What is Rotated in Mental Rotation?

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Two hypotheses regarding mental rotation were contrasted. If subjects rotate each stimulus image to the upright (the image rotation hypothesis), then response time should depend solely on the extent of angular deviation from the upright. But if subjects rotate their frame of reference to match that of the disoriented stimulus (the frame rotation hypothesis), then response time should vary with the angular deviation between the current stimulus and the preceding stimulus. In four experiments, one involving normal and reflected letters (Experiment 1) and the other three involving lexical decisions on Hebrew letter strings (Experiments 2, 3A, and 3B), much stronger evidence for the image rotation hypothesis was found, though weak but systematic effects of frame rotation were also obtained. Increased likelihood that the same orientation would be repeated (Experiment 4) did not yield any stronger frame rotation effects. Also there was no indication of consistent individual differences in the preference for the frame rotation strategy (Experiment 3B). Additional findings pertinent to the application of the mental rotation paradigm to word recognition were discussed.

One experimental paradigm that has generated a great deal of interest is the mental rotation task, originally introduced by Shepard and Metzler (1971). An impressive and consistent finding has been the monotonic relationship between response time and the extent of angular disorientation. This finding has been interpreted by many authors as reflecting the existence of analog processes in cognition where a disoriented stimulus is mentally rotated before it is compared with an internal memorial representation (see Shepard & Cooper, 1982).

The present study deals with the question of what is rotated in a mental rotation task. Consider the following example: Assume that you find a newspaper on your desk, but the main headline (top) is nearest to you, that is, the print is upside down. If you want to read that paper you will probably choose between two courses of action: either to flip the paper 180° or to walk to the opposite side of the

desk. This example involves physical rotation. Analogous strategies may exist in mental rotation. The term *image rotation* designates a strategy in which the image of the stimulus is rotated until it attains its normal, upright orientation; the term *frame rotation* designates a strategy in which the perceiver's system of coordinates (or frame or reference) is rotated until it matches the orientation of the stimulus. The aim of the present study is to determine which of these two strategies transpires in a mental rotation task and whether the choice of strategy may be affected by experimental conditions.

The distinction between image rotation and frame rotation has received some attention in connection with several tasks involving the processing of spatial information. Huttenlocher and Presson (1973) asked children to anticipate how an array of objects would look if it were rotated around its axis. This "array rotation" problem was much easier than a "viewer rotation" problem of anticipating how the array would look from a different perspective. Subsequent work (Huttenlocher & Presson, 1979) indicated that viewer rotation problems are actually easier than array rotation problems when the task requires the identification of objects in specified positions rather than the determination of the appearance of the entire scene. Presson (1982) reported similar findings with adult subjects. Hintzman,

O'Dell, and Arndt (1981) presented subjects with eight spots on a circle and required them to imagine themselves in a particular spot facing a direction indicated by an arrow and to point in the direction of another spot (target). Response time increased with the angular deviation of the arrow from an upright position and did not vary systematically with the target's position relative to the arrow. These findings suggested that orientation shifts were achieved by rotating the arrow–target display until the arrow was upright and then by responding in a manner compatible with the body coordinates, rather than by imposing a rotated coordinate system on the display.

Interestingly enough, however, there has been little work directly contrasting the image rotation and frame rotation strategies in mental rotation tasks like those of Shepard and Cooper (1982). Several findings, however, are pertinent. Cooper and Shepard (1973) found that advance identity and orientation information cancelled the effects of rotation, whereas advance orientation information alone did not. This suggested that subjects are unable to mentally rotate an abstract frame of reference. Hinton and Parsons (1981), on the other hand, found advance orientation information to be effective when the stimulus set consisted only of characters possessing common structural features. But in all cases where subjects are found to benefit from advance information, it is not clear whether this is achieved by rotating one's system of coordinates or by rotating a complete or partial representation of the stimulus. Furthermore, even if subjects are unable to rotate a frame of reference in the abstract, they may still adapt to a new frame of reference when this is induced by the stimulus in view.

The present study applied a different experimental paradigm to the investigation of the frame versus image rotation issue. Let us return once again to the newspaper example. Assume that in addition to the upside-down newspaper there are two books on the desk, one upside down and the other upright. Which book's title would be easier to read after having read the newspaper headlines? The answer, of course, depends on the strategy chosen. Thus, our experimental paradigm focused on sequential effects in mental rotation. The major

variable was the relation between successive orientations. If the image rotation strategy is employed, then decision time will depend solely on the angular deviation of the current stimulus from upright, irrespective of the orientation of the preceding stimulus. If, on the other hand, only the frame rotation strategy is employed, response time will depend on the angular difference between the present stimulus and the preceding stimulus. If the critical determinant of response time is the shortest angular distance that has to be traversed, then according to the image rotation strategy, the relevant angular distance is that between the orientation of the current stimulus and the standard upright (0°). This is labeled *angular deviation from upright* (ADU). For the frame rotation strategy, the distance of concern may be best indexed by the difference between current and preceding orientations. This is labeled *angular deviation from preceding orientation* (ADP). It assumes that after responding to a given stimulus, the orientation of that stimulus reflects the current setting of the perceiver's frame of reference.

One very recent study investigated sequential effects in a single-letter mental rotation task. Rabbitt (P. M. A. Rabbitt, personal communication, September 21, 1982) found no sign of facilitation due to the similarity of orientation for transitions between all letters occurring at the same orientations. However, he did find facilitation between similar letters (such as *P* and *R, S* and *Z,* or *J* and *L*), between recurrence of identical letters in the same orientation, and between dissimilar letters in well-practiced subjects (3,000 trials).[1]

Experiment 1

The first experiment employed the technique developed by Cooper and Shepard (1973). Four letters were presented at six orientations in either their normal or reflected form. The order of presentation was manipulated so that all the possible combinations of preceding and current orientations were equally represented. This allowed for a sys-

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[1] We learned of this work only after the first four experiments were completed.

tematic examination of the effects of ADU and ADP on response time.

