

Mental Rotation, Physical Rotation, and Surface Media

Pierre Jolicoeur

University of Waterloo, Waterloo, Ontario, Canada

Patrick Cavanagh

Harvard University

Subjects made mirror-normal discriminations on alphanumeric characters shown in different orientations in the picture plane. Either the characters or the background rotated during stimulus presentation in Experiments 1-3. Character rotation in the direction of mental rotation facilitated mental rotation, whereas rotation in the opposite direction inhibited it. In Experiment 4, characters were presented in different surface media so as to stimulate only one representation at a time. Mental rotation performance was similar whether the stimuli were defined by luminance, color, texture, relative motion, or binocular disparity, suggesting that mental rotation occurs at a level beyond that of the independent analyses of these different media. These results support those of Experiments 1-3 in excluding the participation of low-level motion analysis centers in the mental rotation processes.

Many visual patterns tend to be seen in a particular orientation that we call upright. Such is the case for alphanumeric characters and for a wide range of common objects. When these patterns are shown at orientations that deviate from the canonical, or upright, orientation, certain perceptual judgments about these patterns take increasingly more time to perform as the patterns are rotated further from upright (e.g., Jolicoeur, 1990; McMullen & Jolicoeur, 1990). One paradigmatic case is that of subjects asked to make left-right discriminations on disoriented patterns. For example, if letters are shown in either their usual format or left-right mirror-reversed about a vertical axis, and if they are also shown in a number of orientations, the time to decide whether the letter is in normal or mirrored format increases sharply as the letter is rotated further from upright (Cooper, 1975, 1976; Cooper & Shepard, 1973; see Shepard & Cooper, 1982, for a review). Increases in mean response time on the order of 2 to 3 ms/° are typical (Shepard & Cooper, 1982). Similar results are found when subjects are asked to decide whether a profile view of a rotated object would point to the left or to the right if it were to be shown upright (Jolicoeur, 1985, 1988; McMullen & Jolicoeur, 1990). One interpretation of the sharp and systematic increase in response time associated with increasing departures from uprightness is that a representation of the pattern is mentally rotated so as to align the top of the represented object with the top of a perceptual frame of reference. In this view, the mental transformation, which we refer to as mental rotation, takes an amount of time that is proportional to the angular difference between the orientation of the stimulus and the orientation of the perceptual frame of

reference (for theoretical discussions of the mental rotation hypothesis see Corballis, 1986; Folk & Luce, 1987; Kosslyn, 1980; Shepard, 1981; Shepard & Cooper, 1982).

Mental Rotation and Physical Motion

The orientation effect found in mirror-normal discrimination experiments suggests that subjects may be performing mental rotations on representations of the visual patterns. Is there any relationship between these postulated mental rotations and the perception of real rotational motion? For example, is the neural substrate that has evolved to support the perception of real motion also used to imagine motion of remembered stimuli or of stimuli shown in novel orientations?

Corballis and McLaren (1982; see also Corballis, 1986) addressed this issue by looking at mental rotation of characters shown after their subjects had adapted to a moving textured disk. The motion of the disk (and therefore the perceived motion aftereffect) could be in the same direction as the postulated mental rotation of the character or in the opposite direction. In fact, the results revealed an interaction between the perceived motion aftereffect and the time to carry out the required mental rotation. The effect was mainly to slow down trials at 60° and 120° when the direction of the aftereffect was clockwise and to slow down trials at 240° and 300° when the direction of the aftereffect was counterclockwise.

We found these results intriguing because the interaction between motion aftereffects and mental rotation discovered by Corballis and McLaren (1982) suggests that the same neural substrate involved in the perception of rotary motion could also be involved during mental rotation. If so, it might be possible to learn something about both mental rotation and motion perception by investigating how these two mechanisms interact and perhaps where in the visual system these interactions take place. For these reasons, we decided to investigate further the relationship between perceived rotational motion and mental rotation. Our approach was twofold. First, we wished to replicate the findings of Corballis and McLaren using a somewhat more direct procedure: Rather than performing mental rotation with a concurrent motion

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Correspondence concerning this article should be addressed to either Pierre Jolicoeur, Department of Psychology, University of Waterloo, Waterloo, Ontario, Canada N2L 3G1, or Patrick Cavanagh, Department of Psychology, Harvard University, Cambridge, Massachusetts 02138.

aftereffect, we combined a common mental rotation task—discriminating between normal and mirrored versions of alphanumeric characters shown in upright and nonupright orientations—with a perceived motion of the character. In fact, we found evidence of an interaction between “real” motion and mental rotation, but only when the stimulus itself was seen to move (Experiment 1). Next, we investigated whether a similar effect could be obtained if the background on which the character was displayed was in motion, rather than the character itself. In this case, there was no evidence of any interaction between the perceived motion and the rate of mental rotation (Experiment 2). In Experiment 3 we replicated these results with a within-subjects design. These results suggested that the locus of the interaction between motion perception and mental rotation was not to be found at an early stage in the visual system. If the interaction occurred at an early stage, we would have expected the vigorous stimulation of motion-sensitive cells created by the rotating background to have caused an interaction with mental rotation.

Experiment 4 provided additional support for our claim that interactions between mental rotation and perceived motion are at a late rather than an early stage of visual information processing. A shape such as a letter or a square can be defined in a number of different surface media: luminance, color, texture, motion, or binocular disparity (Cavanagh, Arguin, & Treisman, 1990; Treisman, 1988). We can change the surface medium without changing the (two-dimensional) message: A square is still a square whether it is defined by color, relative motion, or luminance. Surface features such as color and motion appear to be analyzed independently in the visual system, as is illustrated in Figure 1, possibly in separate

(Allman & Kaas, 1976; van Essen, 1985; van Essen & Maunsell, 1983; Zeki, 1973, 1978) or compartmentalized (Livingstone & Hubel, 1988) regions. In our final experiment, we exploited the functional specialization in the early stages of vision in order to localize and characterize the processes involved in mental rotation.

If mental rotation depends on processes specific to one of these surface media and the pathway that analyzes it, then mental rotation performance for an image defined in that medium should differ qualitatively from mental rotation performance for an image not defined in that medium. For example, if the motion analysis pathway is directly involved in producing a rotation of the mental image, an image that is defined by motion alone may interfere with mental rotation performance. On the other hand, if mental rotation processes are located beyond these independent representations, the nature of the representation should have little or no effect on the performance.

Experiment 1

The subjects in this experiment were asked to perform mirror-normal discriminations on alphanumeric characters presented in various orientations (see Shepard & Cooper, 1982). During their presentation, the characters rotated 10° clockwise or counterclockwise about their centers. If, as expected from Corballis and McLaren's (1982) results, real motion and mental rotation interact somewhere in the visual system, then we would expect character rotations that are in the same direction as the postulated mental rotation to produce faster responses than character rotations that are in the

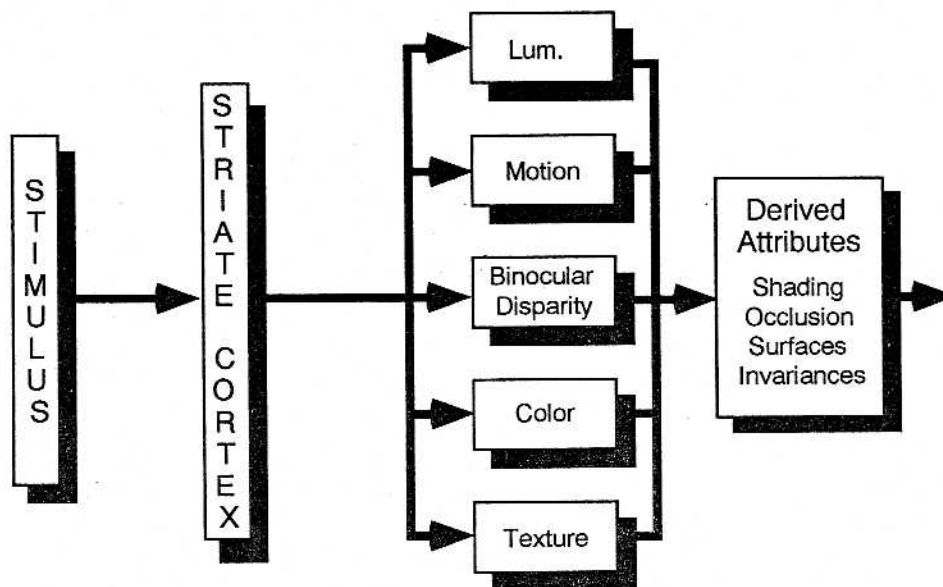


Figure 1. Perceptual pathways in the visual system. (Information from the retina projects [through the lateral geniculate] to the striate cortex, where multifunction cells begin the analysis of orientation, motion, and binocular disparity. Following the striate cortex, information is routed to areas or compartments performing specialized analyses of various attributes. These independent representations may be followed by one or more high-level representations that reintegrate information from all attributes and from which are drawn inferences about shading, occlusion, and surfaces.)

