and thus speed–accuracy trade-offs can be excluded in the interpretation of the RT results.

An interference effect was found, and it was restricted to the two movement conditions that involved a rotation of the hand about the z-axis. Under these conditions, RTs for concordant trials were, on average, about 380 ms lower than those for discordant trials. No such difference was found in any of the other conditions. The mere presentation of an arrow was not sufficient to interfere with mental rotation RT, nor was the execution of a directed translational movement. Rather, interference occurred specifically with rotational movements, provided that the axes of mental rotation and rotational hand movements coincided in space. A rotational movement about the y-axis—an axis perpendicular to the mental rotation axis—did not lead to an interaction between mental rotation and rotational hand movements.

The same pattern of results was found for the reverse interference effect. Only under the two movement conditions involving the z-axis was an influence of mental rotation on simultaneous motor performance found.[11] Occasional transient reversals of the movement direction occurred more often when the directions of mental rotation and rotational hand movement were opposite. The movement was disrupted about twice as often under discordant than under concordant conditions (a little less than twice as often in the z-left condition and about 2.5 times as often in the z-right condition). The number of movement reversals under neutral conditions was an intermediate amount, indicating that concordant mental rotation even smoothed rotational hand movements. Furthermore, in the z-right condition, the rotational movement was executed more slowly on discordant trials (when its direction was opposite to the assumed mental rotation) than on concordant trials. Because there was a significant linear trend of speed—lowest speed with discordant trials, intermediate speed with neutral trials, and highest speed with concordant trials—concordance seems to have accelerated and discordance seems to have decelerated the movement. As above, the interference effect was more pronounced in the z-right than in the z-left condition, where it was even absent. A similar tendency was observed in the RT data: The interference effect was more pronounced when the right hand was used (about 460 ms) than when the rotational movement was executed with the left hand (about 300 ms).

In summary, the symmetric interference of rotational hand movements with mental rotation found in Experiment 2 provides strong evidence that mental rotation and manual object rotation share a common process. The interaction between mental rotation and rotational hand movements was found only when the axes of rotation coincided in space, and it was more pronounced when the dominant right hand was used than when rotations were made with the left hand.

General Discussion

In Experiment 1 we showed that mental and manual object rotation RT functions are identical provided that any of the three Cartesian axes are used. Compared with mental rotation speed, manual object rotation speed was much higher in the case of an oblique axis, for reasons discussed in Experiment 1. For now, with the restriction to Cartesian axes (and probably to conditions in which the axis of rotation coincides with one of the object's axes; see Parsons, 1995), mental and manual object rotation can be considered commensurate. In Experiment 2 we demonstrated that the execution of rotational hand movements leads to an interference with a simultaneously performed mental rotation task. RTs were considerably higher when mental rotation and rotational hand movements were in the same direction than when they were in opposite, discordant, directions. Experiment 2 also clarified which conditions are necessary to yield such an interaction between mental rotation and rotational hand movements. The coincidence of the axes of mental rotation and of rotational hand movements turned out to be the decisive prerequisite for the interaction, which was measurable both in the RT of mental rotation and in the motor performance. In particular, executing an arbitrary rotational movement was not sufficient to cause interference. Thus, the interaction discovered here seems to work at a relatively high level of motor processing, which therefore perhaps should be better termed a level of action planning. The process operating at this level is specific with respect to the spatial operation that is performed, but it only weakly involves the selection of the hand to be used.

The two implications of our common-processing hypothesis—namely, the commensurability of mental and manual object rotation and the interdependence of mental rotation and rotatory movements of the hand—seem to be confirmed. On the one hand, the interference between rotatory hand movements and mental rotation indicates that this common process is involved in generating commands for rotatory hand movements in general (i.e., not just specifically generating commands for hand movements required for object rotations). On the other hand, it seems to be involved in generating commands for the reorientation of the visuospatial representation in mental rotation.