Method

Subjects. Sixteen University of Haifa students (8 females, all right-handed) participated in the study; 14 received course credit, and 2 were paid for participating.

Apparatus. The experiment was controlled by a PDP 11-34 minicomputer. The stimuli were presented on a VT-11 CRT Graphic Display unit.

Stimuli. The stimuli consisted of four Hebrew letters and their mirror images. These are presented in Figure 1. The height of the letters was 1.8 cm. They appeared at one of six orientations: 0°, 60°, 120°, 180°, 240°, and 300° rotated in a clockwise direction (as in Cooper & Shepard, 1973).

Procedure. The subjects sat with their heads resting on a chin-and-head rest, which prevented head rotations. Viewing distance was 80 cm. Subjects were required to determine, as quickly as they could without making errors, whether the letter was normal or reflected and to press a key labeled *normal* with the right index finger or a second key labeled *reflected* with the left index finger.

The session began with 40 practice trials, followed by four blocks of 150 trials each. Stimuli appeared at the center of the screen until the subject responded. There was a 500-ms response-stimulus interval (RSI). Each block of 150 trials consisted of 5 warm-up trials followed by 145 trials. These 145 trials allowed for 144 sequences, and the first stimulus served only as a prime. The 144 sequences were preprogrammed to form all combinations of four factors: orientation of preceding stimulus (6), orientation of current stimulus (6), format (normal or reflected) of preceding stimulus (2), and format of current stimulus (2). The four letters were randomly assigned to each of the trials with the constraints that each letter appeared equally often in both formats, and that over the four blocks each of the four letters appeared once in each of the 144 combinations.

Results and Discussion

In the following analyses, responses outside the range of 250 to 5,000 ms were removed (0.3%). For each subject, mean response times for correct responses and percentage of errors were computed for all 36 combinations of preceding and current orientations. These were averaged over the 16 subjects and are displayed in Table 1.

A two-way analysis of variance (ANOVA) on the latency data yielded a strong effect of current orientation, $F(5, 75) = 60.76, p < .0001$. Preceding orientation yielded a small but significant effect, $F(5, 75) = 3.30, p < .01$. This effect mimics that found for current orientation. It seems that response times are faster
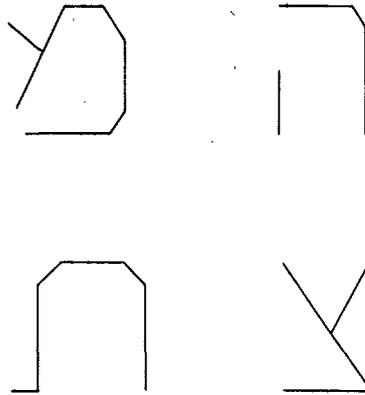

Figure 1. The four Hebrew letters used in Experiment 1.

when they follow a preceding faster response. The effect of current orientation varies as a function of preceding orientation, as indicated by a significant interaction, $F(25, 375) = 2.38, p < .0005$. The error data presented in Table 1 follow a somewhat similar pattern and yield significant effects for the current orientation, $F(5, 75) = 14.89, p < .0001$, and for the interaction, $F(25, 375) = 1.60, p < .05$.

It is interesting to note the slight asymmetry of the effects of current orientation, with the 120° orientation requiring 40 ms more than the 240° orientation, although this difference was not significant, $F(1, 15) = 3.17, p < .10$. We return to the asymmetry effects when we discuss the results of the subsequent experiments.

The deviation of the current orientation from the upright (ADU) greatly influenced response times. The mean response times for 0°, 60°, 120°, and 180° deviations were 719, 808, 975, and 1,277 ms, respectively. In contrast, the respective results for deviations from preceding orientation (ADP) were 909, 929, 973, and 968 ms, respectively. A two-way ANOVA yielded $F(3, 45) = 87.27, p < .0001$, for ADU, and $F(3, 45) = 4.83, p < .01$, for ADP.

Altogether the results of Experiment 1 lend far stronger support for the image rotation hypothesis than for the frame rotation hypothesis. It should be noted, however, that weak but significant effects of ADP were obtained. These may suggest the possibility that perhaps imagined reorientation of frame occurs to some degree for some subjects or trials.

Table 1

Response Latencies (in ms) and Percentage of Errors (in Parentheses) as a Function of Preceding and Current Orientations in Experiment 1

Preceding orientation	Current orientation						
	0°	60°	120°	180°	240°	300°	All
0°	593	742	982	1,277	955	770	903
	(1.7)	(1.6)	(2.8)	(18.9)	(3.9)	(2.0)	(5.0)
60°	675	775	935	1,304	999	822	918
	(3.5)	(1.7)	(5.2)	(15.2)	(5.2)	(1.6)	(5.4)
120°	749	821	914	1,259	1,016	816	929
	(2.3)	(0.8)	(5.1)	(17.3)	(4.3)	(1.2)	(5.2)
180°	759	916	1,068	1,257	974	846	970
	(5.9)	(1.6)	(3.2)	(13.8)	(2.7)	(2.8)	(5.0)
240°	709	833	1,081	1,259	901	827	935
	(1.2)	(1.6)	(7.4)	(16.5)	(2.0)	(1.6)	(5.0)
300°	702	793	1,029	1,329	925	773	925
	(3.9)	(1.6)	(3.1)	(12.9)	(3.1)	(1.2)	(4.3)
All	714	813	1,002	1,281	962	809	930
	(3.0)	(1.4)	(4.5)	(15.8)	(3.5)	(1.7)	(5.0)

Experiment 2

In general, the results of Experiment 1 appear to support the image rotation hypothesis, but perhaps a single letter is not sufficient for inducing the rotation of one's frame of reference. In contrast, a longer string of letters may induce perspective adjustments as in reading misoriented text. Consider, for example, a situation in which we try to read an upside-down book. Once we have gotten the hang of the task, the subjective experience is not of rotating single letters or even single words, but of having adjusted or set ourselves to the orientation of the printed page. Indeed, Kolers and Perkins (1969a, 1969b) have demonstrated the impressive ability of practiced subjects to read texts that have undergone various transformations. They proposed the concept of "orientation set," which means that the subject "need not compute the orientation of every letter or word, but can often carry over the orientation of the prior characters in a way that helps him to process a new character"(1969b, p. 278).

