

Frames and Images: Sequential Effects in Mental Rotation

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Recent studies have shown that response time in mental rotation increases with the angular deviation between the current and preceding stimuli, suggesting a frame rotation process in which the intrinsic frame of the previous stimulus is brought into congruence with the coordinates of the current stimulus. In contrast, we show that this process involves image rotation in which the present stimulus is brought into alignment with the orientation of the previous stimulus. Such "backward alignment" succeeds only for shape-preserving sequences (i.e., identical stimuli at different orientations). Four experiments show that the backward alignment process (a) competes with the uprighting process typically found in mental rotation, and the response is determined by the process requiring the shortest rotational path; (b) is related to the tendency to repeat the previous response; (c) is insensitive to the position of the vertical; (d) is indifferent to the representation of the stimulus in long term memory; and (e) is different from the process underlying preparation for a stimulus in a specified orientation.

A great deal of research has been devoted in recent years to the question of spatial transformation, that is, the process that presumably transpires when information organized in terms of one frame of reference is to be interpreted in terms of another. The present study was motivated by an apparent inconsistency in the experimental literature regarding the nature of this process. Consider the mental rotation task of Cooper and Shepard (1973). This task may be accomplished either by imagining the stimulus to rotate to the upright (image rotation), or by bringing one's perceptual frame of reference into alignment with the coordinates of the stimulus (frame rotation). Cooper and Shepard found that advance information about the orientation of an upcoming stimulus was ineffective in eliminating the necessity for mental rotation unless it was coupled with information regarding the identity of that stimulus. This was taken to support the image rotation hypothesis. A similar conclusion was reached by Hintzman, O'Dell, and Arndt (1981), studying the perception of directions in cognitive maps. In contrast, Hinton and Parsons (1981) observed that when the set of stimuli in a mental rotation task possesses common features (a common "front"), advance orientation information was effective, apparently because subjects could prepare for an "abstract frame" of the stimulus.

This work was completed while Asher Koriat was a member of the Institute for Advanced Studies at the Hebrew University of Jerusalem.

We wish to thank Claus Bundesen, Steven Palmer, Lynn Robertson, and Roger Shepard for their very helpful comments on an earlier version of this article. We are indebted to Zvia Kaplan and Hagit Tal for programming the experiments and to Ofra Ziv and Orna Korant for conducting them.

The work presented in this article was carried out independently of that of Robertson, Palmer, and Gomez (1987). We learned of their work only after preparing the first version of this article. Thus, the present version contains only cursory references to their article, and more work will be needed to bridge the gap between the conclusions of the two papers.

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Huttenlocher and Presson (1973) asked children to indicate how a visual array would look when viewed from a different perspective. This task, too, may be accomplished either by imagining the array to rotate about its own axis, or by transforming the frame of reference itself so that the array may be inspected from a different vantage point. The results suggested that array rotation was easier than frame rotation, although the relative difficulty of the two strategies seems to also depend on the task used (Huttenlocher & Presson, 1979; Presson, 1982).

The foregoing studies suggest that spatial transformation is normally achieved through image rotation and that subjects find it difficult to rotate an abstract frame of reference.

There are two lines of research, however, that suggest the occurrence of frame rotation. First, when subjects perform a mental rotation task while tilting their heads, the gravitationally defined frame tends to dominate over the retinally defined frame (e.g., Attneave & Olson, 1967; Corballis, Nagourney, Shetzer, & Stefanatos, 1978; Corballis, Zbrodoff, & Roldan, 1976). This suggests that subjects can adjust their frame of reference to compensate for head tilts. Because subjects cannot intentionally prepare for an abstract frame of reference (Cooper & Shepard, 1973), perhaps the frame rotation that occurs in head tilt is primarily determined by automatic processes (see Corballis, 1982).

The second line of research centers around the concept of intrinsic frames, and it too implies that the perceptual frame of reference is adjusted to the coordinates of the stimulus through a process that is largely automatic. Recent approaches to perceptual constancy (see Marr, 1982; Palmer, 1983) assume that a shape can retain its perceptual identity despite changes in orientation because it is represented relative to its intrinsic frame as defined by its salient axis of elongation and symmetry. This representation enables a perspective-independent coding, and affords the detection of the orientation-invariant identity of different stimuli. There is evidence that visual shapes tend to be represented relative to their intrinsic upright (e.g., Humphreys, 1983; Wiser, 1981). Furthermore, the results suggest that this representation is not achieved by conferring a rotated system of coordinates all at once on the

stimulus (see Just & Carpenter, 1985). Rather, there seems to be an initial bias toward applying a vertical frame of reference, and this frame undergoes a gradual rotation before it is aligned with the coordinates of the stimulus (Attneave & Reid, 1968; Humphreys, 1983; Palmer, 1980). This frame rotation process is similar to mental rotation, but it operates on the visual code, apparently at a faster rate than that typically observed in mental rotation studies (Simion, Bagnara, Roncato, & Umiltà, 1982).

In sum, the available evidence points to the existence of both image rotation and frame rotation processes. These two processes, however, appear to differ in nature. The image rotation process underlying mental rotation is apparently a subject-initiated imaginal process (Shepard & Cooper, 1982). The frame rotation process, in contrast, appears to be stimulus induced and occurs as an automatic, even mandatory process (Humphreys, 1983; Simion et al., 1982). It is perceptual in nature and operates upon the visual code rather than on an imaginal representation (Bagnara, Simion, & Umiltà, 1984).

This distinction between a subject-initiated image rotation process and a stimulus-induced frame rotation process raises new questions regarding Shepard and Cooper's (1982) view that the mental rotation task is carried out by image rotation. Although subjects are unable to rotate an abstract frame of reference in preparation for a stimulus (Cooper & Shepard, 1973), this should not necessarily imply that they are unable to adjust their frame to the intrinsic frame of a physically present stimulus. An alphanumeric character has a canonical orientation, and this may induce its description relative to its own frame of reference. It is this sort of process that has been assumed to underlie the efficient recognition of alphanumeric characters despite deviations from their upright orientation (see Palmer, 1983).

It is this kind of reasoning that motivated us (Koriat & Norman, 1984) and Robertson, Palmer, and Gomez (1987) to seek evidence for the possibility of frame rotation processes occurring in the context of a Cooper and Shepard mental rotation task. In both studies the image rotation and frame rotation hypotheses were contrasted using sequential effects in mental rotation. The rationale was as follows: If subjects imagine each stimulus rotated to the upright, speed of responding should depend solely on its angular deviation from the upright. But if they rotate their frame of reference to match that of the misoriented stimulus, speed of responding should vary with the angular deviation between the current stimulus and the preceding stimulus. This assumes that after responding to a given stimulus, the perceptual frame of reference is aligned with the intrinsic frame of that stimulus.

In our study (Koriat & Norman, 1984) four experiments used both reflection decisions on alphabetic characters and lexical decisions on rotated letter strings. Much stronger effects were found for the *angular deviation from upright* (ADU) than for the *angular deviation from preceding orientation* (ADP), thereby supporting the image rotation hypothesis. Although the effects of ADP were significant, they were very small relative to those of ADU.

The study of Robertson et al. (1987) was based on much the same idea but arrived at the opposite conclusion. An array of four identical characters was presented at either +90° or

-90° from the upright, and followed by a single character at different orientations. Response times to the single characters were found to vary with its orientation relative to that of the preceding four-character array, leading the authors to conclude "that mental rotation involves the transformation of reference frames rather than the transformation of template-like representations" (p. 368).

In our previous study (Koriat & Norman, 1984) the image and frame rotation processes were conceived of as two mutually exclusive mechanisms. The present study, in contrast, was based on the idea that both processes may be concurrently operative, with the response determined by the process requiring the shortest transformational path. The mental rotation task may thus be viewed as involving frame competition: When two stimuli appear in sequence, the second of these may be interpreted either relative to the intrinsic frame of the first stimulus or relative to the standard, upright frame. Which of these occurs depends upon the extent to which the orientation of the second stimulus departs from that of the preceding stimulus relative to its deviation from the upright. Thus, response times in a sequential mental rotation task are expected to be a joint function of ADU and ADP, with the extent of ADP effects increasing with increased ADU, and vice versa.

Experiment 1 and a Tentative Model

The validity of the frame competition hypothesis was first evaluated by reanalyzing the data of Experiment 1 in our earlier study (Koriat & Norman, 1984). In that experiment four Hebrew letters were presented at six orientations (0°, 60°, 120°, 180°, 240°, and 300°) in either their normal or reflected formats. Presentation order was preprogrammed to allow a systematic examination of the combined effects of ADU and ADP on response time.

The method and procedure are described in detail in Koriat and Norman (1984). For the purpose of the present report we should only note that the 576 trials of the experiment were preprogrammed to produce four replications of all possible 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 equally distributed across all orientation by format conditions, but there was no attempt to control for specific letter sequences.

The original analysis indicated marked effects of ADU, amounting to an overall effect of 558 ms (comparing the 0° and the 180° orientations). In contrast, ADP had a much smaller though significant effect, amounting to only 59 ms overall.

In a new detailed reexamination of these effects the predicted ADU × ADP interaction was indeed obtained, but only for a very specific combination of conditions. Intricate interactions were found involving four factors: letter repetition, format repetition, format of current letter, and orientation of current letter. In view of the complex interactions observed we shall present the results in a somewhat piecemeal manner, focusing on the main trends and omitting report of the pertinent statistical analyses. The results may be best summarized as follows:

1. The effects of ADP were almost totally confined to instances where the current letter was the *same letter* as the preceding one. For nonrepeated letters mean response times for 0°, 60°, 120° and 180° ADPs were 945, 943, 973, and 958 ms, respectively, whereas for repeated letters the respective means were 766, 865, 997, and 1010 ms.

2. For repeated letters, the effects of ADP were entirely confined to those cases where the letter was repeated in the *same format*. For ADPs of 0°, 60°, 120°, and 180° mean response times were 850, 867, 917, and 898 ms for different-format sequences, and 705, 813, 951, and 1017 ms for the same-format sequences.

3. Considering only same-letter-same-format (SLSF) sequences, the effects of ADP were larger for reflected-following-reflected than for normal-following-normal pairs. The overall effect of ADP was 479 ms for reflected-reflected sequences, compared with 212 ms for normal-normal sequences. Robertson et al. (1987) also found the strongest effects of ADP for SLSF sequences when both stimuli were reflected.

4. For SLSF sequences, significant interactions obtained between ADU and ADP with a pattern consistent with that predicted by the frame competition hypothesis. These results appear in Figures 1A and 1B. In Figure 1B, for example, the effects of ADP amounted to less than 300 ms when ADU was 0° and increased to nearly 1,000 ms for ADU = 180°. The results for same-letter-different-format (SLDF; Figure 1C), for different-letter-same-format (DLSF; Figure 1D), or for different-letter-different-format (DLDF) sequences (not shown) were very different, revealing no effect of ADP, and no ADP × ADU interaction. The error data indicated a similar pattern of results. For SLSF sequences, percentage of errors for ADPs of 0°, 60°, 120°, and 180° were 1.0%, 3.1%, 6.0%, and 14.1%, respectively. The respective values for the remaining sequence types combined were 4.6%, 5.3%, 4.6%, and 5.0%.