opposite direction from the postulated mental rotation. These predictions are based on a number of assumptions rooted in what we might call the "mental rotation hypothesis." First, it is assumed that during mental rotation a representation of the character passes through states corresponding to the orientations that begin with the depicted orientation of the stimulus and end with the upright character. It is this postulated trajectory in "orientation space" that can be in a direction that is either congruent or incongruent with the direction of perceived rotary motion of the presented character. We call trials in which the directions of rotation are in the same direction "congruent," and we call trials in which the directions of rotation are in opposite directions "incongruent." For example, if a character is shown at 60° of clockwise rotation from upright, the postulated direction of mental rotation is counterclockwise. Thus, a counterclockwise rotation of the character itself would be a congruent direction of rotation, whereas a clockwise rotation of the character would be incongruent.

We made the characters appear to rotate during their presentation by displaying them in two brief flashes at two orientations that differed by 10°. The terminal orientation of the characters was always either 0°, 60°, 120°, 180°, 240°, or 300°. A consequence of our procedure is that the average orientation (that is, the average departure from upright) of the character was greater in congruent trials than in incongruent trials having the same terminal orientation. For example, consider the congruent and incongruent trials with 60° as the terminal orientation. The two presentation orientations in the congruent case were 70° followed by 60°, yielding an average orientation of 65°. In the incongruent case, the orientations were 50° followed by 60°, yielding an average orientation of 55°. Thus, the average orientation of the characters was larger in the congruent than in the incongruent condition. Assuming no effect of the perceived motion of the characters, we would expect incongruent trials to result in faster responses than congruent trials. Note that we are making exactly the opposite prediction if the congruence between real character rotation and mental rotation acts to slow response times in the incongruent condition relative to the congruent condition.

Method

Subjects

The subjects were 12 undergraduates at the University of Waterloo with normal or corrected-to-normal vision who participated in the experiment for pay. No subject participated in more than one experiment reported in the present article.

Stimuli

The characters were the uppercase letters F, G, J, and R and the digits 2 and 7. The characters 5 and P were used in practice trials. These characters were displayed on a color monitor controlled by an Amiga 1000 microcomputer using a simple Hershey font rendered with an algorithm that produced antialiased lines (Field, 1984; Tanner, Jolicoeur, Cowan, Booth, & Fishman, 1989). At an orientation of 0°, the characters were 4° high and 2.6° wide.

Procedure

The task was to decide whether each displayed character was presented in a normal or a mirrored version, as quickly as possible while keeping errors to a minimum. Subjects indicated their responses by pressing one of two response buttons using the index finger of each hand. All subjects indicated "normal" responses with the right hand and "mirror" responses with the left hand.

There were two experimental conditions—congruent and incongruent—depending on the relationship between the direction of the postulated mental rotation and the rotation of the character during its presentation. The character rotations were produced by presenting each character twice in each trial, for 83 ms in each presentation, at two orientations that were 10° apart. For the trial labeled 60° in Figure 2, for example, the two orientations in a congruent trial were 70° and 60° and the orientations in an incongruent trial were 50° and 60°. In the congruent condition, the character rotated in a clockwise direction for characters displayed at 240°, 300°, and 180° (this last designation was arbitrary and was used for ease of coding in the program that generated the randomly ordered trial orders for each subject); the character rotated in a counterclockwise direction for terminal orientations of 60°, 120°, and (arbitrarily) 0°. In the incongruent condition, the character rotated in a clockwise direction for terminal orientations of 60°, 120°, and (arbitrarily) 0°; the character rotated in a counterclockwise direction for 240°, 300°, and (arbitrarily) 180°.

Each trial had the following structure: First, a fixation point appeared at the center of the screen and remained in view for 750 ms. The fixation point was followed by a blank screen for 500 ms. Then the character appeared in the first orientation for 83 ms and was followed immediately by the character in the second orientation for another 83 ms, after which the screen remained blank until the subject pressed one of the two response buttons.

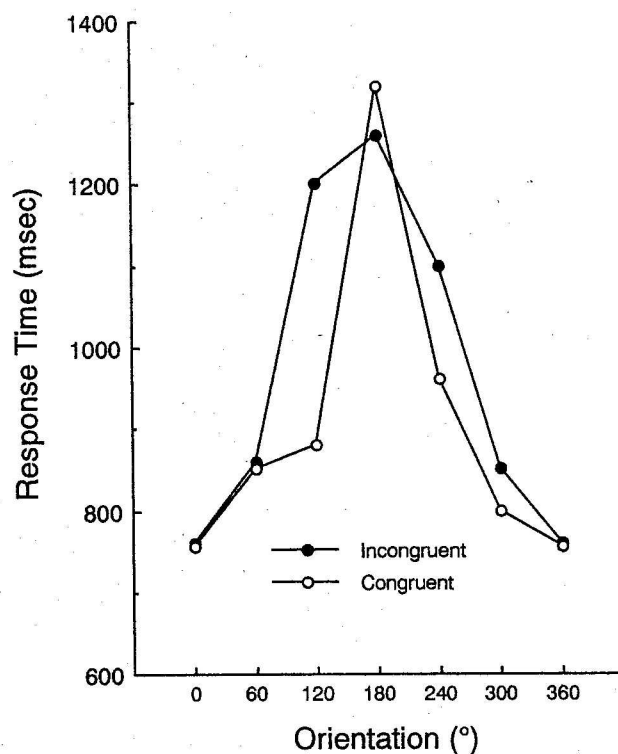


Figure 2. Mean response time in congruent and incongruent conditions as a function of orientation in Experiment 1.

Each subject performed 288 experimental trials defined by the factorial combination of the following variables: version (normal or mirror), character rotation (congruent or incongruent), orientation (terminal, or second, orientation = 0°, 60°, 120°, 180°, 240°, or 300°), and replication (2). The characters (F, G, J, R, 2, or 7) were assigned at random to conditions by the computer. Unbeknownst to the subjects, the trials were arranged into blocks of 24 trials in which each Version × Character Rotation × Orientation combination occurred once. Before performing the experimental trials, each subject completed at least 48 practice trials that used the characters P and 5 (Version × Character Rotation × Orientation × Character). Subjects had to achieve an accuracy level of at least 90% to proceed to the experimental trials. If a subject failed to achieve 90% correct, the practice trials were retaken until the accuracy criterion was met. All subjects met the criterion with one or two sets of practice trials. The viewing distance was held approximately at 64 cm by means of a chin rest.

Results

Response Times

The mean response time for each condition and each orientation was computed for each subject by averaging across characters and responses.¹ These means were submitted to a repeated-measures analysis of variance (ANOVA) in which condition and orientation were within-subjects factors. The mean of these means can be seen in Figure 2.