There is somehow a parallel to the interaction between the

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[11] Although average rotational speeds seem to differ, a post hoc ANOVA of the speed of rotatory hand movements under the three rotation conditions (z-right, z-left, and y-right) revealed no significant differences, $F(2, 26) = 2.67, p = .09$. In addition, the manual rotation speed in this task is much higher than in the perceptual-motor task of Experiment 1. Thus, any biomechanical constraints can be excluded from responsibility for speed differences in the manual object rotation condition of Experiment 1.

perception of rotational motion and mental rotation, which have been suggested to use a "shared representational space [which] must be relatively abstract" (Jolicoeur & Cavanagh, 1992, p. 383). On the basis of the results of the present study, one might suggest such a common representational medium for mental and manual rotation too. A common process for generating rotational hand movements and reorientations of mental images (a) has the advantage that perceptual-motor learning and mental imagery processes could directly profit from each other and (b) could serve as an alternative explanation of the analog nature of mental rotation. The fact that pigeons—that is, a species lacking hands or similar effectors allowing continuous object rotation—show no dependence of mental rotation RT on angular stimulus disparity (Hollard & Delius, 1982) is consistent with this view.

Recently, it has been shown in humans that in a task requiring a left–right judgment of a shape depicting a hand at various orientations, the time to move and the time to imagine moving one's hand, with or without providing a left–right judgment, are very similar (Parsons, 1994). These findings suggest a close link between imagined and real body movement, which was demonstrated in a positron-emission tomography study that showed an activation of "frontal (motor), parietal (somatosensory), and cerebellar (sensorimotor) regions" during imagined hand movements (Parsons et al., 1995, p. 54). Thus, at least when pictures of human body parts are used as stimulus material, there is good evidence that mental rotation of these pictures involves a kind of covert action.

Let us now speculate about the brain structures that are most likely involved in mental object rotation. Mental rotation of visual material surely involves visual areas. Among the visual pathways, processing of the object's location and orientation—which follows the dorsal route terminating in the posterior parietal cortex—should predominate over processing of the object's shape and identity, because orientation is the critical feature in mental rotation tasks. Jeannerod (1994) extended the concept of dissociable processing of shape and location originally formulated by Ungerleider and Mishkin (1982) to "semantic" versus "pragmatic" modes of representation, respectively. In Jeannerod's terms, the pragmatic mode includes, besides location of an object, aspects of object-oriented behavior such as grasping and manipulating, the latter being relevant in manual object rotation. Jeannerod's view is supported by the fact that in monkeys, there are neurons in the posterior parietal cortex (Area 7a) that show movement-dependent properties: These cells respond during active manipulation of visible objects but neither to the presentation of the object alone nor during manipulation of the object in the dark (Mountcastle et al., 1975; Taira et al., 1990). These neurons might play an important role in both dynamic visual imagery and object-oriented action, because Area 7a shows extensive reciprocal connections to the supplementary motor area and the premotor cortex, which together form Brodmann's Area 6 (Johnson, Ferraina, Bianchi, & Caminiti, 1996).

Recently, using functional magnetic resonance imaging, M. S. Cohen et al. (1996) showed an activation of Area 6 in half of their participants during a mental rotation task. Parsons and Fox (1995) also observed bilateral activation of Area 6. We would like to propose that the supplementary motor area and the posterior parietal cortex work closely together in providing the spatial information necessary for motor commands in object-oriented actions. This would explain why mental rotation could influence motor performance, as was shown in Experiment 2. Considering the reciprocity of the connections, one could further speculate that the supplementary motor area in turn might be involved in the modification of visuospatial representations in the posterior parietal cortex. This could explain the present findings that execution of a rotational movement interacts with a visual imagery process.

Let us now leave speculations and return to more practical implications of the present results. Together with the interaction between manual and mental rotation, the commensurability of the two processes that was demonstrated in Experiment 1 also offers a new way of investigating mental rotation. Because the two tasks have been shown to be commensurate, one could directly investigate the movements exhibited in manual rotation instead of running series of sophisticated experiments to analyze the details of the mental rotation process. As already mentioned in the discussion of Experiment 1, this method could be particularly helpful in finding out the path people use to align objects rotated about oblique axes. Furthermore, it is not ultimately clear how the interference of apparent motion (or the manual rotation used here) on mental rotation works (Jolicoeur & Cavanagh, 1992; P. M. Corballis & Corballis, 1993). It may be possible to clarify this issue by carrying out experiments that investigate the influence of apparent motion on both mental and manual rotation. Provided that in both conditions apparent motion influences RT in the same way, one could elucidate how interference works by examining the course of the manual rotation movements.

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