According to the frame competition hypothesis, the current stimulus is interpreted in terms of the frame requiring the shortest transformational path. Thus, if each stimulus is described in terms of ADU and ADP values, then response time should depend on the smallest of the two. The interactive pattern depicted in Figures 1A and 1B is exactly what would be expected on the basis of this hypothesis. However, the observation that this pattern is entirely confined to SLSF sequences raises serious doubts concerning the basic assumption that the ADP effects reflect frame rotation processes (see Robertson et al., 1987).

The results suggest that different processes occur when the current stimulus is the same letter and in the same format as the preceding stimulus than when it is not. This, however, implies a seeming paradox where the choice of processing mode depends, in some sense, on first knowing the format of the current stimulus. It is this paradox that motivated the construction of the model proposed next.

In the proposed model the ADP effect is attributed to a process that we will call *backward alignment*. It is best described with reference to two other processes, apparent rotational motion and mental rotation, both investigated by Shepard and his associates (see Shepard & Cooper, 1982; Shepard & Hurwitz, 1984). According to Shepard (1984), these two processes involve the same general mechanisms in that both

simulate the physical rotation of objects in the external world. In both processes the evidence suggests the internal generation of an ordered sequence of intermediate representations that have a one-to-one correspondence with the series of intermediate orientations of an external rotating object. The two phenomena differ, however, in that apparent rotational movement rests on an automatic perceptual process that directly instantiates the self-identity of the object (i.e., that which remains invariant across the rotational transformation). The mental rotation process, on the other hand, involves the voluntary, effortful simulation in imagery of an external rotation.

The process of backward alignment assumed to underlie the ADP effects falls somewhere between apparent rotational movement and mental rotation. We propose that the mental rotation task is ordinarily carried out through an *uprighting process* in which the stimulus is imagined to rotate to the upright. However, when two successive stimuli, S1 and S2, are identical except for a change in orientation, a process of backward alignment may occur in which S2 is imagined to rotate into alignment with the image of S1. This affords capitalization on processes already performed on S1 and allows simple repetition of the previous response. Backward alignment is thus confined to a sequence involving a *shape-preserving transformation* of the stimulus.

The term *backward alignment* is used here in the temporal sense in that the current stimulus is interpreted with reference to the previous stimulus. The backward alignment process is similar to apparent rotational motion in that both processes apparently rest on a general mechanism that enables the *extraction of transformational invariance*. We assume that backward alignment, like apparent motion, is externally driven, and therefore its inception is more automatic than that of the uprighting process. In this sense it is similar to the type of frame rotation process that apparently occurs when a stimulus is interpreted in terms of its intrinsic frame (see Humphreys, 1983). However, since backward alignment occurs with relatively long time intervals, the correspondence between successive transforms is apparently established by a relatively slow process, perhaps similar to that of the uprighting process.

In sum, the backward alignment account can handle the observation that the ADP effects are confined to a repetition of the same letter in the same format. According to this interpretation, the ADP effects are not due to a frame rotation process as we previously proposed (Koriat & Norman, 1984), and as Robertson et al. (1987) have recently argued, but derive from an image rotation process in which the orientation of the previous stimulus serves as the referent orientation.

In what follows we shall outline a tentative model that incorporates the concept of backward alignment. It assumes the following:

1. The mental rotation task is normally performed by imagining the stimulus to rotate to the upright orientation, as proposed by Shepard and his associates (see Shepard & Cooper, 1982).

2. When the current stimulus (S2) has the same orientation-invariant shape as the previous stimulus (S1), either of two processes may be used: (a) the uprighting process or (b)

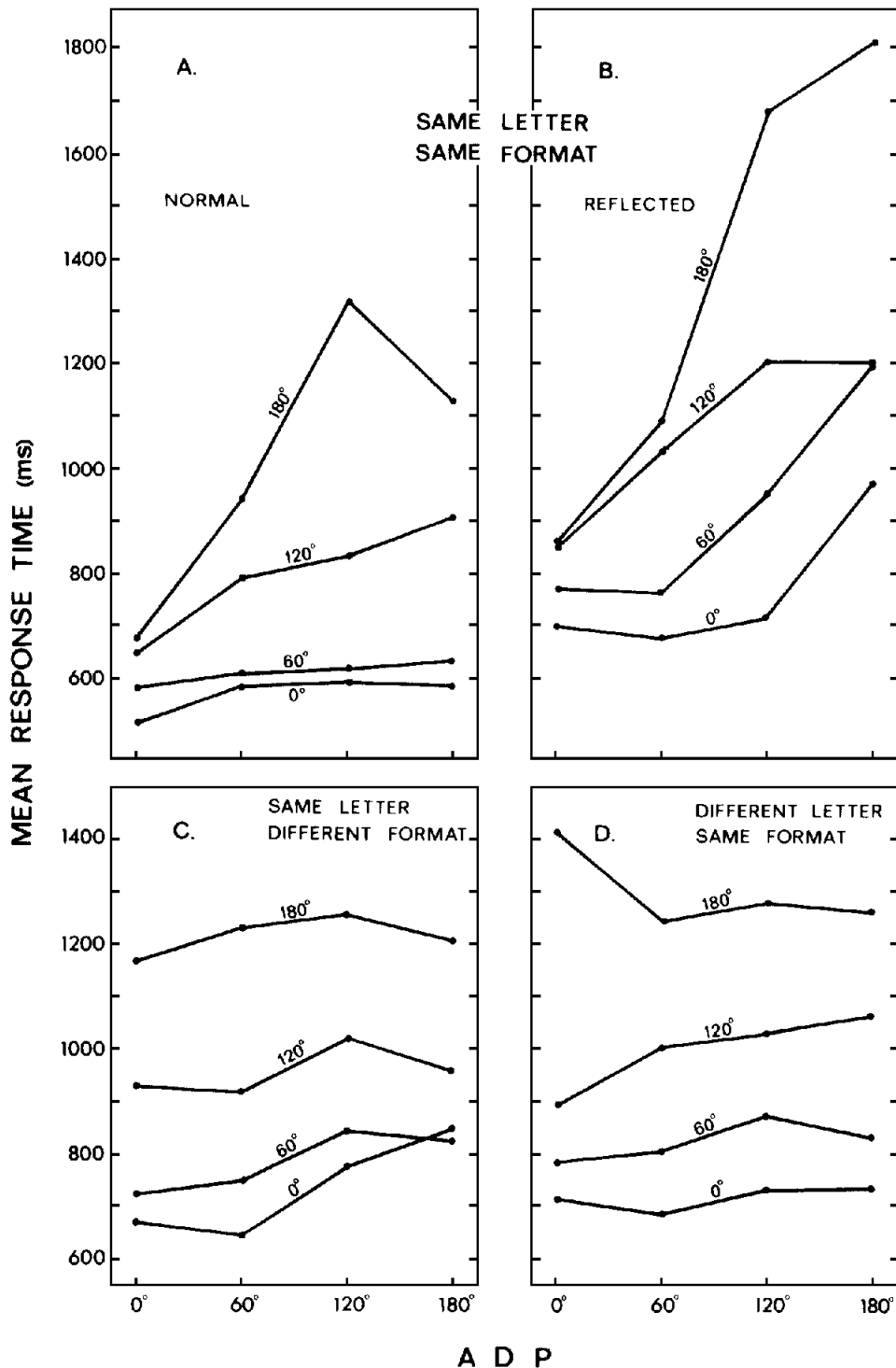


Figure 1. Response time as a function of angular deviation from preceding orientation (ADP), with angular deviation from upright (ADU) as the parameter for different classes of stimulus sequences (Experiment 1).

rotation to the previous orientation, in which the image of S2 is aligned with the trace of S1, and the response is repeated. Unlike the uprighting process, which entails alignment with an abstract orientation (the upright), backward alignment involves alignment with a specific visual representation.

3. Rate of mental rotation (i.e., time per degree) is the same whether rotation is to the upright or to the preceding orientation.

4. In SLSF sequences, the response is determined by the process involving the shortest transformational path. This

assumption implies either that (a) both processes occur in parallel, with the response determined by the first to be completed, or (b) the relative distance of the two referent orientations is first assessed, and the shortest path is then selected. In the latter case backward alignment is used to "implete" the shortest connecting path between S1 and S2, similar to what is assumed to occur for apparent motion (see Shepard, 1984).

Although these assumptions are sufficient to capture the main trends revealed in Figure 1, there are two modifications of Assumption (4) that seem necessary to bring the model into closer agreement with the data.

5. The uprighting process tends to dominate the backward alignment process when $ADP = ADU$, and possibly even when ADU slightly exceeds ADP .

6. This dominance is stronger for normal than for reflected letters. This is because in SLSF sequences two representations compete for the interpretation of S2, the short-term visual trace of S1 and the long-term representation of the normal upright letter. Because the internal representation of the familiar, normal letter may be directly activated over a relatively wide range of disorientations (see Koriat & Norman, 1985a), it may tend to win over the short-term trace of S1. Thus, in comparison to reflected letters, normal letters would be more likely to be compared to their long term visual representations than to the trace of the previous stimuli.

Figure 2 incorporates these assumptions, and presents results predicted for SLSF and non-SLSF sequences. This figure only takes into account the mental rotation stage, although the two processes also differ in the encoding and comparison stages as well, and these differences should also be considered in subsequent work. Some other modifications that might appear necessary are suggested by comparing Figures 1 and 2. However, even in its present form, the model captures the three major trends apparent in the results of Experiment 1: (a) that ADP effects are confined to SLSF sequences, and that (b) for these sequences the effects of ADP increase with increasing ADU , and (c) are more pronounced for reflected than for normal letters.

Experiment 2

According to the frame rotation hypothesis (Koriat & Norman, 1984; Robertson et al., 1987), sequential effects in mental rotation stem from the manner in which S1 is interpreted. In the backward alignment account, in contrast, these effects are attributed to the process underlying the response to S2: In SLSF sequences backward alignment serves to establish the orientation-invariant identity of S2 with S1. Therefore, the occurrence of ADP effects should be contingent on the tendency to repeat on trial n the response executed on trial $n - 1$. This implies that for SLSF sequences we should find a tendency to make the same response on successive trials, for example, if the response to S1 is incorrect, that to S2 will tend to be incorrect as well. This should not obtain for non-SLSF sequences in which the response to S2 is independent of that to S1.