As expected, we found a strong overall effect of orientation, $F(5, 55) = 30.13, p < .0001$. The congruent condition produced faster response times overall (938 ms) than the incongruent condition (1,009 ms), $F(1, 11) = 7.44, p < .02$. Furthermore, as can be seen in Figure 2, the pattern of results across the different orientations was different for congruent and incongruent trials, $F(5, 55) = 3.58, p < .0071$. These analyses included the results for 0° and 180°, for which the definitions of congruent and incongruent were arbitrary. The definitions were arbitrary at 0° because, at this orientation, we did not expect the representation of the character to be mentally rotated in either direction. Yet we still presented the stimulus with either a clockwise or a counterclockwise rotation. Neither of these directions should be more or less congruent or incongruent than the other, and thus the definitions were arbitrary. Similarly, for trials at 180° the subject could mentally rotate the character in either direction with equal efficiency. Thus, again, neither direction of rotation during the presentation of the character would be expected to be better or worse than the other, and again our original definitions were arbitrary. For these reasons, we also analyzed the data without these two orientations. Our goal in this analysis was to determine whether there was an interaction between congruence and orientation. Additive effects of congruence and orientation would suggest that the effects of congruence were constant across different degrees of mental rotation, perhaps owing to a startup cost difference between the two congruency conditions. In contrast, an interactive pattern of results would suggest that the congruency difference was having an effect throughout the course of the mental rotation.

In this analysis, the results were averaged across equivalent clockwise and counterclockwise orientations (60° and 300°; 120° and 240°). These means were submitted to an ANOVA in which orientation (60° or 120°) and congruence were within-subjects factors. As expected from what can be seen in Figure 2, congruent trials (887 ms) were faster than incongruent trials (1,004 ms), $F(1, 11) = 11.11, p < .007$. Trials with a final orientation $\pm 60^\circ$ from upright (843 ms) were faster than those $\pm 120^\circ$ from upright (1,048 ms), $F(1, 11) = 20.38, p < .0009$. Finally, the effects of incongruence were larger for trials with a terminal orientation of 120° than for those with a terminal orientation of 60°, $F(1, 11) = 5.63, p < .037$. In fact, the time to perform 60° of mental rotation in the incongruent condition was more than double what it was in the congruent condition (286 ms versus 124 ms). These findings suggest that the congruence effect took place throughout the mental rotation rather than simply retarding the onset of the rotation.

Errors

The percent error rate for each subject was computed for each condition and each orientation. These error rates were submitted to the same type of ANOVA used to analyze the response times. The mean percent error rates for all orientations and conditions (averaging over responses and characters) are listed in Table 1.

The only significant effect in the analysis was due to the large overall effect of orientation on the error rates, $F(5, 55) = 3.92, p < .005$ ($p > .37$ in all other cases). The results in Table 1 do not suggest that the response time results were due to speed-accuracy trade-offs.

Discussion

The main results were clear-cut: Incongruent trials resulted in slower response times than congruent trials, as would be expected if a character rotation in the direction opposite to the shortest direction of mental rotation interfered with a subject's ability to perform the mental rotation relative to trials in which the direction of character rotation was in the same direction as the postulated mental rotation. These results converge nicely with those of Corballis and McLaren (1982; Corballis, 1986). One nice feature of our experiment is that it was much easier to carry out than the Corballis and McLaren procedure. Recall that in their procedure, the subject was adapted to the motion of a rotating disk between each mirror-normal discrimination trial. In contrast, our procedure re-

¹ The results were analyzed with response included as a factor for every experiment reported in this article. In these analyses, we found an interaction between response and orientation that is commonly found: Orientation effects were more linear for mirror trials than for normal trials (see Koriat & Norman, 1985). However, response effects were not systematically associated with the effects that are the focus of the present study, namely the congruity of the directions of perceived motion and mental rotation, or the effects of surface media on mental rotation. Therefore, we present the results collapsed across responses.

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

Condition	Orientation					
	0°	60°	120°	180°	240°	300°
Congruent	1.4	2.8	5.2	9.4	3.5	3.5
Incongruent	2.4	3.1	3.8	5.9	5.2	2.8

quired no special adaptation in order to demonstrate the interaction between perceived rotation and mental rotation.

Consider the possibility that the present results reflect an interaction between the motion of the character and the imagined motion in mental rotation. In this view, it would be more difficult to carry out the mental rotation when the character is first seen rotating in the wrong direction than when it is seen rotating in the same direction as the one required to bring the character upright along the shortest rotational path.

We would only entertain this possibility if we could rule out other potential accounts of the results. One such account could be formulated based on the representational momentum phenomenon studied by Freyd, Finke, and their colleagues (e.g., Finke & Freyd, 1985; Finke, Freyd, & Shyi, 1986; Freyd & Finke, 1984, 1985; Freyd & Johnson, 1987; Kelly & Freyd, 1987). The representational momentum phenomenon is a distortion of memory induced by viewing a sequence of views of a shape (or a visual configuration) that suggests a continuous transformation along certain dimensions (such as orientation or location). In our experiment, the two views inducing the perceived rotation could also have distorted (rotated) the subject's memory for the visual pattern. This distortion would be associated with a rotation of the stimulus memory image toward 0° for congruent trials and with shifts toward 180° for incongruent trials, and thus a smaller amount of mental rotation would have been required to bring the representation of the characters to upright for congruent than for incongruent trials.

We believe that our results cannot be explained in this way, however, for two reasons. The first reason is that the magnitude of representational momentum effects on memory is too small to account for the effects we observed, and the second is based on the larger congruency effect found for 120° trials than for 60° trials. We present these arguments in greater detail in the following paragraphs.

In the studies that have examined the representational momentum effect for rotational transformations, the memory distortions have been uniformly small in magnitude, amounting to between 2° and 3° of additional rotation along the implied rotational trajectory. The situation is slightly more complicated, however, by the report of a relation between the implied velocity of rotation and the degree of memory distortion. Fortunately, Freyd and Finke (1985) performed the experiment required to estimate the magnitude of this effect, and their findings suggest that this relationship is well approximated by the following linear function:

$$\Theta = 1.90 + 0.019v,$$

where Θ is the degree of distortion and v is the implied velocity of the presentation sequence (in °/second). Using the Freyd and Finke equation and the rotational velocity in our experiments (120°/s), the magnitude of the memory distortion should be 4.2°. Furthermore, the effect of orientation on response time in our experiment was 2.8 ms/° (using the mean response time difference between 180° and 0° divided by 180°). Therefore, assuming that the representational momentum effect was the same in the clockwise and counterclockwise directions, the predicted effect of character motion on response time should be 24 ms. In contrast, the actual difference between incongruent and congruent trials (averaging across 60° and 120° trials) was 205 ms, almost an order of magnitude larger.

One could argue, however, that the response time estimates at 180° and 0° were affected by the perceived rotation of the characters. In this view, trials at 180° were artificially fast because either the character rotation facilitated mental rotation in that direction or the character rotation biased subjects' memory for the character in a direction closer to 0°. (Note that this bias would be closer to 0° for both directions of rotation.) Similarly, at 0°, the response time estimates may be too long. If so, our estimate of the rate of rotation may be too high. We can address this difficulty by using the results from Experiment 2, in which the biasing manipulation was ineffective (see the *Results* section of Experiment 2). Using these data, the effect of orientation on response time is 3.36 ms/°, yielding a total estimated representational momentum effect of 28 ms. Again, the magnitude of this effect is much too small to account for our findings.

The second argument against an effect of representational momentum in our experiment is that the size of the incongruent-congruent difference was significantly larger at 120° than at 60°. To our knowledge, there is no reason for the magnitude of memory distortion predicted by representational momentum to differ at these two orientations.

One interpretation of the results is that the direction of character rotation induces a tendency in the subject to mentally rotate the character along the longer of the two possible rotation paths to uprightness. This account of the interaction between perceived and imagined rotations was one of several considered by Corballis and McLaren (1982). In Experiment 1 of Corballis (1988), subjects viewed a line, representing a hand on the face of a clock, that rotated through a 30° angular rotation about a clock face in either a clockwise or a counterclockwise direction. One of the tasks was to decide whether the hand would move to the right or to the left as it passed through the location at 6 o'clock. The results suggested that a mental rotation process was used to perform the task. In addition, the results also suggested a shift in the shape of the orientation functions consistent with a tendency to rotate the long way around in the direction of the rotation of the clock hand. Our present results do not allow us to rule out this possibility.