Accordingly, in Experiment 2 we used a task that combines reading and mental rotation. Subjects were presented with Hebrew five-letter strings appearing in one of six possible orientations and were instructed to determine whether each string was a word. (There are no two Hebrew print letters that are mirror images of each other, like b and d in English. In handwritten script there is one such pair.) Perhaps a five-letter string is more likely to induce the adoption of the frame rotation strategy than a single letter. Furthermore, in the lexical decision task, letter sets vary from one stimulus to the other, and there is a much smaller chance of relying on specific features as may be the case when a small number of letters is used (cf. Eley, 1982).

Apart from the main purpose of contrasting the image and frame rotation strategies, the present study may also serve in relating the mental rotation literature and the work of Kolers and his associates on reading of transformed texts. To the best of our knowledge the present study represents the first attempt to systematically apply the mental rotation paradigm to words and wordlike strings.

Method

Subjects. Twenty subjects (11 females, 19 right-handed) participated in the study; 17 received course credit, and 3 were paid for participating. Hebrew was the primary language for all subjects.

Stimulus materials. A total of 320 five-letter words were compiled from Balgur (1968), which lists Hebrew word frequencies in primary school material. Half were low frequency (7 or less in 200,000), and half were high frequency (10 or more). Half of the words in each category were transformed into nonwords by replacing one letter with another letter, yielding high-frequency and low-frequency nonwords.

Table 2

Response Latencies (in ms) and Percentage of Errors (in Parentheses) as a Function of Preceding and Current Orientations in Experiment 2

Preceding orientation	Current orientation						
	0°	60°	120°	180°	240°	300°	All
0°	811	1,082	2,175	2,125	2,079	1,044	1,553
	(3.7)	(5.7)	(17.0)	(12.0)	(11.2)	(7.0)	(9.4)
60°	847	1,015	2,130	2,066	1,986	1,084	1,488
	(5.0)	(6.2)	(9.6)	(10.8)	(13.4)	(3.1)	(7.4)
120°	853	1,076	2,087	2,011	1,971	1,129	1,511
	(1.9)	(5.7)	(14.0)	(10.4)	(15.0)	(4.6)	(7.1)
180°	860	1,062	2,052	2,014	1,968	1,153	1,518
	(2.5)	(3.6)	(15.2)	(9.7)	(6.9)	(6.2)	(7.3)
240°	847	1,120	2,050	2,068	1,921	1,059	1,521
	(3.1)	(5.6)	(8.8)	(8.9)	(12.9)	(3.2)	(8.6)
300°	861	1,009	2,028	2,044	1,966	1,022	1,521
	(3.3)	(7.5)	(7.9)	(11.3)	(5.6)	(8.7)	(8.0)
All	847	1,061	2,087	2,055	1,981	1,082	1,519
	(3.3)	(5.7)	(12.1)	(10.5)	(10.8)	(5.5)	(8.0)

Apparatus and procedure. The same apparatus and procedure as in Experiment 1 were used. The subjects were asked to classify letter strings as words or nonwords as quickly as they could without making errors and to indicate their response by pressing one key labeled *word* with their right index finger or a second key labeled *nonword* with their left index finger. They were informed that the letter strings would appear in one of six orientations and were shown drawings of one word and one nonword in all six orientations. The session began with 30 practice trials, followed by two experimental blocks. The first block consisted of 145 trials, and after a 2-min break, the second block of 145 trials began, preceded by 4 warm-up filler trials. For each subject, the blocks of 145 trials were preprogrammed to allow for four replications of each of the 6 × 6 (Preceding Orientation × Current Orientation) combinations; the first stimulus in each block served only as a prime. Two different orders of orientations were used, and their assignment to blocks was counterbalanced over subjects.

For each subject, the letter string presented on each trial was selected at random with the constraint that the four replications of each Preceding Orientation × Current Orientation condition included one high-frequency word, one low-frequency word, one high-frequency nonword, and one low-frequency nonword.

All strings appeared unpointed (see Koriat, 1983) at the center of the screen, and each word subtended about 5 cm horizontally and 0.8 cm vertically. Each letter string remained in view until the subject responded. RSIs were not constant and varied between approximately 0.05 s and 1 s, due to hardware limitations.

Results and Discussion

In the following analyses, responses in excess of 5,000 ms and less than 350 ms were excluded (0.2%). In the first analysis only the effects of preceding and current orientations were evaluated. Mean latencies for correct responses and mean percentage of errors were calculated for each subject for each of the 36 Preceding Orientation × Current Orientation conditions (with a maximum of 8 observations per subject per cell). These means were averaged over subjects and are presented in Table 2. The effect of current orientation was very large, $F(5, 95) = 80.46$, $p < .0001$, whereas the effect of preceding orientation was small and not significant, $F(5, 95) = 1.75$, $p < .15$. The interaction was also not significant, $F(25, 475) = 1.22$, $p < .25$. Percentage of errors also yielded a highly significant effect for current orientation, $F(5, 95) = 12.04$, $p < .0001$, and revealed the same relation to current orientation found for response latencies. Preceding orientation did not yield a significant effect, $F(5, 95) = 1.03$, but the interaction was significant, $F(25, 475) = 1.60$, $p < .05$. Inspection of Table 2 does not reveal any systematic trend to account for the interaction apart from a tendency for percentage of errors to be somewhat higher following a 0° orientation.