In Experiment 2 a task similar to that of Experiment 1 was used. Only two stimulus characters were used to allow a larger

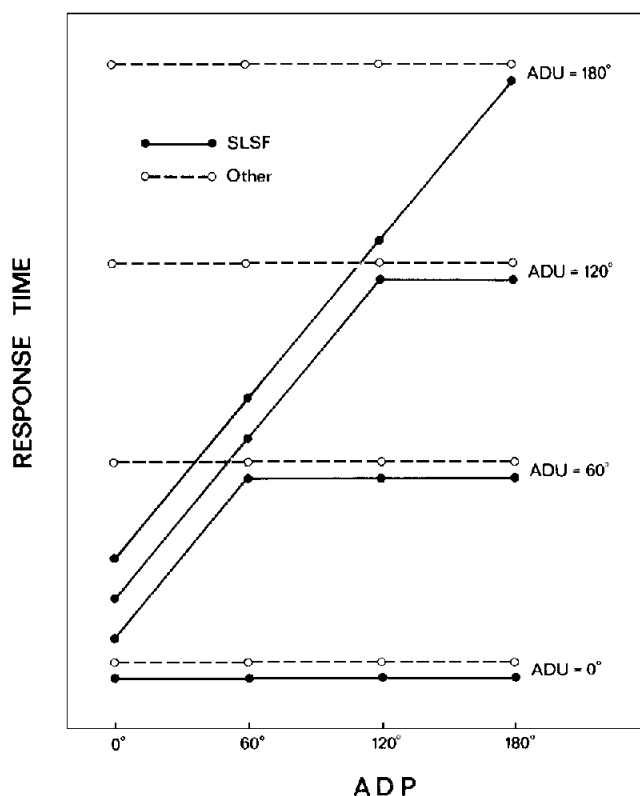


Figure 2. Predicted effects of angular deviation from preceding orientation (ADP) on response time (in arbitrary units) with angular deviation from upright (ADU) as the parameter for same-letter-same-format (SLSF) sequences and for other sequences. (The figure assumes that when ADP is smaller than ADU it is likely to be selected with a probability of .80.)

proportion of SLSF repetitions, and speed instructions were used in order to increase the likelihood of errors (thus allowing the analysis of successive errors). The backward alignment account predicts first, that response repetition should be more likely to occur for SLSF sequences than for the other sequences, and second, that only for SLSF sequences should the likelihood of response repetition decrease with increasing $ADPs$.

Method

Subjects. A total of 16 University of Haifa students participated in the experiment for course credit. None had participated in the previous experiment.

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

Stimuli. Two dissimilar Hebrew letters served as stimuli (see inset, Figure 3). The height of the letters was 1.0 cm (.7°). 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 that prevented head rotations. Viewing distance was 80 cm. Subjects classified the letters as normal or reflected by pressing the

key on their right for "normal" and the key on their left for "reflected." They were urged to respond as quickly as they could while trying not to make too many errors. It was stressed that speed was more important than accuracy. At the end of each block they were shown their average response times and were urged to try and increase their speed. On each trial the stimulus remained on until the subject responded, and was replaced after a 500-ms response-stimulus interval.

The experiment included one practice block (40 trials), followed by eight experimental blocks of 135 trials each. Each block consisted of 7 warm-up trials followed by 128 experimental trials. The last warm-up trial served as a prime for the first experimental trial. For Blocks 2-7 the stimulus in the last warm-up trial was identical to the last stimulus in the previous block. The stimulus order was preprogrammed so that the 1,024 sequences represented all possible combinations of six factors: preceding letter (2), current letter (2), preceding orientation (8), current orientation (8), preceding format (2), and current format (2). Six different orientations (and not 8) were actually used (as in Experiment 1), but the orientations 0° and 180° appeared twice as often as the other orientations, allowing a more balanced representation of ADP and ADU values. Different orders of presentation were randomly generated for each subject, conforming to the aforementioned restrictions.

Results

Responses outside the 250-5,000 ms range (0.9%) were eliminated. Percentage of errors averaged 11.0%, and response time averaged 605 ms. In comparison, the respective figures for Experiment 1 were 5.0% and 930 ms.

The tendency to repeat a response was assessed with the aid of point-biserial correlations between successive responses, calculated for each subject and for each ADP × Sequence Type combination. Of the 256 correlations, 16 were eliminated because all responses to either S1 or S2 were correct. The means, using Fisher Z transforms, of the remaining correlations are presented in Figure 3 for all ADP × Sequence Type combinations.

A two-way analysis of variance (ANOVA) on the Fisher Z transforms (with one correlation coefficient of 1.00 changed to .99) yielded $F(3, 45) = 8.87, p < .0005$, for sequence type; $F(3, 45) = 3.77, p < .02$, for ADP; and $F(9, 119) = 29.95, p < .0001$, for the interaction. For each value of ADP the correlations are higher for SLSF sequences than for any of the other sequence types, and for these sequences they evidence the strongest increase with decreasing ADP.

Mean serial correlation was significantly different from 0 for SLSF sequences, $t(15) = 2.92, p < .02$, but not for DLSF sequences, $t(15) = 1.02$. For both types of sequences, however, it increased significantly with decreasing ADP, $F(3, 42) = 10.48, p < .0001$, for SLSF sequences; $F(3, 41) = 7.06, p < .001$, for DLSF sequences. A two-way ANOVA using only SLSF and DLSF sequences yielded significant effects for sequence type, $F(1, 15) = 5.78, p < .05$; and for ADP, $F(1, 44) = 15.19, p < .0001$, but not for the interaction, $F(3, 39) = 2.16, p < .11$.

The data were also analyzed in terms of the likelihood of repeating an error on two consecutive trials. Mean proportion of error repetitions yielded a very similar pattern to that depicted in Figure 3. First, SLSF sequences exhibited the

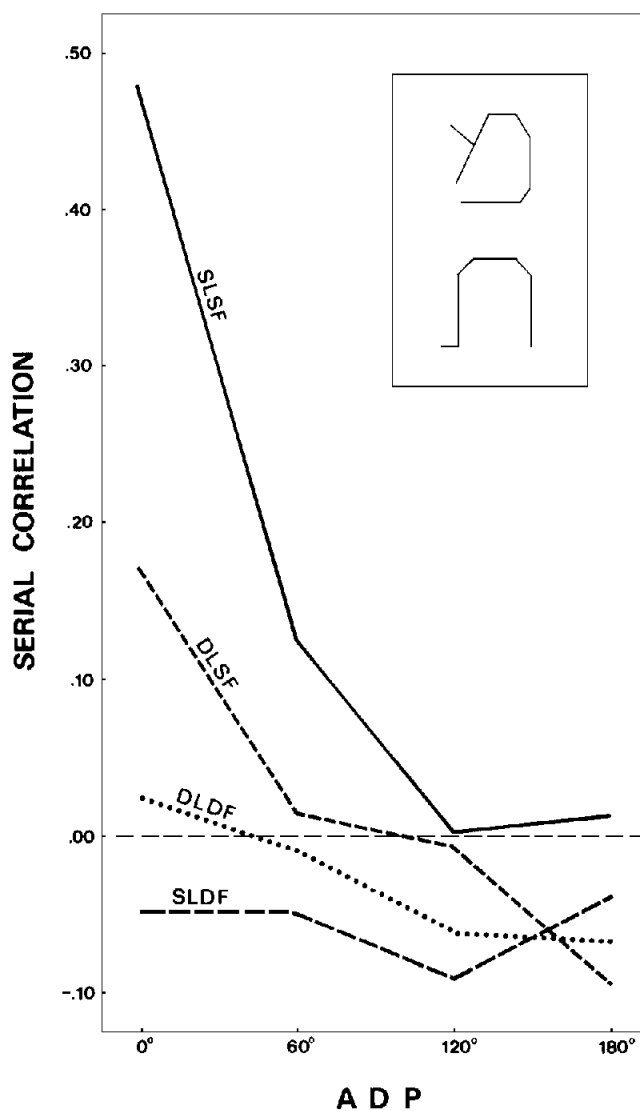


Figure 3. Mean serial correlations for same-letter-same-format (SLSF), same-letter-different-format (SLDF), different-letter-same-format (DLSF), and different-letter-different-format (DLDF) sequences (Experiment 2). (The letters used as stimuli appear in the inset.)

largest proportion of error repetitions. This was not due to a higher error rate for SLSF sequences, as these, in fact, evidenced the lowest error rate. Mean percentage of errors for SLSF, SLDF, DLSF, and DLDF sequences were 8.2%, 14.7%, 10.6%, and 10.7%, $F(3, 45) = 11.87, p < .0001$. Despite the smaller error rate for SLSF sequences the probability of repeating an error on a subsequent trial was .16 for these sequences, compared with .09 for non-SLSF sequences. Second, for SLSF sequences error repetitions tended to decrease with increasing ADPs from .28 to .10. DLSF sequences evidenced the next highest proportion of error repetitions, as well as a slight effect of ADP.

We shall next examine the latency data for correct responses. These indicated a very similar pattern to that ob-

served in Experiment 1. The SLSF sequences yielded strong ADP effects, whereas the remaining three types of sequences evidenced only slight differences in mean response time among them, $F(2, 30) = 6.79, p < .005$, and slight (and nonmonotonic) effects of ADP, $F(3, 45) = 5.45, p < .005$. They also did not differ in the extent of ADP effects, $F(6, 90) = 1.34, ns$. Mean response times for non-SLSF sequences were 630, 605, 615, and 633 ms. The respective means for SLSF sequences were 469, 571, 584, and 614 ms.

Figure 4 compares mean response time for SLSF sequences and the other three types of sequences combined, as a function of ADP, ADU, and format. The results for SLSF sequences are very similar to those of Experiment 1: The effects of ADP are significant, $F(3, 45) = 91.17, p < .0001$; they are stronger for reflected than for normal characters, $F(3, 45) = 8.66, p < .0001$; and they increase with increasing values of ADU, $F(9, 135) = 6.23, p < .0001$. Unlike in Experiment 1, letter and

format repetition in Experiment 2 yielded only facilitatory effects. Surprisingly, this appears to be true even for ADP of 180° . For this ADP, a same-shape repetition required an average of 614 ms, compared with 633 ms for nonrepetition sequences, $F(1, 15) = 10.26, p < .01$, suggesting that a backward alignment process may occur even for the maximal deviation of 180° .

The results for percentage of errors for both SLSF and SLDF sequences mimicked those of response time. For SLSF sequences percentage of errors increased with increasing ADPs, from 5.1% to 12.2%, $F(3, 45) = 13.98, p < .0001$. Similarly, the SLDF sequences yielded the largest percentage of errors, which, like the response time data, were indifferent to ADP. However, for the DLSF sequences error rate increased monotonically with increasing ADPs, from 7.6% to 14.2%, $F(3, 45) = 8.94, p < .0001$. This effect, it should be recalled, had no parallel in the response time data.