Experiment 2

The subjects in this experiment were asked to perform mirror-normal discriminations on alphanumeric characters

shown at six orientations (0°, 60°, 120°, 180°, 240°, and 300°) while the characters were displayed on a background that was rotating either clockwise or counterclockwise. If perceived motion and mental rotation interact at a relatively low level in the visual system, then superimposing a target character (for mental rotation) on a moving background should also produce the type of effect that we observed in Experiment 1. This expectation is based on the notion that the moving background should provide vigorous stimulation of motion-sensitive cells at a relatively low level in the visual system (Hubel & Wiesel, 1962, 1968). And, if the interactions between mental rotation and perceived motion take place early on, the stimulus conditions in the present experiment should produce the same sort of interactions that we observed in Experiment 1.

Method

Subjects

The subjects were 12 undergraduates at the University of Waterloo with normal or corrected-to-normal vision who participated in the experiment for pay.

Stimuli

Characters. The characters were the same as in Experiment 1. These characters were displayed on a color monitor controlled by an Amiga 1000 microcomputer using a simple Hershey font rendered with a standard line-drawing algorithm in which the lines were 2 pixels wide. The characters were displayed at full intensity for 6 subjects and at Intensity 5 (on the 0–15 Amiga intensity scale) for another 6 subjects. The characters were shown at six orientations (0°, 60°, 120°, 180°, 240°, and 300° of clockwise rotation from upright) in either a normal or a left–right mirror-imaged version. When a character was displayed, it was superimposed on a moving background, described in the next paragraph. The background moved “under” the character and in a large region surrounding it. The visual angle subtended by the characters was the same as in Experiment 1. The visual angle of the moving background was $9.8^\circ \times 9.8^\circ$.

Background. The background was a disk with a radius of 200 pixels (on the 400×640 Amiga screen). This disk was divided into 54 underlying wedges of equal size running from the center of the disk to the perimeter. The wedges were “painted” such that there were 18 visible wedges—9 of the wedges were black and they alternated with the other 9, which were grey (Intensity 5 on the 0–15 Amiga scale). Thus, each of the visible wedges was composed of three underlying wedges. This allowed us to produce an impression of smooth rotary motion by shifting the visible wedges in increments of one third of the wedge width. The wedged disk was set to rotate $360^\circ/\text{s}$. This speed of rotation was chosen because it approached the apparent speed of mental rotation (approximately $400^\circ/\text{s}$)—faster rotation speeds tended to degrade the impression of smooth motion (as judged informally by people in the laboratory).

Procedure

The task was to decide whether each displayed character was presented in a normal or a mirrored version, as quickly as possible while keeping errors to a minimum. Subjects indicated their responses

by pressing one of two response buttons using the index finger of each hand. All subjects indicated “normal” responses with the right hand and “mirror” responses with the left hand.

There were three experimental conditions—congruent, incongruent, and neutral—depending on the relationship between the direction of the postulated mental rotation and the motion of the background disk on which the character was displayed. In the congruent condition, the disk rotated in a clockwise direction for characters displayed at 240° and 300° and also for characters shown at 0° (this last designation was arbitrary, as in Experiment 1); and the disk rotated in a counterclockwise direction for characters at 60° and 120° and also (arbitrarily) for characters at 180°. In the incongruent condition, the disk rotated in a clockwise direction for characters at 60° and 120° and (arbitrarily) for characters at 180°; the disk rotated in a counterclockwise direction for characters at 240° and 300° and (arbitrarily) for characters at 0°. In the neutral condition, the background oscillated between clockwise and counterclockwise motion. Each oscillation was associated with a 40° rotation of the wedges in the disk, and the neutral condition was the same for all orientations of the characters.

Each trial had the following structure: First, the wedged disk appeared by itself, without any character in the display, with a clockwise or counterclockwise rotary motion, or with an oscillatory motion. This part of the trial lasted 833 ms. Second, the character appeared superimposed on the moving background and remained in view (with the background undergoing continuing motion) until the subject made a response. The entire display was terminated as soon as the subject responded. The response time was measured starting from the onset of the character to the subject’s button press, to the nearest 60th of a second. The intertrial interval was 2 s. A complete experimental session, including practice trials, took about 40 min.

Each subject performed 216 experimental trials defined by the factorial combination of the following factors: version (normal or mirror), background (congruent, incongruent, or neutral), orientation (0°, 60°, 120°, 180°, 240°, or 300°), and character (F, G, J, R, 2, or 7). Unbeknownst to the subjects, the trials were arranged into blocks of 36 trials in which each Version \times Background \times Orientation combination occurred once and in which each character appeared six times. Before performing the experimental trials, each subject completed at least 48 practice trials that were a random subset of the factorial combinations of version, orientation, character (P or 5), and background (3). Subjects had to achieve an accuracy level of at least 90% to proceed to the experimental trials. If a subject failed to achieve 90% correct, the practice trials were retaken until the accuracy criterion was met. All subjects met the criterion with one or two sets of practice trials. The viewing distance was kept to approximately 93 cm by means of a chin rest.

Results

Six subjects were tested with the character displayed at full intensity and the background disk at a lower intensity. After a preliminary analysis we found no effects of background condition on the effects of character orientation on response times. We reasoned that the null effect could be due to the large difference in intensities of the stimuli if subjects could ignore the less intense rotating background. To investigate this possibility, we tested another 6 subjects with the character shown at the same intensity as the background disk (Intensity 5 on the 0–15 Amiga intensity scale). The analyses revealed no significant differences between the two groups of 6 subjects. For this reason, we present the results of all 12 subjects without regard to group membership.

Reaction Times

The mean reaction times for the 3 conditions and 6 orientations were computed for each subject by averaging across characters and responses. These means were submitted to a repeated-measures ANOVA in which condition and orientation were within-subjects factors. The mean of these means can be seen in Figure 3.

As expected, we found a strong overall effect of orientation, $F(5, 55) = 39.57, p < .0001$. However, there was no interaction between orientation and condition ($F < 1$). There were no overall differences between conditions ($F < 1$). This analysis included the results from trials with a character shown at 0° and 180°, for which the designation of congruent and incongruent rotations was arbitrary. To avoid a possible dilution of subtle effects, we also analyzed the results from trials in which the character was shown at 60°, 120°, 240°, and 300° in a separate ANOVA, as in Experiment 1. In addition, this analysis considered only the two conditions that, on a priori grounds, we would expect to have the largest differences—namely, the congruent and incongruent conditions. This analysis corroborated the analysis in which all orientations were included: There was no hint of an interaction between orientation and condition ($F < 1$).

Errors

The percent error rate for each subject was computed for each condition and each orientation. These error rates were submitted to the same type of ANOVA used to analyze the response times. The mean percent error rates for all orientations and conditions (averaging over responses and characters) are listed in Table 2.

The only significant effect in the analysis was the large overall effect of orientation on the error rates, $F(5, 55) = 9.24, p < .0001$ ($p > .21$ in all other cases). As for the analysis of response times, we also examined the results from characters shown at 60°, 120°, 240°, and 300° in a separate ANOVA. This analysis also failed to show any interaction between character orientation and background type ($F < 1$ in all cases). The results in Table 2 do not suggest that the failure to observe significant interactions between conditions and orientations in the analysis of response times might have been due to speed-accuracy trade-offs.