The results of main interest may be summarized by comparing the effects of ADU and ADP. Mean response latencies for 0°, 60°, 120°, and 180° deviations from upright were 844, 1,071, 2,031, and 2,059 ms, respectively. The respective values for deviations from preceding orientation were 1,463, 1,498, 1,513,

and 1,531 ms. A two-way, ADU × ADP ANOVA yielded for ADU, $F(3, 57) = 80.42$, $p < .0001$, and for ADP, $F(3, 57) = 4.23$, $p < .01$. Percentage of errors yielded a significant effect only for ADU, $F(3, 57) = 13.17$, $p < .0001$.

The effects of ADP are not confined to a repetition of the exact same orientation but decrease systematically with the deviation from an exact repetition. The extent of this effect from 0° to 180° deviations is quite small, 68 ms, compared with 1,215 ms found for deviation from upright. Comparing the mean response times for a 180° deviation from the

preceding orientation to no deviation (0°), we found that for 13 subjects, response time was longer for the former, for 6 subjects it was shorter, and for 1 subject there was no difference.

In conclusion, although response time varies in a systematic manner with the angular deviation from preceding orientation, the extent of this variation is quite limited. In contrast, angular deviation from the upright exerted a very large effect on response time.

The task of rotating wordlike letter strings is of interest in its own right, and we examine
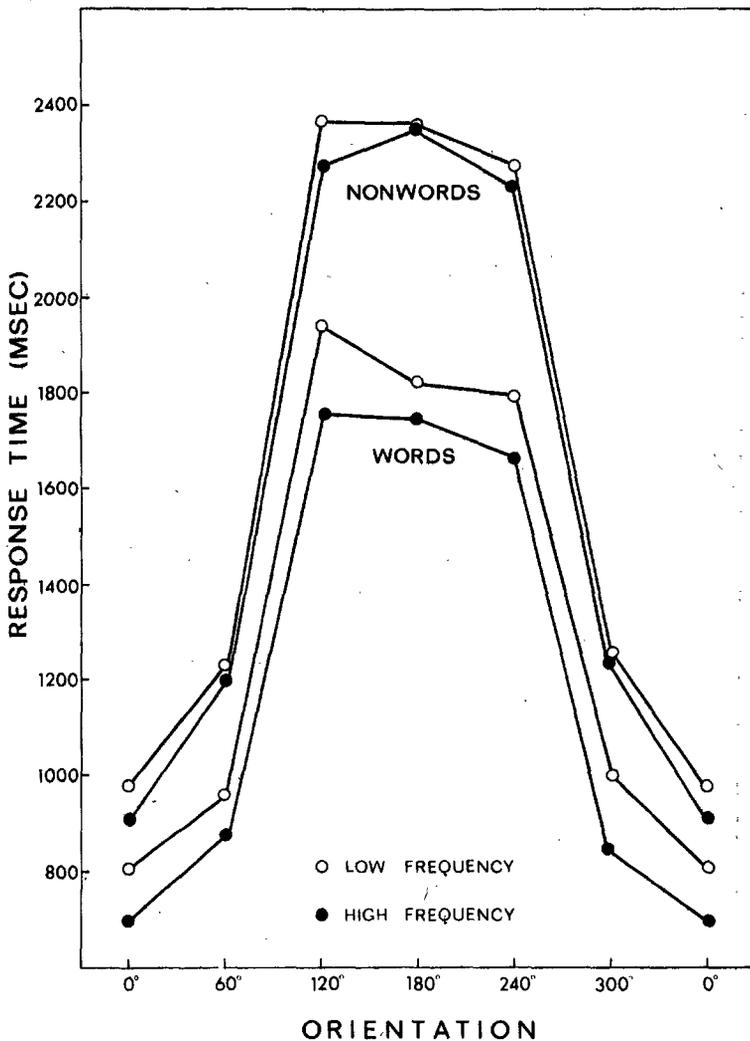

Figure 2. Response time (in ms) as a function of angle of rotation of current stimulus in Experiment 2 for words and nonwords of different frequency levels.

it in greater detail. Presented in Figure 2 is mean response time as function of angle of rotation of the current stimulus for words and nonwords of different frequency levels. The results are generally similar to those obtained for single letters, although in absolute terms the effects are much larger.

Three aspects of Figure 2 deserve further examination. First, the responses for upside-down (180°) presentations are faster than would have been expected on the basis of the responses for smaller deviations, assuming a linear increase with angular deviation. This is clearly discrepant from typical results obtained for single letters (see Cooper & Shepard, 1973, and our Table 1). The relative ease of processing upside-down letter strings (the upside-down effect) is consistent with previous findings on reading misoriented text. Chou (1929) found reading upside-down Chinese characters easier than 90° or 270° rotations, and Aulhorn (1948) found higher reading speeds for upside-down text than for smaller degrees of disorientation. As far as the 180° orientation is concerned, the results of Experiment 2 lie midway between those found for single letters and those found for the reading of connected text. For single letters the 180° rotation yields the slowest response time; for connected text it impairs reading speed relatively slightly compared with normal text, whereas for single words or word-like stimuli, the response time is comparable to that found for 120° and 240° rotations. This pattern suggests either that the relative ease of processing upside-down letter strings is due to lexical and semantic factors or that it is easier to adopt an "orientation set" (Kolers & Perkins, 1969b) when the sample of letters displayed is more extensive. The observation of similar findings for words and nonwords in the present experiment may be seen to favor the latter, but the somewhat stronger upside-down effect found for words than for nonwords (Figure 2) seems consistent with the former explanation.