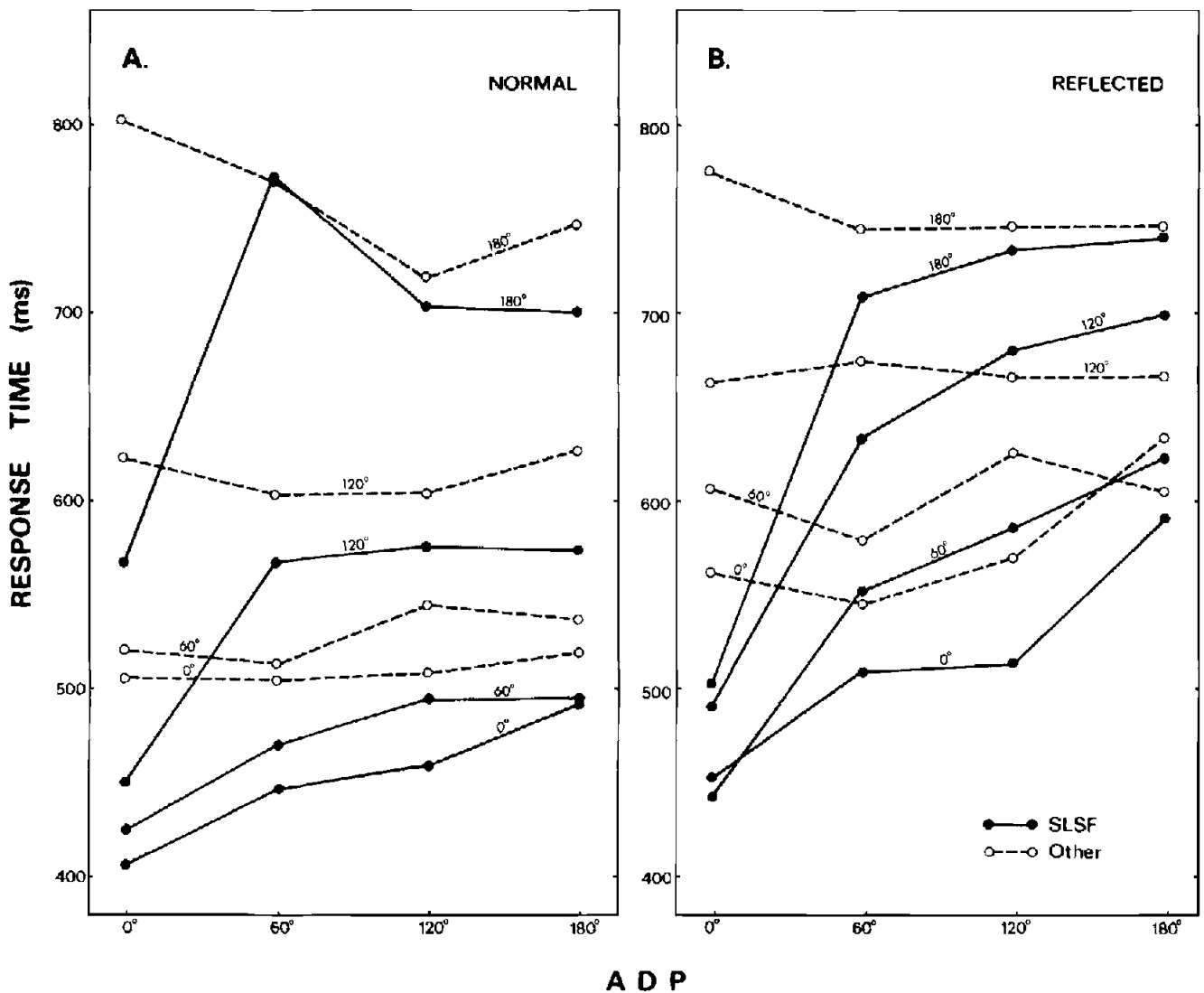


Figure 4. Response time as a function of angular deviation from preceding orientation (ADP), with angular deviation from upright (ADU) as the parameter for same-letter-same-format (SLSF) and other sequences, plotted separately for normal and reflected letters (Experiment 2).

Discussion

The response time results of Experiment 2 are very similar to those of Experiment 1, in spite of the fact that Experiment 2 used speed instructions and only two letters. Thus, ADP effects were confined to SLSF sequences, and for these sequences they increased with increasing ADUs.

The results for both response repetition and proportion of errors were somewhat less unequivocal. Although the results for SLSF sequences were consistent with our hypotheses, DLSF sequences were also found to yield a large proportion of response repetitions, as well as significant ADP effects. They also evidenced significant ADP effects for error rate of nearly the same magnitude as those observed for SLSF sequences. This, together with the finding that SLDF sequences yielded the smallest indication of response repetition, suggests that format repetition has a greater effect than letter repetition. A similar observation was made by Robertson et al. (1987, Experiments 1 and 3) for response times.

The results for DLSF sequences are consistent with a process of intrinsic frame rotation, and suggest that what remains after responding to S1 is an abstract intrinsic frame characterized by the orientation and format of S1. S2 may then be interpreted within this frame. The observation that the ADP effects are confined to same-format sequences may indicate either that this frame is used only when that of S2 happens to match it, or that a process of backward frame alignment occurs. Both of these processes must assume some preliminary knowledge of the format of S2, or of its agreement with that of S1. The observation that the ADP effects for DLSF sequences obtain for percentage of errors and response repetitions, but not for response time may hint that the process of frame matching operates in an all-or-none fashion and does not have to be established through mental rotation. Rather, the intrinsic frame of S1 is adopted in responding to S2, with the probability of frame matching increasing with smaller ADPs. This idea deserves further research, because it implies a procedure for distinguishing between different types of sequential effects.

Experiment 3

In Experiment 2 speed instructions were used to allow analysis of response dependencies. Experiment 3 used accuracy instructions as well as a larger sample of orientations. Apart from testing the main predictions of the backward alignment model, Experiment 3 had three additional aims:

Comparing ADU and ADP Rotation Functions

Because SLSF sequences involve a mixture of two mental rotation processes (uprighting and backward alignment) the latency-ADP function for these sequences should reflect conjointly on two factors, the likelihood of using one or the other process and the time required for mental rotation. In contrast, the latency-ADU function for non-SLSF sequences may directly reflect the uprighting process. Consequently, even if the two processes function at the same speed, we should expect systematic differences between the empirical function relating

response time to ADP for SLSF sequences and that relating response time to ADU for non-SLSF sequences.

One difference concerns the shape of the two rotation functions. We know that the ADU function is typically positively accelerated, indicating relative indifference to small ADUs (e.g., Cooper & Shepard, 1973; Hock & Tromley, 1978). In contrast, the ADP function for SLSF sequences should, perhaps, be negatively accelerated, indicating relative indifference to large ADPs. This is because for large ADPs, backward alignment takes longer, but the likelihood of backward alignment occurring decreases.

The second difference concerns the rotation functions for normal and reflected letters. Previous results (see Koriat & Norman, 1985a) suggest that normal characters can be readily recognized despite small departures from the upright, whereas reflected characters require mental rotation to near-upright and tend to induce more extensive comparison processes. We propose that these differences are confined to the uprighting process, in which the stimulus is compared to a long-term visual representation. In the case of backward alignment, S2 is matched against the short-term visual trace of S1, and therefore the (theoretical) rotation function should be the same for normal and reflected characters. This proposition cannot be tested directly, but it implies that the difference between reflected and normal characters should decrease as the probability of backward alignment increases. It should be small for $ADP = 0^\circ$, and should increase with increasing ADP. This contrasts with what we know about the effects of ADU, where this difference is largest for small ADUs, and decreases with increasing ADU.

Qualitative Differences

The uprighting process is assumed to proceed toward the upright, generally along the shortest path, and to end when the upright orientation is reached. Because backward alignment is assumed to be stimulus driven, it does not have to obey the rules governing the uprighting process. Thus, it may proceed in a direction away from the upright and even cross the upright. These possibilities will be examined by investigating the effects of ADP on several selected orientation sequences.

Interactions Between the Two Processes

Two hypotheses may be advanced regarding possible interactions between the uprighting and backward alignment processes. Both assume that in backward alignment it is the image of S2 that is brought into alignment with that of S1.¹ According to the *prepared image hypothesis*, backward alignment can take advantage of the images generated during a previous uprighting process, and therefore should prove particularly beneficial when S2 corresponds to one of the phases of the rotation of S1.

¹ At present this assumption rests only on introspections, but it is open to further research. We should note that it implies rotation in the direction opposite to that which generally characterizes apparent motion.

According to the *direction consistency hypothesis*, backward alignment is more likely to occur when it is in the same direction as that of the uprighting process (i.e., toward the upright) than when it is in the opposite direction. Thus, for SLSF sequences such as 30°–330° both processes require a rotation in the same direction, and the initiation of an uprighting process does not preclude taking advantage of processes related to S1.

Method

Apparatus and procedure. The apparatus and procedure were the same as in Experiment 2, with the following exceptions. The letters (inset in Figure 3) appeared in 12 different orientations, 0° to 330°, in 30° steps. In each of two sessions one practice block (80 trials) was followed by eight experimental blocks of 151 trials each consisting of 7 warm-up trials, followed by 144 experimental trials. For Blocks 2–16 the stimulus in the last warm-up trial was identical to that of the last stimulus in the previous block. The 2,304 sequences represented all possible combinations of six factors: preceding letter (2), current letter (2), preceding orientation (12), current orientation (12), preceding format (2), and current format (2). The instructions were similar to those of Experiment 1 (i.e., no special emphasis on speed).

Subjects. A total of 16 University of Haifa students participated for course credit. None had participated in the previous experiments.

Results

Response latencies outside the range 250–5,000 ms were eliminated (0.1%). Preliminary analyses of the correct response times indicated strong ADP effects only for SLSF sequences, which increased from 509 ms for ADP 0° to 662 ms for ADP 180°, $F(6, 90) = 64.60, p < .0001$. Similarly, percentage of errors increased from 0.3% to 3.9%, $F(1, 15) = 7.98, p < .0001$. For the other sequences, a Sequence Type \times ADP ANOVA on response time indicated significant effects only for sequence type, $F(2, 30) = 6.87, p < .005$. Mean response times for SLDF, DLSF, and DLDF sequences were 674 ms, 653 ms, and 671 ms, respectively. Separate one-way ANOVAs for each of three sequences yielded no significant ADP effects. A similar two-way ANOVA on percentage of errors yielded $F(2, 30) = 6.64, p < .005$, for sequence type, but no significant effects for either ADP or the interaction. Mean percentage of errors for SLDF, DLSF, and DLDF sequences were 5.0%, 4.1%, and 2.9%, respectively. It should be noted that for DLSF sequences there was a slight increase in percentage of errors from ADP = 0° (3.4%) to ADP = 180° (5.1%), but unlike Experiment 2 it was not significant, $F(6, 90) = 1.61, p < .15$.

Comparing ADU and ADP rotation functions. Figure 5 presents mean response time as a function of absolute orientation. An ANOVA on these data indicated significant effects for orientation, $F(11, 165) = 78.74, p < .0001$; for format, $F(1, 15) = 62.68, p < .0001$; and for their interaction, $F(11, 165) = 6.23, p < .0001$. The largest differences between reflected and normal letters obtain for small ADUs. Percentage of errors increased systematically with increasing ADU from an average of 1.3% at 0° to an average of 10.3% at 180°.