Discussion

The main results were clear-cut: There was no indication that the direction of rotation of the background either helped or hindered the mental rotation of the target character. These results were surprising to us and contrast sharply with those obtained in Experiment 1 and with those reported by Corballis and McLaren (1982; Corballis, 1986). It appears that the character itself must be perceived to be in motion in order to produce an interaction between motion and the rate of mental rotation. This, in turn, suggests that the level in the visual system at which mental rotation and perceived motion interact is probably relatively late. If the interactions were at an early stage, one would expect a background rotating through

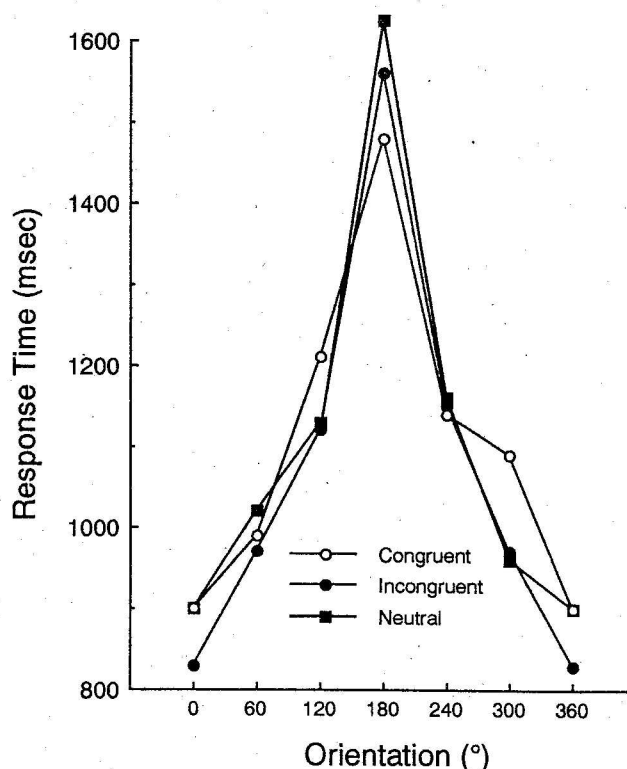


Figure 3. Mean response time in congruent, incongruent, and neutral conditions as a function of orientation in Experiment 2.

the character and immediately surrounding it to have revealed the interaction, given that this background provided vigorous stimulation of motion-sensitive cells with receptive fields serving the same location as the target character.

One alternative interpretation of the results of Experiment 2 is that the background motion could have induced a perceived rotation of the character in the direction opposite that of the rotating background and that these two perceived motions had opposite and equal effects in the interaction with mental rotation. The net result would be the null effects of background rotation on the measured rate of mental rotation in congruent and incongruent trials. We find this account unlikely for the following reason: Although it was possible occasionally to see the character rotate in the direction opposite that of the rotating background, this induced rotation tended to be relatively weak compared with the vivid perception of motion created by the moving background. Given the difference in the strength of the perceived rotations (the weak induced rotation of the character and the vivid rotation of the

Table 2
Mean Error Rates (%) for Conditions and Orientations in Experiment 2

Condition	Orientation					
	0°	60°	120°	180°	240°	300°
Congruent	4.2	3.5	4.9	13.9	9.7	1.4
Incongruent	7.6	4.2	1.4	12.5	9.0	2.8
Neutral	6.2	4.2	4.9	20.8	8.3	1.4

background), we doubt that the two effects could cancel each other out so exactly as to leave no net effect.

Experiment 3

The results of Experiments 1 and 2 suggested the hypothesis that the interaction between perceived motion and mental rotation occurs when the character is perceived to rotate but not when a character is displayed on a rotating background. The purpose of Experiment 3 was to provide a better controlled test of this hypothesis in a within-subjects design.

We refined the procedures used in Experiments 1 and 2 in a number of ways. First, we equated the exposure duration of the target character across the two principal conditions (rotating character or rotating background). It is possible that the effects of perceived rotation could have been larger in Experiment 1 (rotating character) than in Experiment 2 (rotating background) because the character was exposed briefly in Experiment 1 but left on the screen until the subject's response in Experiment 2. In Experiment 3 we exposed the target character briefly (166.7 ms) in both conditions. Second, we added a neutral control condition for the rotating character condition. Third, we changed the neutral condition for the rotating background condition from the oscillating motion used in Experiment 2 to a stationary background. Fourth, the character was exposed five times in the rotating character condition, with a $2\frac{1}{2}^\circ$ change in orientation from exposure to exposure, in order to improve the appearance of the motion. Finally, we adjusted the size of the displays so that the visual angle of the target character was the same across the two conditions from a viewing distance of 93 cm.

Method

Subjects

The subjects were 12 undergraduates at the University of Waterloo with normal or corrected-to-normal vision who participated in the experiment for pay.

Stimuli and Procedure

The basic task was the same as in Experiments 1 and 2. The trials were blocked by condition (rotating character or rotating background). The order of blocks was counterbalanced across subjects, with half of the subjects receiving each order. There were 216 experimental trials in each block, representing the factorial combination of the two versions of the characters (normal or mirror), the orientation of the characters (0° , 60° , 120° , 180° , 240° , or 300°), the congruency condition (congruent, neutral, or incongruent), and the six characters (F, G, J, R, 2, or 7). The trials were ordered as in Experiment 2. Each block was preceded by 36 practice trials that were a random subset of the 72 trials resulting from the factorial combination of the two versions of the characters, orientation, congruency condition, and the two practice characters (P and 5). The practice trials were repeated if the subject made more than five errors. No subject required more than two blocks of practice trials in order to achieve this level of accuracy. In addition, half of the subjects receiving each order of blocks responded "normal" with the dominant hand and "mirror" with the nondominant hand. The other half of

the subjects had the opposite hand-response assignment. A chin rest helped maintain a viewing distance of approximately 93 cm in both blocks of trials.

Rotating character. The characters were displayed using anti-aliased lines at a size that matched the visual angle used in Experiment 1 when viewed from a distance of 93 cm. The characters were displayed in five exposures of 33.3 ms, so that the total exposure duration was 166.7 ms. The orientation of the character changed by $2\frac{1}{2}^\circ$ with each new exposure in the congruent and the incongruent conditions. The initial and final orientations were the same as in the congruent and incongruent conditions in Experiment 1. In the neutral condition, the character was displayed for 166.7 ms at 0° , 60° , 120° , 180° , 240° , or 300° .

Rotating background. The displays were identical to those used in Experiment 2 except for those in the neutral condition, for which the background disk was stationary. The intensity was 12 for the characters and 8 for the background wedges (on the Amiga 0-15 intensity scale).

Results

Response Times

The mean response time for each condition and each orientation was computed for each subject by averaging across characters and responses. These means were submitted to a repeated-measures ANOVA in which condition and orientation were within-subjects factors and the order of blocks was a between-subjects factor. The mean of these means can be seen in Figure 4.

The most important results are those involving the motion conditions (rotating character vs. rotating background) and the congruency of the motion with respect to the direction of the postulated mental rotation. The effects of congruency depended on the motion condition, $F(2, 20) = 11.44$, $p < .0005$; furthermore, this interaction depended on the orientation of the characters, which produced a three-way interaction between the motion conditions (rotating character vs. rotating background), the congruency of the motion, and orientation, $F(10, 100) = 2.28$, $p < .02$. This latter interaction was the most complex significant interaction in the analysis. All of the other significant effects resulted from collapsing across the various factors in this three-way interaction. There were large differences across the congruency conditions, $F(2, 20) = 16.45$, $p < .0001$. As expected, we found strong overall effects of orientation, $F(5, 50) = 54.61$, $p < .0001$, which depended on the congruency between the direction of perceived motion and the direction of the postulated mental rotation, $F(10, 100) = 5.32$, $p < .0001$. The effects of orientation also depended on the type of motion (rotating character vs. rotating background), $F(5, 50) = 2.62$, $p < .036$.

As can be seen in Figure 4, the results for the three levels of congruency in the rotating character condition were ordered as one might expect if the incongruent rotation slowed processing and if the congruent rotation sped up processing relative to the neutral condition. This pattern was not found in the rotating background condition, for which the mean response times in the neutral condition were longer than in the congruent or the incongruent condition, with the latter two conditions producing similar results.