Second, note the lack of symmetry in the curves of Figure 2, in that the 120° orientation requires on the average about 100 ms more than the 240° orientation. This holds for all four curves in Figure 2, although to a somewhat larger extent for words than for nonwords. A two-way ANOVA involving words versus nonwords and a 120° versus a 240° ori-

entation yielded $F(1, 19) = 12.24$, $p < .005$, for a 120° versus a 240° orientation, but the interaction was not significant.

Third, note that the effects of rotation are greater for nonwords than for words. The increase in response time from 0° to the average of the three difficult orientations (120°, 180°, and 240°) is 1,031 ms for words and 1,384 ms for nonwords, $t(19) = 6.08$, $p < .001$. This may suggest that the processes of mental rotation and lexical access are carried out partly in parallel, so that when a letter string constitutes a word, it is recognized as such before rotation is completed.

We expected a similar difference between high-frequency and low-frequency words; although the difference was in the expected direction, it was small and not significant.

Experiment 3A

The results of Experiment 2 very clearly favored the image rotation hypothesis over the frame rotation hypothesis for the lexical decision task as well. However, in light of the small systematic effect of ADP, perhaps stronger evidence for this strategy could be obtained if the interstimulus interval were greatly reduced. In Experiment 2 the RSI was quite long and variable due to hardware limitations. The possibility exists that although the frame rotation strategy is adopted, the new frame is not maintained until the appearance of the subsequent stimulus but tends to return to the standard orientation very rapidly. Experiment 3A was an exact replication of Experiment 2 except that special hardware and software provisions were made to permit the replacement of one stimulus by its successor almost immediately upon the pressing of the response key.

Method

Subjects. Twenty subjects (13 females, 18 right-handed) participated in this study for course credit. None had participated in the two previous experiments. Hebrew was their primary language.

Procedure. The apparatus and stimulus materials were identical to those of Experiment 2. The procedure was also the same except that the RSI was approximately 20 ms.

Results and Discussion

As in Experiment 2, all responses outside the range 350–5,000 ms (0.2%) were excluded

Table 3

Response Latencies (in ms) and Percentage of Errors (in Parentheses) as a Function of Preceding and Current Orientations in Experiment 3A

Preceding orientation	Current orientation						
	0°	60°	120°	180°	240°	300°	All
0°	828	945	1,722	1,781	1,636	979	1,315
	(5.6)	(3.8)	(7.5)	(6.9)	(13.8)	(3.8)	(6.9)
60°	882	975	1,828	1,742	1,610	949	1,331
	(3.8)	(8.1)	(8.1)	(11.9)	(6.9)	(8.1)	(7.8)
120°	932	1,046	1,814	1,695	1,700	1,073	1,377
	(3.8)	(4.4)	(13.8)	(13.1)	(12.0)	(6.9)	(9.0)
180°	887	1,065	1,828	1,706	1,630	1,021	1,356
	(5.6)	(10.0)	(13.2)	(13.1)	(9.4)	(8.1)	(9.9)
240°	902	1,066	1,785	1,725	1,728	1,031	1,373
	(4.4)	(8.1)	(10.6)	(8.8)	(15.0)	(6.9)	(9.0)
300°	818	1,031	1,746	1,670	1,623	964	1,309
	(5.6)	(10.0)	(7.5)	(13.3)	(11.3)	(7.5)	(9.2)
All	875	1,021	1,787	1,720	1,655	1,003	1,343
	(4.8)	(7.4)	(10.1)	(11.2)	(11.4)	(6.9)	(8.6)

from the analysis. Presented in Table 3 are the mean latencies for correct responses and percentage of errors as a function of preceding and current orientations.

A two-way ANOVA on response latencies yielded a very large effect for the current orientation, $F(5, 95) = 92.74, p < .0001$, and a smaller but significant effect for the preceding orientation, $F(5, 95) = 5.30, p < .0005$. The latter effect was not found in Experiment 2. The weak effect of preceding orientation closely mimics the effect of the current orientation as was the case in Experiment 1. The interaction between preceding and current orientation was not significant, $F(25, 475) = 1.36, p < .15$. The percentage of errors indicated a significant effect for current orientation only, $F(5, 45) = 9.52, p < .0001$.

As in Experiment 2 the effect of ADU was very large, $F(3, 57) = 95.91, p < .0001$. Mean response times for 0°, 60°, 120°, and 180° deviations were 871, 1,015, 1,724, and 1,726 ms, respectively. The effect of ADP was much smaller and did not attain the accepted significance level, $F(3, 57) = 2.28, p < .09$. Again, as in Experiment 2, there is a systematic trend for the response times to increase with greater deviations from preceding orientation. Mean response times were 1,317, 1,323, 1,340, and 1,354 ms for deviations of 0°, 60°, 120°, and 180°, respectively. The respective means for percentage of errors were, 10.2%, 7.7%, 9.2%,

and 6.8%, respectively; $F(3, 57) = 3.09, p < .05$. This raises the possibility that even the trend observed for response latency is due to a speed–accuracy trade-off. Comparing the results of Experiments 2 and 3A, it appears that reducing the RSI resulted in an overall speeding up of response time by about 175 ms but was not accompanied by an increase in error rate. The extent of this effect varied greatly as a function of current orientation with differences of −28, 61, 194, 335, 433, and 58 ms for 0°, 60°, 120°, 180°, 240°, and 300° orientations, respectively. A two-way, Experiment (2 vs. 3A) × Current Orientation ANOVA yielded $F(5, 190) = 4.52, p < .001$, for the interaction. The differences indicate that the effects of current orientation are smaller in Experiment 3A than in Experiment 2 and suggest the intriguing possibility that rate of mental rotation may be speeded up by increasing the pace of presentation.