Figure 6 shows the effects of deviation from preceding orientation in a presentation format comparable to that of

Figure 5. In this figure relative orientation is defined as the angular deviation of S2 from S1 in a clockwise direction (i.e., increasing with increased angular deviation of S2 from S1 in a clockwise direction). In Figure 6A the results are grouped according to ADU, and in Figure 6B they are presented separately for normal and reflected characters.

Several features of Figure 6 are noteworthy:

1. Non-SLSF sequences exhibit no effect of ADP whatsoever, whereas SLSF sequences indicate systematic and sizable effects. Mean response times for non-SLSF sequences are roughly equivalent to the respective SLSF means at ADPs of 180°, suggesting that the effect of shape repetition is mainly facilitatory.

2. ADP effects for SLSF sequences increase markedly with increasing ADUs (Figure 6A), consistent with previous findings and with the model proposed. Note that for ADUs of 0°–60° the weak effects of relative orientation obtain for non-SLSF sequences as well, $F(6, 90) = 6.18, p < .0001$. This might have been taken to suggest the operation of a frame rotation process for relatively small ADUs. However, a similar analysis carried out for ADUs of 150°–180° indicated a significant *increase* in response time with decreasing ADP, $F(6, 90) = 3.18, p < .01$. We suspect that both of these effects reflect the general tendency of response times to be faster following an easy item than following a hard item (see Koriat & Norman, 1984). For small ADUs, larger ADPs are associated with larger values of preceding ADUs, whereas for large ADUs they are associated with smaller values of preceding ADUs. Indeed, response time increased systematically (from 653 to 696 ms) as the preceding ADU increased, $F(6, 90) = 17.76, p < .0001$. The data for percentage of errors did not indicate a similar effect.

3. Comparing Figures 6B and 5, it is clear that while response time is a positively accelerated function of ADU, particularly for normal characters, it increases in a negatively accelerated manner with increasing ADPs. This is what would be expected if the ADU rotation function mainly reflects rotation time, whereas the ADP rotation function reflects both the likelihood of backward alignment (which decreases with increased ADP), and rotation time (which increases with increased ADP). An ANOVA on the data of Figure 6B yielded significant effects for relative orientation, $F(11, 165) = 23.45, p < .0001$; for sequence type, $F(1, 15) = 60.20, p < .0001$; and for their interaction, $F(11, 165) = 32.73, p < .0001$. The effects of format were significant, $F(1, 15) = 66.74, p < .0001$, and were stronger for SLSF than for non-SLSF sequences, $F(11, 165) = 13.51, p < .005$. Relative orientation had a stronger effect on normal than on reflected letters, $F(11, 165) = 3.46, p < .0005$. The triple interaction was also significant, $F(11, 165) = 3.09, p < .001$.

4. Response latencies are generally longer for reflected than for normal letters. However, the difference is largest for small ADUs and decreases with increased ADU (Figure 5). In contrast, it is smallest for small ADPs and increases with increased ADP for SLSF sequences (Figure 6B). A two-way ANOVA for SLSF sequences yielded a significant interaction between format and relative orientation, $F(11, 165) = 4.12, p < .0001$.

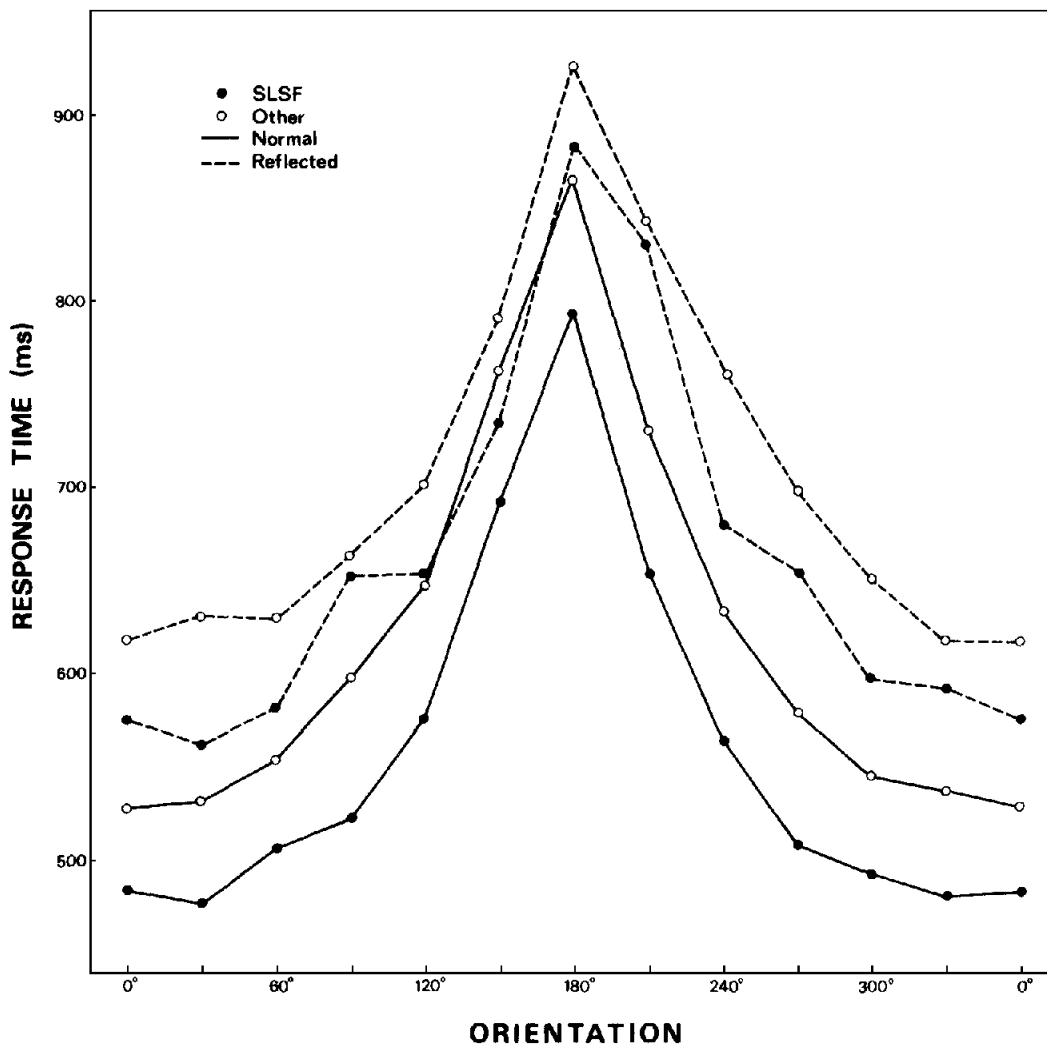


Figure 5. Response time as a function of stimulus orientation for normal and reflected characters for same-letter-same-format (SLSF) and other sequences (Experiment 3).

Qualitative differences between the uprighting and backward alignment processes. As typically conceptualized, the uprighting process always proceeds towards the upright along the shortest path, and is completed when the upright orientation or some near-upright orientation is reached. We shall examine backward alignment in the light of this characterization by focusing on four types of S1-S2 sequences.

1. Consider the situation in which S1 is upright. Here the mental rotation operation is the same whichever process is involved. Yet, for this situation mean response time was faster for SLSF (602 ms) than for non-SLSF sequences (653 ms), $t(15) = 4.21, p < .001$. This was true even when sequences in which S2 was upright were excluded. Conceptually, even when S1 is upright the backward alignment process may be distinguished from the uprighting process in terms of the internal representation that is used as a reference. In the case of the uprighting process it is the long-term, permanent representation, whereas in the case of backward alignment it is the short-term trace of the preceding stimulus. Accessing the latter and

repeating the same response appears to require less time than arriving at an independent decision on the basis of the internal representation.

2. When S2 was upright but S1 was not, mean response times for SLSF and non-SLSF sequences were 535 and 571 ms, respectively, $t(15) = 5.79, p < .0001$. When S1 is upside-down but S2 was not, mean response time for SLSF sequences was 626 ms, compared with 677 ms for non-SLSF sequences, $t(15) = 4.20, p < .001$. Both of these observations suggest that backward alignment may occur even when it calls for mental rotation *away from the upright*.

3. Would backward alignment proceed *beyond the upright*? Consider sequences in which the orientation of S2 is either 30° or 330°, and the orientation of S1 is on the other side of the upright, at an angular deviation of less than 180°. For these sequences response times were faster for SLSF sequences (565 ms) than for the other sequences (609 ms, $t(15) = 5.27, p < .0001$). Thus, although the uprighting process apparently ends when the upright orientation is reached, backward align-

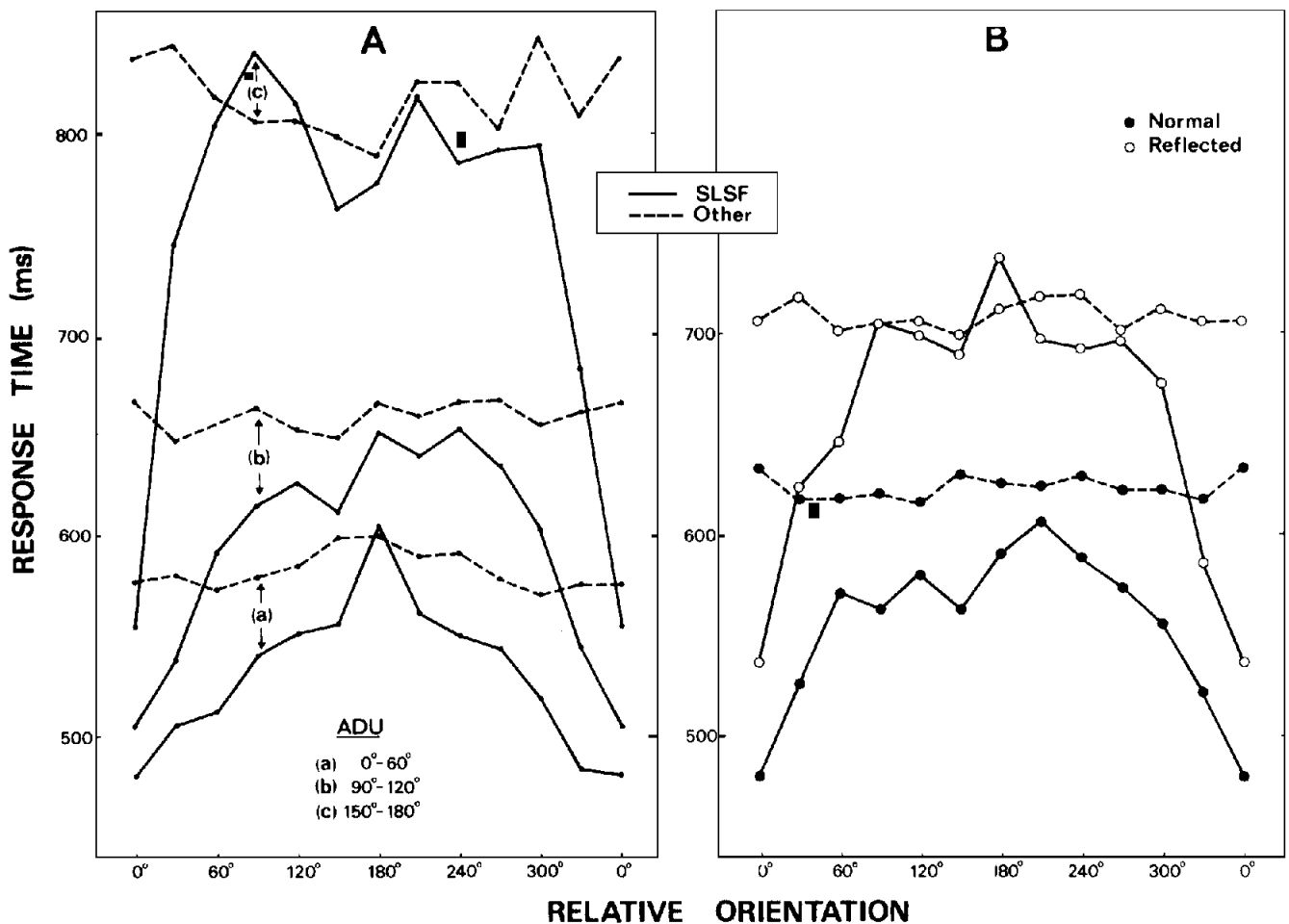


Figure 6. Response time as a function of relative orientation for same-letter-same-format (SLSF) and other sequences plotted (A) with ADU as a parameter and (B) for normal and reflected characters separately (Experiment 3).

ment may traverse the upright and, despite the larger angular distance, the response may end up taking less time than when an uprighting process is used.