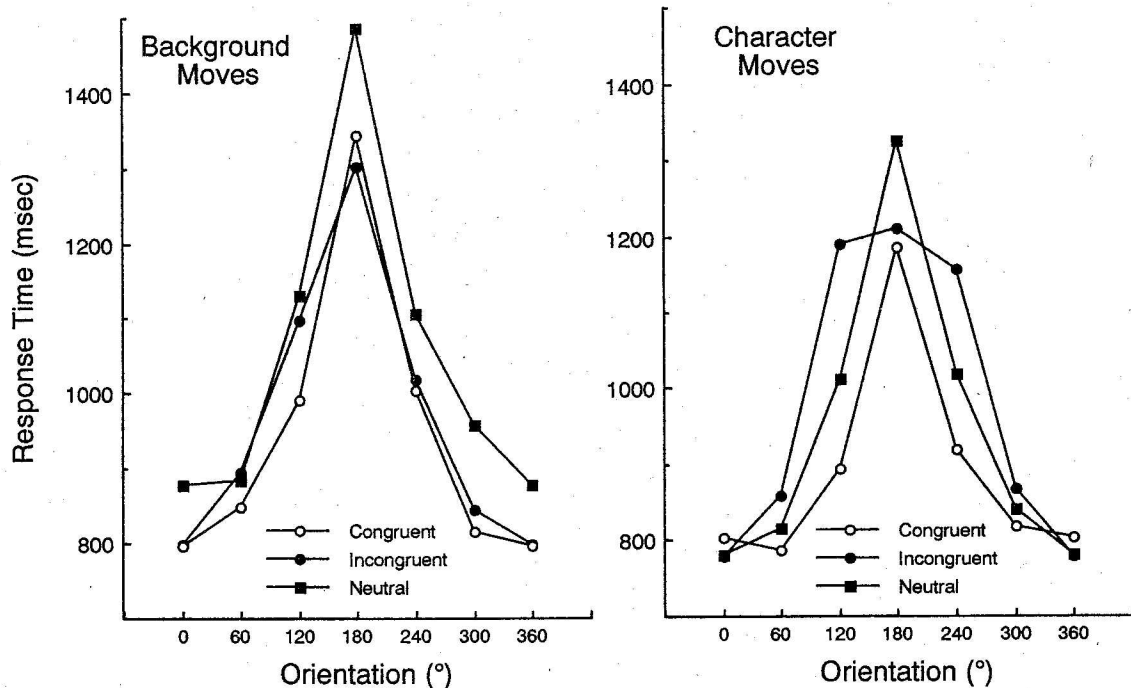


Figure 4. Mean response time in congruent, incongruent, and neutral conditions as a function of orientation for the rotating background and rotating character conditions in Experiment 3.

We also examined the results in terms of the factor used to code for the order in which the two motion conditions were seen by the subjects. Other than an effect that appears to be due to simple speedup with practice, there were no significant effects involving the order of blocks. The mean response time for the group performing the mental rotation task with the rotating background first and the rotating character second was 999 ms for the rotating background condition and 817 ms for the rotating character condition. The mean response time for the group performing the mental rotation task with the rotating character first and the rotating background second was 1,022 ms for the rotating background condition and 1,100 ms for the rotating character condition. This pattern produced a two-way interaction between block order and motion type, $F(1, 10) = 22.11, p < .0009$. There were no other significant effects.

These analyses included the results for 0° and for 180°. As in Experiments 1 and 2, the definition of congruent and incongruent for these orientations was arbitrary. We also analyzed the results for just those orientations for which our definitions of congruent and incongruent motions were meaningful. As before, we averaged across equivalent clockwise and counterclockwise orientations (60° and 300°; 120° and 240°). These means were submitted to an ANOVA of the same type as that just reported but in which orientation had only two levels (60° or 120°). The results from this analysis mirrored the pattern of results presented in the first analysis. The most complex significant interaction was that involving the type of motion, congruency, and orientation, $F(2, 20) = 8.32, p < .003$. The other interesting significant effects resulted from collapsing across various dimensions in this three-way

interaction. All three possible two-way interactions were significant, as were two of the main effects (congruency and orientation), $p < .015$ in every case. There were no other significant effects.

We also analyzed the results excluding the neutral condition in order to compare the magnitude of the incongruent-congruent difference across the two motion-type conditions. This difference was significantly larger in the rotating character condition than in the rotating background condition, $F(1, 10) = 12.74, p < .0051$. Furthermore, the three-way interaction between orientation, motion type, and congruency was highly significant, $F(1, 10) = 22.42, p < .0008$. As can be seen in Figure 4, this pattern resulted from an additive pattern of results between orientation and congruency in the rotating background condition in contrast to an overadditive pattern for the rotating character condition. We confirmed this interpretation of the three-way interaction by performing separate analyses on the data for each motion type. In the rotating background condition the difference between incongruent and congruent trials only approached statistical significance, $F(1, 10) = 3.98, p < .075$, and did not interact with orientation, $F < 1$. In contrast, in the rotating character condition the difference between incongruent and congruent trials was highly statistically significant, $F(1, 10) = 40.32, p < .0001$, and the effect was larger at 120° than at 60°, $F(1, 10) = 17.54, p < .002$.

Errors

The percent error rate for each subject was computed for each condition and each orientation. These error rates were

submitted to the same type of ANOVA used to analyze the response times. The mean percent error rates for each orientation, each congruency condition, and each motion condition are listed in Table 3. There were more errors as the target character was rotated further from upright, $F(5, 50) = 13.48$, $p < .0001$. The effects of congruency of motion on error rates depended on the type of motion, $F(2, 20) = 5.52$, $p < .015$. These were the only two significant effects in the ANOVA. As can be inferred from the means listed in Table 3, the error rates mirrored the pattern of results found in the response times, which suggests that the response time results were not contaminated by speed-accuracy trade-offs.

Discussion

Overall, the results replicated and extended the different patterns of results that we observed across Experiments 1 and 2 in a within-subjects design. The results for the three levels of congruency in the rotating character condition were ordered as one might expect if the incongruent rotation slowed processing and if the congruent rotation sped up processing relative to the neutral condition. In Experiment 1, because there was no neutral condition, it was not possible to determine whether both directions of motion (congruent and incongruent) had an effect on the time to perform the normal-mirror task. The present results suggest that there is both facilitation and inhibition associated with motion of the target character. At 180° the mean for the neutral condition was greater than those for the other two conditions, and they in turn converged to a similar value. This pattern of results is what we would expect if rotating the character either clockwise or counterclockwise toward 180° facilitated mental rotation from this orientation. Corballis and McLaren (reported in Corballis, 1986) found a similar pattern of results, except that there was no evidence for facilitation relative to the neutral condition at $\pm 60^\circ$ and $\pm 120^\circ$, only inhibition. Their results in the $\pm 60^\circ$ to $\pm 120^\circ$ range had the same overadditive effect of congruency that we found in the present experiment and in Experiment 1.

In contrast, the results in the rotating background condition were different in a number of ways from those in the rotating character condition. The difference between congruent and incongruent trials was significantly smaller in the rotating

background condition than in the rotating character condition. In fact, the difference was not significant in the rotating background condition. Furthermore, there was no interaction between orientation and congruency, which appears to be a hallmark of the congruency effect (see Corballis, 1986; Corballis & McLaren, 1982). Also, the mean response times were longer in the neutral condition than in either the congruent or the incongruent conditions, which is quite unlike what we found for the neutral condition in the rotating character condition. We suspect that the static background disk in the neutral condition for the "rotating" background condition may have slowed the encoding of the character by a constant amount. The results are consistent with this hypothesis in that the effects of orientation and congruency were additive in the rotating background condition.

Experiment 4

In this experiment, we attempted to determine the level of the visual system at which mental rotation occurs, and we made a further test of the possibility that the process of mental rotation involves the low-level motion analysis centers of the visual cortex. Similar attempts to localize visual processes have been successful in the past using a criterion of binocularity. For example, binocular cells do not appear in the visual system until the first area of the visual cortex, and visual tasks that transfer interocularly (e.g., the "tilt aftereffect," see Gibson, 1933; Movshon, Chambers, & Blakemore, 1972) must therefore involve visual areas at or beyond the striate cortex. Similarly, Julesz (1971) demonstrated several visual tasks that can be performed on "cyclopean" images, images presented as random dot stereograms such that no image is visible monocularly. These processes are necessarily located at or beyond the striate cortex.

Behavioral and physiological studies suggest the existence of independent pathways specialized for the analysis of different surface media. Each of these pathways performs some specialized analysis of its particular medium, but each should also be capable of representing two-dimensional shape. Stimuli that selectively activate one of these visual pathways can be produced by defining images by variations in a single medium—for example, color, relative motion, luminance, texture, or binocular disparity—as shown in Figure 5. With these images, we can test the ability to encode shape within these media and study the recovery of scene properties from the two-dimensional image so defined. Julesz (1971), for example, showed that we can perceive shape defined only by binocular disparity in random-dot stereograms. Recent studies by Cavanagh (1987, 1988, 1989) have made similar demonstrations for images defined by color, relative motion, and texture.