Although the effects of angular deviation from the upright were smaller in Experiment 3A than in Experiment 2, the same trends were found (see Figure 3). First, mean response times for a 180° orientation are clearly faster than expected, even faster than those for a 120° orientation. Indeed, a t test comparing the 120° and the 180° orientations yielded $t(19) = 2.75, p < .02$. As in Experiment 2, this upside-down effect is more pronounced for words than for nonwords and for high-

frequency words than for low-frequency words, but these effects are not significant.

Second, Figure 3 also displays the same type of asymmetry obtained in Experiment 2. For all four types of letter strings, the mean response times for 120° orientations are greater than those for 240° orientations. A t test comparing the 120° and 240° orientations yielded the following: $t(19) = 4.02$, $p < .001$.

Third, it appears that the effects of deviation from upright are stronger for nonwords than for words. Thus, the increase in response time from a 0° orientation to the average of the three most difficult orientations (120°, 180°, and 240°) was 731 ms for words and 949 ms for nonwords, $t(19) = 4.96$, $p < .001$.

A similar trend is evident for the comparison between low-frequency and high-frequency words. The increase in response time from a 0° orientation to the average of the three difficult orientations was 699 ms for high-frequency and 767 ms for low-frequency words, $t(19) = 2.28$, $p < .05$.

Experiment 3B

The results of the three previous experiments clearly favored the image rotation hypothesis. The systematic, though small, effects of ADP found in the three experiments suggest the possibility that although most subjects adopt the image rotation strategy, some may rely to some extent on the frame rotation strategy. Indeed, examination of the data indicated individual differences in the effects of deviation from preceding orientation; a few subjects manifested quite systematic effects.
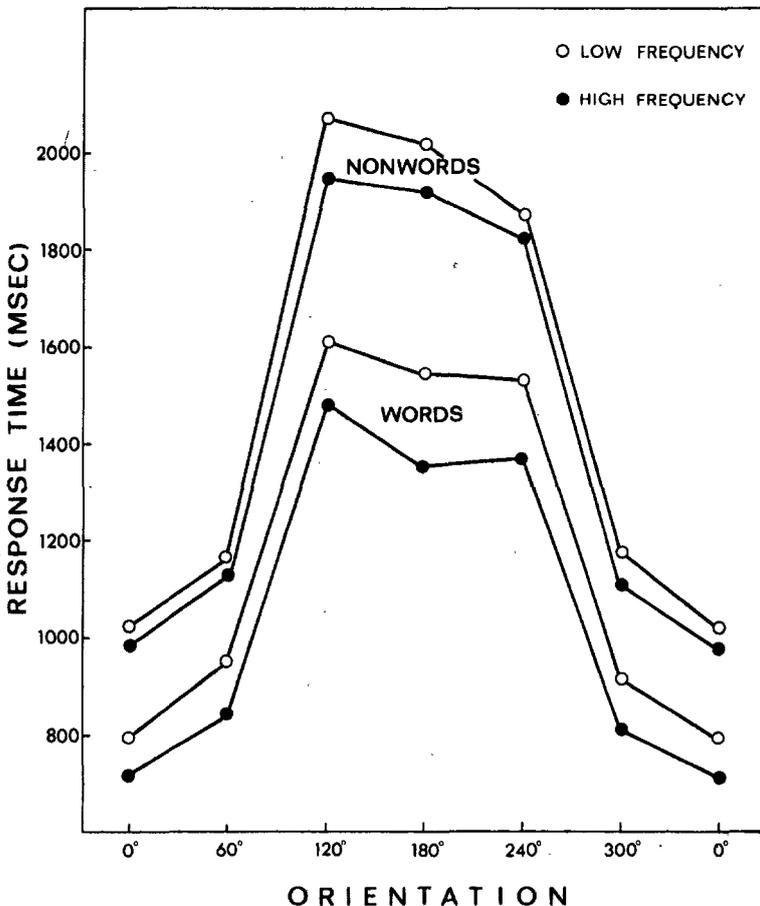

Figure 3. Response time (in ms) as a function of angle of rotation of current stimulus in Experiment 3A for words and nonwords of different frequency levels.

In an attempt to examine the possibility of consistent individual differences in preferred strategy of mental rotation, 7 subjects in Experiment 3A were identified whose data showed the strongest evidence for the frame rotation strategy. We were able to contact 6 of these subjects and asked them to participate in a repeat session. For these 6 subjects, response times in the first session for 0°, 60°, 120°, and 180° ADPs averaged 1,303, 1,358, 1,410, and 1,419 ms, respectively. For the remaining 13 subjects, the respective means were 1,306, 1,293, 1,290, and 1,300 ms.

All 6 subjects took part in a second administration of Experiment 3A for course credit. The procedure in Experiment 3B was exactly the same as in the first session except that the assignment of words and nonwords to particular orientations and trials was in a new random order. The second session took place between 10 days and 27 days after the first session.

Results

Averaging over the 6 subjects, mean response times for ADPs of 0°, 60°, 120°, and 180° were 1,183, 1,189, 1,203, and 1,200 ms, respectively. When these results are compared with those obtained in Experiment 3A for the remaining 13 subjects, there is little indication that choice of strategy of mental rotation may represent a stable cognitive style.

Experiment 4

Experiment 3B indicated that the systematic ADP effects are not the result of consistent individual preferences for the frame rotation strategy. Perhaps both strategies are available to the subjects, but the frame rotation strategy is employed less often or to a lesser degree than the image rotation strategy. If this is the case, is it possible to encourage reliance on the frame rotation strategy by making it more expedient? This possibility was examined in Experiment 4.