4. Finally consider the possibility of backward alignment across the 180° orientation. When S2 was either 150° or 210°, and S1 was on the other side of the 180° orientation, but at an ADP of less than 180° we found somewhat faster response times for SLSF (669 ms) than for non-SLSF sequences (694 ms), $t(15) = 2.04$, $p < .06$.

The faster response times observed for SLSF sequences in the previous analyses could stem from the fact that these sequences involve response repetition. However, all of the foregoing analyses were repeated comparing only SLSF and DLSF sequences, in which the same response is repeated, and the results were essentially the same as those presented above.

In conclusion, backward alignment does not seem to conform to the constraints assumed to characterize the uprighting mental rotation process. It may proceed beyond the upright, may follow a direction that is away from the upright, and may cross over across the 180° orientation. This is consistent

with our conceptualization that it is more automatic and more data driven than the uprighting process.

Interactions between the uprighting and backward alignment processes. The prepared image hypothesis predicts that for SLSF sequences the effects of S1 on S2 should be particularly pronounced when the orientation of S2 is intermediate between that of S1 and the upright. To examine this possibility, we confined ourselves to same-side orientation sequences, that is, sequences in which both orientations were smaller than 180° or both larger than 180°. All sequences with ADP of 0° were excluded, as were all sequences in which one of the orientations was either 0° or 180°. Of the remaining sequences, 16 were chosen. These formed eight pairs, matched for ADP and ADU values. In one member of each pair the orientation of S1 was intermediate between that of S2 and the upright, whereas in the other it was S2 that occupied the intermediate orientation. Table 1 lists the 16 sequences and the mean response times. For SLSF sequences, response time was significantly shorter when S2 occupied the intermediate orientation than when it was farther away from the upright, $t(15)$

Table 1
Mean Response Times (in Milliseconds) for Same-Side Sequences for S1 and S2 as a Function of Orientation (in Degrees)

Orientation		Response time	
S1	S2	SLSF	Other
S1 closer to upright			
90	60	489	569
150	90	574	604
120	90	499	617
150	120	537	668
210	240	533	691
240	270	503	623
210	270	572	618
270	300	487	594
<i>M</i>		524	622
S2 closer to upright			
30	60	542	612
30	90	566	624
60	90	537	629
90	120	586	652
270	240	592	703
300	270	582	661
330	270	553	605
330	300	486	618
<i>M</i>		555	638

Note. S1, S2 = successive stimuli; SLSF = same-letter-same-format sequence.

= 4.59, $p < .0005$. This pattern was obtained for 14 of the 16 subjects. Although a similar analysis for non-SLSF sequences also yielded a significant difference, $t(15) = 2.38$, $p < .05$, the effect obtained for SLSF sequences was significantly larger, $F(1, 15) = 8.68$, $p < .01$. These results are consistent with the idea that the internal representations generated in the process of mental rotation may be utilized when the succeeding stimulus corresponds to one of these representations.

According to the direction consistency hypothesis, backward alignment is more likely to occur when it calls for a rotation towards the upright than when it calls for a rotation away from it. The results for same-side sequences seem to argue against this hypothesis, but because the ADP effects are not confined to same-side sequences, it is of interest to evaluate the hypothesis over the entire range of orientation sequences.

Perhaps the simplest approach (although it is somewhat crude) is to compare the effects of ADP for two groups of absolute orientations: from 30° to 150°, and from 210° to 330°. These are matched for ADU, but for the first group the uprighting process calls for a counterclockwise rotation, whereas for the second it calls for a clockwise rotation.

Figure 7 presents mean response time for the two groups of orientations as a function of relative orientation for SLSF sequences. In calculating these means we first corrected the response time data of each subject by partialing out the contribution of preceding ADU. This is because, as we noted earlier, response time tends to be faster following a stimulus with a small ADU than following a stimulus with a large

ADU, and this could account for part of the difference between the two groups of orientations. It may be seen that the two rotation curves display different types of asymmetry. A two-way ANOVA for these data yielded $F(1, 15) = 2.06$, *ns*, for current orientation; $F(11, 165) = 30.54$, $p < .0001$, for relative orientation; and $F(11, 165) = 4.34$, $p < .0001$, for the interaction.

The pattern displayed in Figure 7 suggests that direction consistency affects response time mainly beyond the 60° or 90° ADPs, where the response to S2 is more strongly facilitated when S1 lies in the direction of the upright than when it lies in the opposite direction. Thus, given an S2 at 120° orientation, backward alignment is more likely when the orientation of S1 is 60° than when it is 180°.

If the direction consistency hypothesis is correct, backward alignment across the 0° orientation (same direction, e.g., from 90° to 330°) should be more likely to occur than backward alignment across the 180° orientation (opposite directions, e.g., from 90° to 210°). Excluding 0° and 180° orientations and considering all orientation sequences with an ADP of less than 180° in which S1 and S2 lie on different sides of the 180° orientation, we compared those sequences where backward alignment along the shortest path requires crossing the upright and those in which it involves crossing the 180° orientation. For the across-0° sequences mean response time for SLSF and non-SLSF sequences were 559 ms and 598 ms, respectively, $t(15) = 4.66$, $p < .0005$. The respective means for the across-180° sequences were 697 ms and 714 ms, $t(15) = 1.73$, *ns*. Essentially the same results were obtained when the effects of preceding ADUs were partialled out.

Discussion

The response time data of Experiment 3 replicate the major findings of Experiments 1 and 2, in that the ADP effects were entirely confined to SLSF sequences, and for these they increased with increasing ADUs, and were stronger for reflected than for normal characters. ADP effects were mainly facilitatory so that at ADP = 180°, the response times for SLSF sequences attained a level similar to those of non-SLSF sequences. Systematic ADU effects were obtained even when ADP = 0°, consistent with the assumed bias toward using the uprighting process. However, as in Experiment 2, systematic ADP effects were also found when ADU = 0°. When both of these findings are considered together they appear to call for a probability mixture model of the sort proposed by Robertson et al. (1987): Choice of reference orientation is generally determined by the process requiring the shortest rotational path, but this occurs with a probability that is greater than .5 but not necessarily 1.0. Also, as in Experiment 2, the ADP-latency function evidences a negatively accelerated trend even for ADU = 180°, which should also call for some modification of the model. We should note that the error data for DLSF sequences did not evidence the same sort of ADP effects observed in Experiment 2. This may suggest that processes of intrinsic frame rotation may only occur under specific conditions, such as those using speed instructions (Experiment 2), or using brief interstimulus intervals (Robertson et al., 1987).

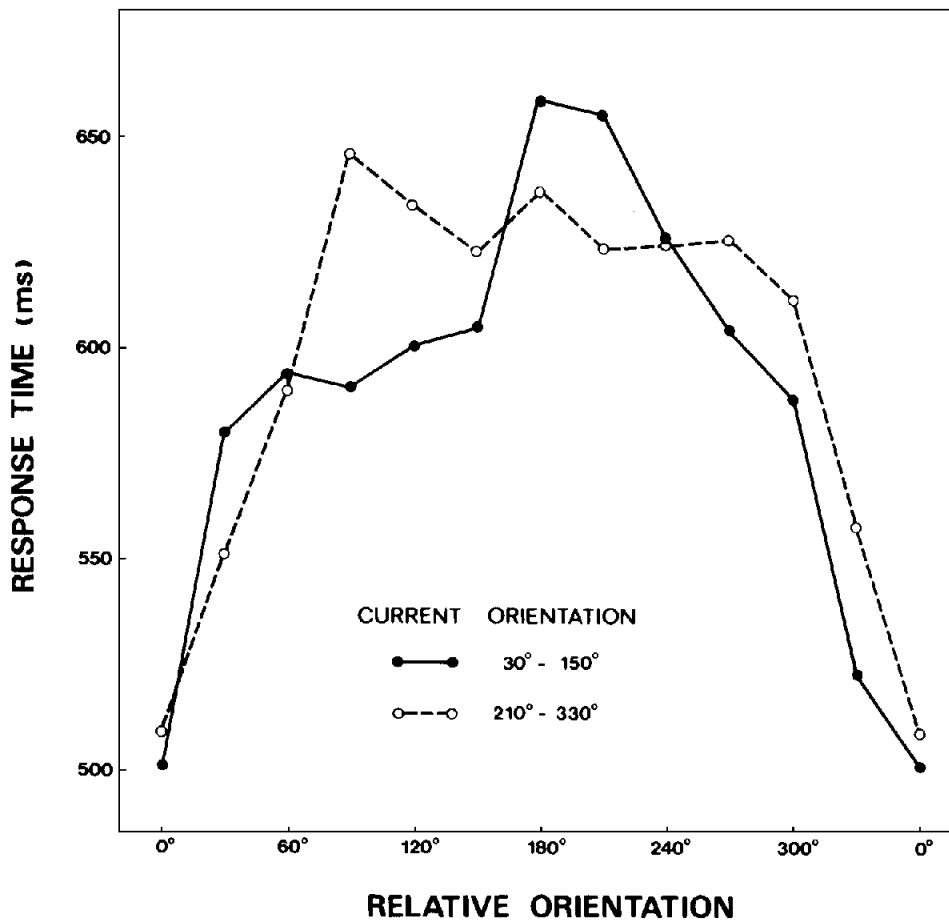


Figure 7. Response time as a function of relative orientation for same-letter-same-format (SLSF) sequences for two groups of absolute (current) orientation (Experiment 3).