If mental rotation depends on processes specific to one of these specialized pathways, then mental rotation performance will vary as a function of the surface medium in which the test characters are presented. For example, if the motion pathway is directly involved in producing a rotation of the mental image, an image that is defined by motion alone may interfere with mental rotation performance. On the other hand, if mental rotation processes are located beyond these

Table 3
Mean Error Rates (%) for Conditions and Orientations in Experiment 3

Motion condition	Orientation					
	0°	60°	120°	180°	240°	300°
Rotating character condition						
Congruent	5.6	6.9	5.6	19.4	8.3	5.6
Neutral	2.8	4.9	4.9	13.9	5.6	2.8
Incongruent	2.1	2.8	5.6	16.0	9.0	2.8
Rotating background condition						
Congruent	2.1	3.5	5.6	9.0	4.2	5.6
Neutral	2.1	3.5	4.9	18.1	5.6	4.1
Incongruent	4.9	4.9	5.0	11.8	10.4	2.8

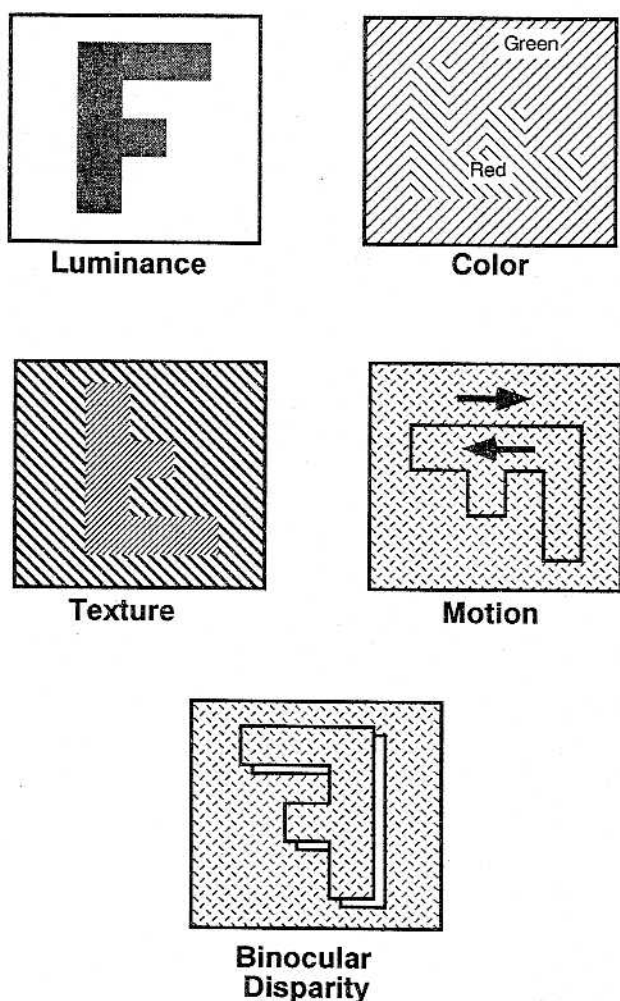


Figure 5. Individual perceptual pathways can be isolated by presenting stimuli that are defined by variations of a single stimulus attribute.

independent pathways, the nature of the representation should have little or no effect on such performance. To test these possibilities, we used a mental rotation task involving stimuli defined in each of five different media: luminance, color, relative motion, texture, or binocular disparity.

Method

Subjects

Ten subjects (5 men and 5 women) from the Psychology Department of the Université de Montréal participated in the experiment. The average age was 28 years (range = 21–39 years). Subjects were screened for color vision and perception of depth from binocular disparity, and all had normal or corrected vision.

Stimuli

The test stimuli were the six characters F, G, J, R, 2, and 7 presented on a computer-controlled monitor. The characters were

presented one at a time in the Helvetica Bold font at the center of the display. They subtended $4^\circ \times 2^\circ$ of visual angle (height \times width), and the entire display subtended $10^\circ \times 10^\circ$ of visual angle. When the test character was not on the screen, a 0.5° fixation bull's-eye was present at the center of the screen. The stimuli were presented in one of four orientations (0° , 90° , 180° , or 270°) and in either a normal version or a mirror-image version (a 180° rotation about the y axis of the normal vertical version). Depending on the condition, either or both the background and the character shapes were filled with a random dot texture; individual texture elements were 0.04° square, were 50% light and 50% dark, and had a Michelson contrast between the light and dark elements of 75%. The mean luminance of the background was 26 cd/m^2 . The texture was black and white except in the color condition. In the luminance condition, random texture filled both background and character, and the mean luminance of the character area was darker than that of the background, the Michelson contrast between the two mean luminances being 30%. In the color condition, the random dot texture was light and dark red in the background area and light and dark green in the character area. The mean luminance of the green character areas was set to a predetermined equiluminance point (described in the next paragraph). In the texture condition, the background was a uniform gray, and the character area was filled with black and white random texture of the same mean luminance as the uniform area. In the motion condition, the random dot background moved leftward at $1.4^\circ/\text{s}$, and the identical texture in the character area remained stationary. In the stereo condition, a random dot stereogram was presented with a 0.095° crossed disparity between the cyan and red random dots filling the character area and a 0.0° disparity between the cyan and red random dots filling the background area. The two areas had equal mean luminance. The image was viewed through red/cyan stereo glasses to separate the left and right eye images, which when fused appeared black and white with the character floating in front of the background.

Procedure

Equiluminance. Before starting the experiment, we established an equiluminance setting for each subject individually. The subjects were shown a subjective contour figure (Bradley & Petry, 1977) with random red texture as the background and random green texture filling the components of the inducing figure. The textures were produced as described previously. With his or her head in a chin rest, the subject viewed the display monocularly with the dominant eye and adjusted the relative luminance of the two areas until the subjective contour disappeared or reached a minimum strength. This adjustment was performed four times, and the average value was used to set the equiluminance of the color condition in the main experiment. The subjective contour reaches a minimum strength at equiluminance (Brussell, Stober, & Bodinger, 1977; Shioiri & Cavanagh, 1991). We also verified that characters defined by a luminance difference (as in the luminance condition) were not visible until the contrast between the mean luminance of the background and that of the character area reached about 10%. This high threshold was due to the presence of the 75% contrast random dot texture and ensured that even if the luminances of the red and green were not exactly matched in the color condition, the stimuli would be visible only because of the color difference and not because of any residual luminance difference.

Experimental conditions. The task was to determine whether the test stimulus was presented in a normal or a mirror-image version. The stimulus could be presented in any of four orientations. Using their right hands, subjects tilted a lever to the right if the test was a normal version and to the left if it was a mirror-image version. The subjects were asked to respond quickly while avoiding errors. The

five stimulus conditions—luminance, color, texture, motion, and stereo—were each presented as a separate session of 96 trials (eight combinations of four orientations and two versions, repeated 12 times each in a completely randomized order). Each trial started when the subject tilted the response lever. After a 250-ms delay, a warning tone sounded and was followed 500 ms later with the presentation of the test stimulus, which remained on the screen until the subject responded. A double tone sounded when the subject made an error. The subjects were requested to fixate the central bull's-eye before and after the presentation of the test. The subjects were first familiarized with the stimuli (defined by luminance) in the different orientations and in the normal and mirror-image versions, and then they proceeded to a practice session of 96 trials (with stimuli defined by luminance). If a subject made more than 12 errors, another practice session was presented. If after three practice sessions a subject still made more than 12 errors, he or she was replaced (1 subject was replaced). The five experimental conditions were then presented in a random order. Each session took about 10 min, and between each session, the subject took a 5-min break. Any session with more than 12 errors was repeated (three sessions were repeated in all). A chin rest was used, and viewing was binocular for all conditions except the color condition, where the display was viewed only with the dominant eye to avoid stereoscopy (Vos, 1960). Stereo glasses were used to view the three-dimensional anaglyphs in the stereo condition.