In the four previous experiments, no advantage could be gained by maintaining the same frame of reference from one stimulus to the next, because the orientation of each stimulus was independent of that of the preceding one. In Experiment 4 we introduced sequential dependence, so that the probability that a given orientation would be repeated in the next trial was .80. Increasing the probability of orientation repetition from .17 to .80 should encourage the maintenance of an adopted frame of reference while also better simulating the task of reading transformed texts where each and every word is identically disoriented (see Kolers & Perkins, 1975). When a stimulus orientation was not repeated it was equally likely to be at any of the other five orientations. The questions of interest are, first, whether repetition of the same orientation over a series of stimuli results in faster response times than nonrepetitions, and second, whether response times to stimuli in nonrepeated orientations vary more strongly with their deviations from the preceding stimuli than they vary with their deviation from the upright. An affirmative response to the first question may also be consistent with the image rotation strategy, because there can be many reasons why repeating the same rotation yields faster response times. An affirmative response to the second question, however, is much more difficult to accommodate with the image rotation view.

Method

Subjects. Twelve paid subjects (6 females) participated in this study. Hebrew was their primary language. None had participated in Experiments 2 or 3A.

Procedure. The apparatus was the same as that used in the previous experiments. The stimulus materials were similar to those of Experiments 2, 3A, and 3B with the following exceptions. The two stimulus lists each included 151 items. The 150 stimulus sequences of each list were preprogramed so that each orientation appeared 25 times, 20 times following the same orientation and once following each of the other five orientations. The order of the orientations was otherwise random except for the constraint that the same orientation could not be repeated more than 7 times consecutively. The allocation of stimulus items to trials was determined randomly for each subject. In addition, for all subjects the order of orientations was derived from a common base list, but the specific orientations were varied systematically between subjects according to a balanced square design. The RSI was the same as that employed in Experiments 3A and 3B. The instructions were those employed in the three previous experiments except that subjects were also told that there was a high probability that a given orientation would repeat itself.

Results and Discussion

In all the analyses to be reported below, responses in excess of 5,000 ms and less than

350 ms were excluded (0.7%). A two-way, ADU × ADP ANOVA on subject means yielded $F(3, 33) = 130.65$, $p < .0001$, for ADU. Mean response latencies for 0°, 60°, 120°, and 180° deviations from upright were 909, 1,136, 2,104, and 2,087 ms, respectively. The effects of ADP, however, were not significant ($F < 1$). Mean response latencies for 0°, 60°, 120°, and 180° deviations from preceding orientations were 1,533, 1,572, 1,584, and 1,546 ms, respectively. A similar analysis of the error data also yielded a significant effect for ADU but not for ADP.

Surprisingly, it appears that in spite of the manipulation of the probability of orientation repetition, the effects of ADP are even less systematic than those found in Experiments 2, 3A, and 3B. One possible reason for this may be the small number of observations on which the nonrepetition means were based. In an attempt to somewhat alleviate this imbalance, all nonrepetition trials were collapsed and compared with repetition trials. Mean response latency for all nonrepetitions was 1,566 ms compared with 1,533 ms for repetitions. A t test yielded $t(11) = 1.39$, ns. A similar analysis of the error data indicated a slightly larger incidence of errors for nonrepetitions (8.8%) than for repetitions (7.0%), $t(11) = 1.83$, $p < .10$.

In the present design each of the orientations could be preceded by zero to seven trials in the same orientation. Somewhat surprisingly, we found no significant improvement as a function of number of preceding stimuli in the same orientation. Also, no evidence was found to support the possibility that when a shift to a new orientation is required, the length of the run of identical orientations preceding it affects response time.

The results of Experiment 4 are rather discouraging. In spite of our attempt to motivate reliance on the frame rotation strategy, no stronger evidence of the effects of preceding orientation were found. These results may suggest that the frame rotation strategy cannot be readily adopted under the conditions of the present experiment. It would seem that the weak evidence found in the previous experiments for the frame rotation strategy does not reflect occasional strategy shifts initiated by the subject.

General Discussion

Our experiments contrasted two alternative hypotheses concerning the process of mental rotation. According to the image rotation hypothesis, it is the stimulus image that is rotated to an upright position, whereas according to the frame rotation hypothesis, the perceiver rotates his or her system of coordinates until it is aligned with that of the rotated stimulus.

Our experimental paradigm utilized sequential effects in a mental rotation task. If subjects do rely on the frame rotation strategy and if their rotated frame of reference persists over the short interstimulus interval, response time should vary with ADP. The image rotation strategy, on the other hand, implies that response time depends solely on ADU.

In what follows we first review and discuss the findings directly pertinent to the question of what is rotated in mental rotation. Then we discuss issues that emerge from the extension of the mental rotation paradigm to word recognition.

There are four findings that pertain directly to the question of what is rotated in mental rotation.

1. Overall, response times evidenced far greater dependence on ADU than on ADP. This was true for both single-letter stimuli (Experiment 1) and wordlike stimuli (Experiments 2–4).

2. Response times tended to increase with increasing ADPs. Although the effects were relatively weak, they were systematic and found consistently in Experiments 1–3B.

3. There was no evidence supporting the existence of stable individual differences in the tendency to rely on the frame rotation rather than on the image rotation strategy (Experiment 3B).

4. Conditions seemingly conducive to the adoption of the frame rotation strategy proved ineffective. Increasing the likelihood that the current orientation would be repeated from .17 to .80 did not enhance the effects of ADP (Experiment 4).

In sum, these results clearly support the image rotation hypothesis and yield only very slight evidence for the frame rotation hypothesis. We expected particularly pronounced ADP effects for the lexical decision task, be-

cause we assumed this task would induce orientation adjustments on the part of the subject. However, this task revealed no stronger ADP effects than the single-letter task of Experiment 1.