The results of Experiment 3 also support our assumption that the backward alignment process differs from the uprighting process in both the representation that serves as a reference and in the nature of the mental rotation process involved. Although the pertinent evidence is indirect, it suggests that backward alignment is solely responsive to the visual codes of S1 and S2, and, unlike the uprighting process, is indifferent to the manner in which the stimuli are internally represented in permanent memory. As for the mental rotation process itself, the results of Experiment 3 suggest that in contrast to the uprighting process, backward alignment is stimulus initiated and activated without regard to the location of the vertical.

Finally, evidence exists for interactive effects between the two processes. Some support was found for the prepared image hypothesis suggesting that imaginal processes that occur in the wake of S1 may be used in the backward alignment process activated by S2. However, the direction consistency hypothesis also gained some support, in that the effects of ADP were stronger when backward alignment was presumed to proceed towards the upright. This may stem from two processes. First, when an uprighting process is initiated, a switch to backward alignment is more likely to occur for

same-direction than for conflicting-direction sequences. Second, switching directions of rotation from one trial to another, as such, may delay response time. Some support for the latter possibility comes from the observation that even for the uprighting process, such a switch delays the response slightly. Looking only at non-SLSF sequences, and excluding all sequences in which the orientation of either stimulus was 0° or 180°, sequences involving a switch in direction of rotation required 656 ms, compared with 646 ms for those involving the same direction of rotation, $t(15) = 3.20$, $p < .01$.

Experiment 4

Cooper and Shepard (1973) found that advance information regarding the orientation of the upcoming stimulus was ineffective in eliminating the effects of stimulus orientation. Hinton and Parsons (1981), on the other hand, found this information to be effective when the stimulus set consisted only of characters with similar features, a "front" that faces to the right (e.g., F, G, L, and R), but not when it included characters presumably having inconsistent fronts (e.g., F, R, J and 7).

Experiment 4 examined whether sequential effects in mental rotation are also sensitive to the specific characteristics of the set of letters used as stimuli. Perhaps, with conditions similar to those of Hinton and Parsons (1981), ADP effects might extend to non-SLSF sequences. However, the process of backward alignment, as conceptualized here, differs from that of mental rotation that presumably underlies the preparation of an image (Cooper & Shepard, 1973) or of an intrinsic frame (Hinton & Parsons, 1981). It is data driven and activated ad hoc only after the presentation of S2. Therefore, it is expected to be relatively insensitive to either the expectations of the subject or the set of stimuli used.

Experiment 4 differed from the previous experiments in two aspects. First, it used two conditions that differed in the sets of stimuli used (FGLR and FGJ7). Second, sequential dependence was introduced, so that the probability that a given orientation would be repeated on the next trial was .80. This manipulation was intended to encourage subjects to prepare for a particular orientation. Thus, each S1 stimulus provided both advance information regarding the orientation of the upcoming stimulus and a potential referent representation for the backward alignment of S2 in SLSF sequences. If the process of backward alignment is the same as that underlying the preparation for a given orientation, then the combination of sequential dependence with frame consistency (condition FGLR) should yield ADP effects for non-SLSF sequences and reduce, or perhaps eliminate, the differences between SLSF and other sequences.

Method

Subjects. A total of 16 University of Haifa students participated in the experiment. None had participated in the previous experiments.

Stimuli. The stimuli were six characters, F, G, L, R, J, and 7, and their mirror images. The height of the letters was 1.8 cm, and they appeared at one of six orientations, 0°, 60°, 120°, 180°, 240°, and 300°.

Design and procedure. The two conditions, Condition FGLR and Condition FGJ7, differed only in the set of stimulus characters used. Eight subjects were assigned to each condition.

Stimulus order was preprogrammed to produce a total of 1,024 critical sequences (S1-S2) and 3,136 filler sequences. The 1,024 critical sequences represented all combinations of preceding orientation (8), current orientation (8), preceding format (2), and current format (2), with four sequences in each combination. The four letters were equally represented and were randomly distributed with the constraint that of the four sequences in each combination, one was an SLSF sequence. There were actually only six different orientations, but, as in Experiment 2, 0° and 180° appeared twice as often as the other orientations.

The remaining 3,136 sequences all involved orientation repetitions (i.e., S1 and S2 in the same orientation), and were included in order to produce a .80 likelihood of orientation repetition throughout the entire experiment. The positions of the critical sequences were random throughout the list, with the constraint that no orientation was repeated more than seven times in sequence. The choice of letter and format for the filler trials was random. The sequence of stimuli was programmed separately for each of the subjects.

The entire experiment consisted of 30 blocks, 10 blocks per session, each session on a different day. Each block consisted of 145 trials. The first 6 trials of each block (in the case of the first block, the first 11 trials) were warm-up trials, with the last warm-up trial serving as

a prime for the first experimental stimulus. For Blocks 2–30 this stimulus was identical to the last stimulus in the previous block. Each session began with 60 practice trials. Subjects were instructed to try and take advantage of the sequential dependency by preparing for orientation repetitions. The apparatus was the same as in the previous experiments.

Results

Response times outside the range of 250–5,000 ms were eliminated (1.3%). An initial analysis yielded very similar results to those obtained in the previous experiments: The effects of ADP were still markedly stronger for SLSF than for non-SLSF sequences, and for the former sequences they increased with increasing ADUs. But, surprisingly, ADP effects for non-SLSF sequences were obtained for *both* conditions, and not only for the frame consistency (FGLR) condition. The results are summarized in Figure 8 (left panel).

For non-SLSF sequences a Condition \times ADP ANOVA on correct response times yielded highly significant effects for ADP, $F(3, 42) = 37.81, p < .0001$, which interacted with condition, $F(3, 42) = 8.41, p < .0002$. A similar ANOVA on percentage of errors yielded significant effects for ADP, $F(3, 42) = 19.39, p < .0001$; for condition, $F(1, 14) = 15.51, p < .005$; and for their interaction, $F(3, 42) = 8.66, p < .0001$. Both response time and percentage of errors increased with increasing ADPs, and this increase, if anything, was somewhat larger for Condition FGJ7 than for Condition FGLR. The difference is largely due to the fact that in Condition FGJ7 both percentage of error and response time are markedly lower for ADP = 0° relative to the other ADPs. When the analysis was confined to ADPs larger than 0°, a two-way ANOVA for response time yielded $F(2, 28) = 4.92, p < .02$ for ADP, and $F < 1$ for the Condition \times ADP interaction.

For SLSF sequences a Condition \times ADP ANOVA for response times yielded $F(3, 42) = 64.76, p < .0001$, for ADP. A similar ANOVA on percentage of errors yielded $F(3, 42) = 10.27, p < .0001$, for ADP; and $F(3, 42) = 3.31, p < .05$, for the Condition \times ADP interaction, suggesting somewhat more pronounced ADP effects for Condition FGLR than for Condition FGJ7.

We also compared the two conditions focusing only on the two letters in common, F and G, using only sequences in which S2 was one of these two letters. As can be seen (Figure 8, right panel) the results are very similar to those obtained for all letters. Condition \times ADP ANOVAs on SLSF and non-SLSF sequences yielded virtually the same pattern of results obtained in the analyses which included all the letters.

Thus, the expected difference between the two conditions was not obtained. Rather, the results presented in Figure 8 suggest first that for non-SLSF sequences ADP effects are greater for the FGJ7 than for the FGLR condition, whereas SLSF sequences tend to evidence the reverse pattern, and second that the effects of same-shape repetition is largely facilitatory for Condition FGJ7, whereas for Condition FGLR it tends to be inhibitory for high ADP values.

While the ADP effects for non-SLSF sequences did not vary with the set of letters used, they may still depend on the two successive letters having consistent fronts. Two analyses explored this possibility. First, focusing on Condition FGJ7

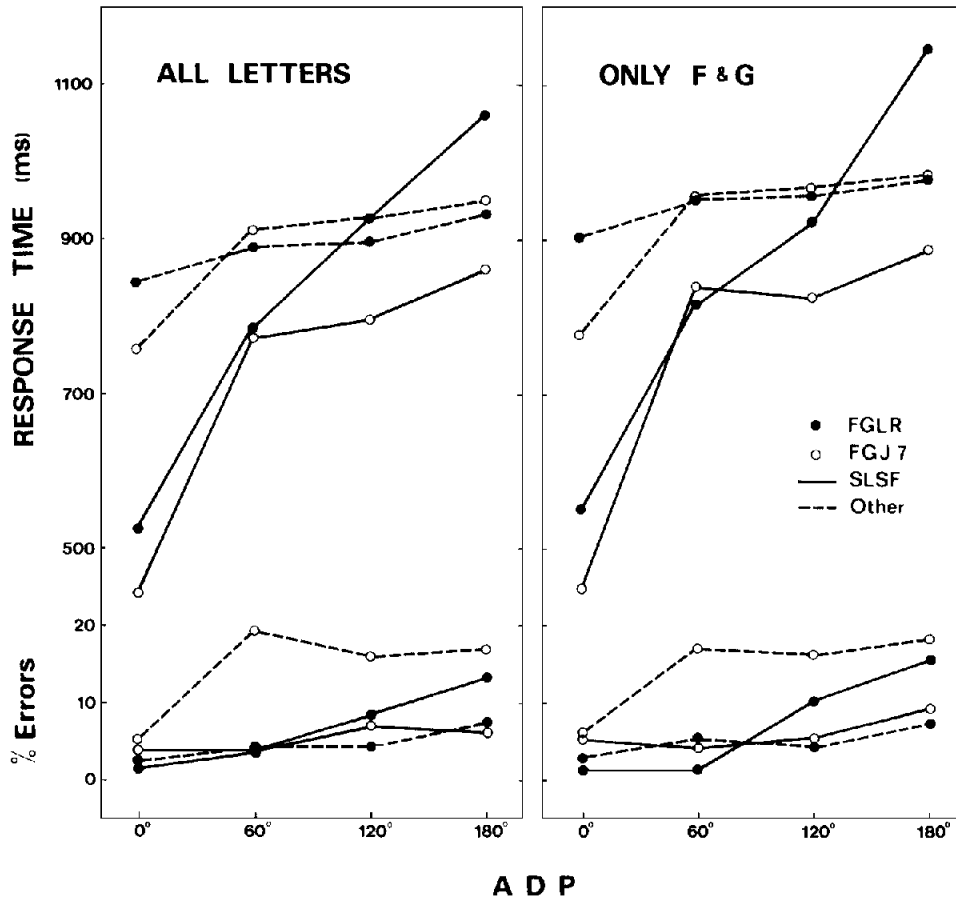


Figure 8. Response time and percent errors as a function of angular deviation from preceding orientation (ADP) for same-letter-same-format (SLSF) and non-SLSF sequences in Conditions FGLR and FGJ7. (The left panel is based on all four characters and the right panel is based on the common characters (FG) only (Experiment 4).

alone, we compared DLSF sequences in which the two letters had similar fronts (i.e., F-G, G-F, J-7, 7-J) with those in which they had different fronts (e.g., F-J, 7-G, etc.). A two-way ANOVA indicated that ADP effects were no stronger for the former than for the latter. The second analysis was based on the different-letter sequences in Condition FGLR. The results indicated that for these sequences the effects of ADP were no stronger for same-format than for different-format sequences.