Results

Response Times

The means of the correct responses, averaged across characters and versions, were submitted to a repeated-measures ANOVA that included medium and orientation as within-subjects factors. The mean response times, averaged across characters, versions, and subjects, are shown in Figure 6 as a function of medium and orientation. Although there were slight overall differences in reaction time between the different media, $F(4, 36) = 3.25, p < .025$, there was no interaction of medium with orientation, $F(12, 108) = 1.22, p > .27$. As expected, there was a large and highly significant overall effect of orientation, $F(3, 27) = 48.14, p < .0001$. Table 4 lists the estimated rate of mental rotation (in $^{\circ}$ /second) for each surface medium. These rates were estimated by fitting a regression line to the group mean response times, with 270° coded as a 90° .

Error Rates

The error rates, shown in Table 5, generally followed the same pattern as the reaction times, indicating that a speed-accuracy trade-off was not a significant determinant of the observed reaction time performance.

Discussion

The results provided no indication of differential processing for the various surface media. The most straightforward explanation of these results is that the processes involved in mental rotation are located beyond the stage of functional specialization defined by the media under investigation. These processes appear to access all representations of letter shape equally well. It may be that there is a high-level representation

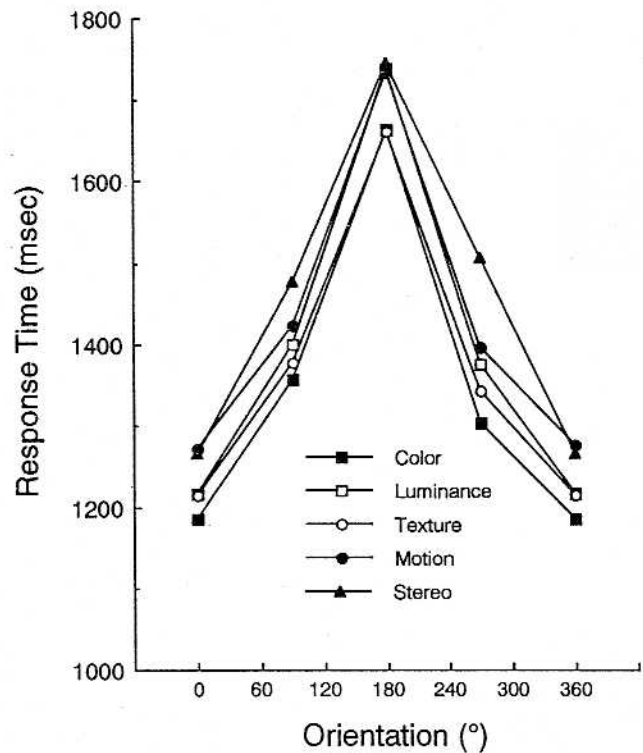


Figure 6. Mean response time for each surface medium and orientation in Experiment 4.

that integrates the shape information of the separate pathways, as suggested by Treisman (1986), and that mental rotation processes operate on this representation. However, a final common representation is not necessary if we consider that the processes involved may simply access all lower level representations equally well.

Because our data imply similar processing of shape information, no matter how it is defined, we could also suggest that the mental rotation processes operate on an earlier, common representation, such as that in the striate cortex which precedes the specialized analyses. This does not seem likely, however. Activity at the level of the striate cortex typically produces conscious visual sensations. Direct stimulation of the striate cortex in alert humans generates visible flashes, for example (Penfield & Rasmussen, 1952), and these have even been used as the basis of visual prostheses for the blind (Brindley & Lewin, 1968). If mental rotation processes actually manipulated images at the level of the striate cortex,

Table 4
Mental Rotation Rate as a Function of Surface Medium in Experiment 4

Medium	Rotation rate ($^{\circ}$ /second)
Color	375
Luminance	345
Texture	403
Motion	388
Stereopsis	375

Table 5
Error Rates (%) as a Function of Surface Medium and Test Letter Orientation in Experiment 4

Medium	Orientation			
	0°	90°	180°	270°
Color	3.7	4.6	10.9	2.1
Luminance	4.1	4.2	13.3	4.6
Texture	3.7	5.4	13.7	3.3
Motion	4.5	5.0	11.7	5.5
Stereopsis	3.7	3.7	12.1	6.3

subjects should report visible changes in the stimulus. Subjects do not report any changes, so we feel it is unlikely that mental rotation processes operate at the level of the striate cortex. The common representation indicated by our results should therefore lie beyond the level of specialized cortical representations. More to the point, however, our results show that the motion pathway (or at least that part of it involved in the representation of stimuli defined only by relative motion) plays no special role in effecting transforms of mental images. The results of Experiment 2, in which real background motion did not interact with mental rotation performance, also converge on this conclusion.

General Discussion

The results of Experiment 1 and those of Corballis and McLaren (1982; Corballis, 1986) converge in suggesting that perceived motion and imagined motion in mental rotation tasks can interact significantly. These results are intriguing because they suggest that the mental activity performed during mental rotation may be linked to the perception of physical or real motion, as proposed by Shepard and others (e.g., Shepard, 1981; Shepard & Cooper, 1982). In their view, mental rotation may have evolved as an ability in humans (and possibly in other mammals) from an advantage conferred to organisms that were able to predict the position and orientation of (mainly) rigid objects in real three-dimensional space. The interactions discovered here and by Corballis and McLaren (1982) raise some interesting issues regarding the nature of the mental representation of shapes during mental rotation and of "real" motion during perception.

The present study contributes techniques for the study of these issues and some new results. First, in Experiments 1 and 3 we replicated the interaction discovered by Corballis and McLaren (1982) within a more tractable procedure. Their procedure required that the subject be readapted to a rotary motion stimulus between each trial of the mental rotation task. In contrast, our procedure simply displayed each character briefly in two or more orientations, such that the character appeared to rotate in one direction or the other. In comparing Experiments 1 and 2, we hypothesized that the motion of the character was the critical factor in provoking an interaction between perceived rotation and mental rotation, a finding that we replicated in Experiment 3. The perception of rotary motion (Experiments 2 and 3) or translation motion (Experiment 4) of the background concurrent with mental rotation appears to leave mental rotation processes unaffected. In the experiment of Corballis and McLaren

(1982), the motion aftereffect made the entire adapted area, character and background, appear to rotate, and so the relative importance of figure and ground motion could not be determined.

Our experiments provide some preliminary evidence concerning the location in the visual system of the interaction between perceived motion and mental rotation. Our argument is as follows: If the mental rotation operation takes place at a relatively low level in the visual system, then performing a mental rotation while simultaneously stimulating congruent or incongruent motion-sensitive cells should give rise to an interaction (as tested in Experiments 2 and 3), or it should produce some general increase in the amount of time required to perform the task (as tested in Experiment 4). This approach is similar to that adopted by others who have studied the potential interactions between perception and imagery (e.g., Finke, 1980). We found no influence of rotations of the background on mental rotation. This suggests that the specific motion congruence effects found in Experiments 1 and 3, and by Corballis and McLaren (1982; Corballis, 1986), are not due to interactions at early levels in the visual system. Experiment 4 demonstrated that mental rotation was just as efficient regardless of the surface medium used to present the character. In particular, we found no evidence of a general interference effect on mental rotation when the characters were created by stimulating motion-sensitive cells. Both approaches suggest that the motion-mental-rotation interaction found when the character itself appears to rotate occurs at a relatively abstract level of processing.

Corballis (1986) summarized his results as follows:

But whatever the mechanism, perceived and imagined rotation clearly do interact. This further substantiates the idea that perception and imagery share a common representational space, and lends further credence to the notion that there is a truly rotational element underlying mental rotation. (p. 161)

If this claim is correct, our new results suggest that this shared representational space must be relatively abstract. One possibility suggested by Corballis and McLaren (1982) is that the interaction between perceived and imagined rotation could result from a bias in the selection of the rotation path selected in the mental rotation process (see also Corballis, 1988). For example, in an incongruent trial with the character shown at 120°, the clockwise rotation of the character could increase the probability of rotating the character the long way around, rather than through the shortest rotational path. Our present data do not allow us to exclude this possibility; however, it may be possible to examine this issue in the future by designing experiments that would allow one to inspect the response time distributions in more detail.

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