Our results are consistent with those of Hintzman et al. (1981), obtained with a quite different experimental procedure. They are also in line with Cooper and Shepard's (1973) interpretation of the lack of effects of advance orientation information as indicating that subjects cannot rotate an abstract frame of reference. On the other hand, Corballis and his associates (Corballis, Nagourney, Shetzer, & Stefanatos, 1978; Corballis, Zbrodoff, & Roldan, 1976) found essentially the same function relating reaction time to orientation when the subjects tilted their heads as when they held their heads upright. This was taken to indicate that subjects can adjust their frames of reference to compensate for head tilts. Subjective upright was also found to be influenced by the physical surroundings and to some extent by verbal instructions. Taken together, these results suggest (see Corballis, 1982) that although subjects find it difficult to control their frame of reference at will, its adjustment may be affected by automatic processes.

This may explain our failure to obtain larger effects of ADP in Experiment 4, where the benefits of orientation repetition presumably depended on the intentional adoption of the frame rotation strategy. Furthermore, it follows that the systematic effects of ADP found in Experiments 1–3B are due to automatic activation rather than to a controlled frame rotation strategy: The orientation of one stimulus would appear to "prime" or activate a frame of reference that is congruent with it. This is consistent with the findings of Corballis and his associates, suggesting that under certain conditions, subjects make a partial frame adjustment that creates a subjective frame of reference distinct from the gravitational or retinal axes.

It remains a puzzle, however, why Huttenlocher and Presson (1973, 1979) obtained results that apparently show that subjects may be induced to adopt a frame rotation strategy by simply formulating the problem posed in terms of array rotation or perspective change. We did not explicitly ask subjects to adopt the frame rotation strategy, but the results of Experiment 4 suggest that this manipulation would not have been effective. One challenging issue for subsequent research is to determine the critical differences between the tasks of Huttenlocher and Presson and the standard mental rotation task in order to better understand our failure to obtain stronger evidence for the frame rotation strategy.

Let us now examine the extention of the mental rotation paradigm to lexical decision. As indicated, the advantage of this task is that it does not allow reliance on a limited number of features and can be related to studies on reading transformed texts. It is interesting to compare the results found for single letters (Experiment 1 and Cooper & Shepard, 1973) with those obtained for letter strings (Experiments 2–4). The two tasks differ in both the nature of the stimuli used (normal or reflected single letters and strings of normal letters), as well as in the classificatory requirement (normal–reflected and word–nonword judgments). Yet, both revealed several common regularities. First, both yielded the same basic monotonic relation between response time and angular disorientation. Second, both showed strong evidence for the image rotation strategy while also yielding slight evidence for the frame rotation strategy. Third, both manifested a certain degree of asymmetry in the effects of orientation on reaction time (120° rotation somewhat slower than 240°). These lines of similarity support the assumption that both tasks are based on common underlying processes. On the other hand, there is a striking difference between the results obtained for the two tasks at the 180° orientations. Response times for the letter strings are much faster than would be expected from the assumption of a constant rate of mental rotation, whereas those for single letters are more or less consistent with this assumption. This difference may be due to the lexical decision task being more akin to a reading task. Such tasks presumably elicit a horizontal scanning response that is beneficial for horizontal letter strings, whether upright or inverted. Alternatively, it is possible that the task of distinguishing single letters from their mirror images is particularly difficult for upside-down letters because of right–left confusions. Both of these arguments imply

that processes in addition to mental rotation occur in these two tasks. Further research is needed to clarify this point.

Another point that calls for further research arises from the comparison of our lexical decision data with findings on identification and classification of alphanumeric characters. Tasks of the latter type have been shown to yield very weak effects of orientation or no effects at all (Corballis & Nagourney, 1978; Corballis, Zbrodoff, Shetzer, & Butler, 1978). On the face of it, the lexical decision task has much in common with the letter identification task, and yet we found strong orientation effects for lexical decision. A point deserving examination is the question of whether this difference is due to the fact that in our experiments we used five-letter strings rather than single letters. We are currently examining the effects of string length on lexical decision times for rotated strings.

Another issue involves the asymmetric effects in the rotation function. Response times for 120° orientations were consistently slower than for 240° orientations. This asymmetry may be due to the upward versus downward direction of the letter strings. Since Hebrew is a left-going language, in the 60° and 120° orientations the required reading direction is upward, whereas in the 240° and 300° orientations the direction is downward. It would seem that reading in a downward direction is easier than in an upward direction. For example, when words are presented vertically, as on book backs or vertical shop signs, they are almost invariably printed top-down. Similarly, like most languages Hebrew is read from the top to the bottom of the page. This explanation implies that English letter strings should yield asymmetry in a direction opposite to Hebrew. If this is true, it may suggest that the speed of responding to disoriented words or wordlike stimuli depends not only on the extent of mental rotation required, but also on specific characteristics of the disoriented stimuli. On the other hand, if English letters yield asymmetry similar to that found for Hebrew, this may suggest the possibility that rotation in a clockwise direction is easier or faster to execute than rotation in a counterclockwise direction. The findings of Simion, Bagnara, Roncato, and Umilta (1982) are generally consistent with the latter hypothesis, but these were obtained using a somewhat different experimental paradigm. Asymmetric effects in mental rotation have been reported by others (e.g., Chou, 1929; Dearborn, 1899; Smith, Cambria, & Stefan, 1964), but they are difficult to interpret.

In conclusion, as far as the central question of what is rotated in mental rotation is concerned, our results strongly favor the image rotation hypothesis. We did also find some weaker evidence for the frame rotation hypothesis. Several explanations for the latter findings were examined, but definite conclusions concerning its etiology await further research. Future research should also address the question of why subjects are able to adopt a viewer rotation strategy in imagining the rotation of an array of objects (Huttenlocher & Presson, 1979; Presson, 1982), whereas the mental rotation tasks of the present study evidence little trace of the frame rotation strategy.

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