These results suggest that the effects of ADP on different-letter sequences are not due to a backward alignment process in which the abstract frame of S1 is aligned with the abstract frame of S2.

Discussion

In Experiment 4 we attempted to mimic the advance information paradigm (Cooper & Shepard, 1973) under conditions that are amenable to the occurrence of backward alignment. The sequential dependency allowed each stimulus (S1) to serve as a prime for the subsequent stimulus (S2) in two capacities, first as a valid predictor of the orientation of S2 and second, as a potential reference representation for the

backward alignment of S2. If backward alignment rests on a process similar to that underlying the use of advance orientation information, then it should also prove sensitive to the manipulation investigated by Hinton and Parsons (1981). Specifically, with advance orientation information ADP effects should extend to non-SLSF sequences when the stimuli share certain structural features.

The results are rather clear: There is no evidence that frame consistency increases the extent of ADP effects for sequences not involving a shape-preserving transformation, and, if anything, the results point in the opposite direction. Evidently, the backward alignment process differs from the process by which advance orientation information reduces the need for mental rotation to the upright. It depends strictly on the characteristics of the stimulus sequences in question, and is insensitive to the characteristics of the stimulus ensemble as a whole.

Other results are less simple to interpret. In comparing the results of Experiment 4 with those of the previous experiments, two differences emerge. First, the effects of ADP for SLSF sequences were somewhat stronger in Experiment 4. The overall extent of these effects, from 0° to 180°, amounted

to 312, 145, and 153 ms for Experiments 1, 2, and 3, respectively, compared with 476 ms for Experiment 4. The difference between Experiment 4 and Experiment 1 (both of which involved four stimulus letters and comparable overall response times) mainly stems from the fact that response times for ADP = 0° were substantially faster in Experiment 4. Second, only in Experiment 4 were significant ADP effects obtained for non-SLSF sequences. The extent of these effects for Experiments 1, 2, and 3 were 35, 3, and -1 ms, respectively, compared with 139 ms for Experiment 4. Here, too, the largest difference was between ADP of 0° and the remaining ADPs. It should be stressed that the ADP effects did not evidence a speed-accuracy trade-off, because the error data also indicated the same pattern of ADP effects.

We propose that both the increased ADP effects for SLSF sequences and the significant ADP effects for non-SLSF sequences derive from the sequential dependency manipulation introduced in Experiment 4. Perhaps we succeeded in creating a condition that results in frame rotation in the general sense of rotating a system of coordinates into alignment with a specified orientation. A similar effect has been reported by Robertson et al. (1987). They obtained somewhat stronger effects of relative orientation in a sequential dependency condition in which the orientation of S2 was always closer to that of S1 than to the upright. If indeed frame rotation in the broad sense is taking place in Experiment 4, its occurrence would seem to require not only a specification of the expected orientation in the abstract (as in Cooper & Shepard, 1973), but also a physically present stimulus whose intrinsic frame conveys this orientation (as in Experiment 4). Under these conditions the stimulus-supported advance orientation information is of some benefit even without information about the identity of the stimulus or its general visual characteristics. Clearly, the effect of advance orientation information was overall rather modest, but was quite pronounced for ADP = 0°.

General Discussion

The present study examined the mental rotation task of Cooper and Shepard (1973), focusing on the nature of the transformation that occurs. This task may involve either one of two processes. In the image rotation process the stimulus is imagined to rotate to the upright, whereas in the frame rotation process, the perceptual frame of reference is aligned with the coordinates of the stimulus. Current views of this task favor the image rotation process (see Shepard & Hurwitz, 1984). This is based on the finding that advance information on the orientation and identity of an upcoming stimulus eliminates the need for mental rotation, whereas advance orientation information alone does not. We argued that this finding, by itself, does not necessarily imply that subjects do not adjust their frame of reference to the coordinates of the stimulus when the stimulus is physically present. In fact, there is evidence that stimuli with natural axes tend to be spontaneously interpreted relative to their intrinsic frame (see Humphreys, 1983; Palmer, 1983). Therefore, although subjects may not be able to adopt a frame of reference in the abstract, they may still adopt such a frame when it coincides with the

intrinsic frame of the stimulus, and may do this spontaneously and automatically.

To test this possibility we examined sequential effects in mental rotation. Both our previous study (Koriat & Norman, 1984) and the recent study by Robertson et al. (1987) indicated significant ADP effects, suggesting the possibility that the current stimulus (S2) was perceived relative to the intrinsic frame of the previous stimulus (S1). Although the present study replicated these findings, the detailed analyses raised serious doubts concerning the frame rotation interpretation of the ADP effects, and disclosed the operation of a particular type of mental rotation, the effects of which closely mimic those of frame rotation.

Altogether the results suggest a distinction between two mental rotation processes, both involving image rotation. The uprighting process is that described by Shepard and his associates (see Shepard & Cooper, 1982): The stimulus is imagined to rotate to the upright and then matched to the long-term internal representation. In the backward alignment process the current stimulus is imagined to rotate into alignment with the short-term trace of the previous stimulus. This process is confined to stimulus sequences in which the same exact stimulus is repeated except for a possible change in orientation. Thus, for same-shape sequences two possibilities are available for recovering the "familiar" shape of the stimulus, either by imagining it rotated back into its canonical upright, or by imagining it rotated back into the orientation of the previous stimulus. The model we have proposed describes how the combined operation of the two processes may account for the complex pattern of results obtained.

In what follows we shall examine the general characteristics of the backward alignment process, then evaluate the specific model proposed, and finally, discuss the issue of image versus frame rotation in general.

The Backward Alignment Process

Shepard and his associates (see Shepard, 1981, 1984; Shepard & Cooper, 1982) have accumulated a great deal of evidence on the commonalities between mental rotation and apparent rotational motion. The backward alignment process seems to be intermediate between the two processes, sharing certain characteristics with apparent rotational motion and yet differing from it. Thus, it is particularly sensitive to shape-preserving transformations, perhaps more so than apparent motion (see Bundesen, Larsen, & Farrell, 1983), and seems to be motivated by the same general tendency to extract invariances in the flow of information. Consistent with this characterization is the finding that the relation between response time and sequential orientational disparity was either entirely confined to shape-preserving sequences (Experiments 1, 2, and 3) or most strongly observed for them (Experiment 4). These are the sequences likely to yield optimal apparent rigid rotation with suitable interstimulus intervals.

In discussing apparent motion, Shepard (1984) noted that there are limits of space and time over which we can integrate information available in the sensory arrays. Thus, the results for apparent rotational motion suggest that the transforma-

tional path between two perspective views of an object must be impleted, and that this impletion takes time. The backward alignment process may be seen to extend the temporal intervals over which sensory information may be integrated, beyond those for which apparent motion occurs. This is achieved by using mental rotation as a vehicle by which one shape is brought into congruence with the other.

In apparent rigid motion the impletion of the transformational path between disparate stimuli gives rise to the phenomenal experience of the same object undergoing transformation. This illusion of a persisting object does not obtain over the longer time intervals for which backward alignment occurs. Rather, backward alignment allows establishing that two stimuli are identical except for orientation, and allows repetition of the same response. Indeed, the response repetition data of Experiment 2 suggest that the sequential effects in mental rotation rest on a process that establishes the identity of successive stimuli.

Shepard (1975, 1981, 1984) noted that the uprighting process is a subject-initiated, voluntary, and effortful process, whereas apparent motion is automatic, obligatory, and stimulus-instigated (but see Corballis, 1986). Backward alignment occupies an intermediate position in that its activation tends to be more automatic and data-driven than that of the uprighting process. This is suggested by the observation (Experiments 1, 2, and 3) that backward alignment is confined to shape-preserving sequences, for which both ends of the transformational path are present in the sensory array. The results of Experiment 4 also suggest that backward alignment differs from the active process of imagining a stimulus to rotate to a specified orientation. Also consistent with the assumption that backward alignment is data driven are the results of Experiment 3 suggesting that, unlike the uprighting process, backward alignment is largely indifferent to the location of the vertical relative to the locations of S1 and S2.

A further distinction is that the uprighting process bridges between a disoriented stimulus and its permanent internal representation, whereas backward alignment, like apparent motion, relates a stimulus and a short-term sensory code. Consequently, backward alignment should depend strictly on the visual correspondence between successive stimuli and should not be affected by the characteristics of their internal representations in long-term memory. Indirect evidence for this contention was obtained in Experiment 3.

Although the inception of backward alignment may have much in common with apparent motion, the data suggest a process that proceeds at a slower rate. We have tentatively proposed that the rate of mental rotation is the same whether the stimulus is to be aligned with the previous stimulus or the upright. It is important to see whether the results suggest otherwise. The rate of the uprighting process may be best estimated from the effects of ADU on non-SLSF sequences. The extent of these effects from 0° to 180° was 562, 151, 323, and 375 ms for Experiments 1 through 4, respectively ($M = 353$ ms). The best estimate for the rate of backward alignment is based on the effects of ADP for SLSF sequences with ADU = 180°. The extent of these effects for Experiments 1 to 4 were 662, 191, 246, and 594 ms, respectively ($M = 368$ ms). On the basis of these results it seems fair to retain the tentative

assumption of a comparable rate of mental rotation in both processes.

Evaluation of the Proposed Model

Let us turn next to examination of the specific model advanced. Taken together, the results of all the experiments are consistent with the major predictions of the model: (a) In the first three experiments ADP effects were entirely confined to the shape-preserving, SLSF sequences, and in Experiment 4 they were substantially more pronounced for SLSF than for non-SLSF sequences. (b) In all four experiments, the effects of ADP for SLSF sequences increased markedly with increasing ADU, consistent with the idea that response time is determined by the process involving the shortest transformational path. (c) All four experiments yielded systematic effects of ADU even for ADP = 0°, which suggests a bias toward using the upright as the referent orientation. (d) In all four experiments the effects of ADP were stronger for reflected than for normal characters (this was true for Experiment 4 as well, but was not reported earlier), consistent with the assumption that the bias toward the uprighting process is stronger for normal than for reflected characters. (e) The evidence available suggests that the effect of same-shape repetitions is by and large facilitatory. This was clearly true for Experiments 2 and 3, and for Condition FGJ7 of Experiment 4. The results of Experiment 1 and those of Condition FGLR in Experiment 4, however, suggest that some inhibitory effects may occur.

There are, however, several departures from the predicted results that may call for some modification of the model. First, there was some indication that ADP effects obtain even when ADU = 0°. This suggests the possibility that there is actually no particular bias towards using an uprighting process. Rather, the choice between the two processes according to the smallest angular deviation is not perfect. Such a choice process should result in both ADP effects for ADU = 0°, and ADU effects for ADP = 0°. A similar idea was proposed by Robertson et al. (1987), except that in their account the probability mixture pertains to that between frame rotation (rather than backward alignment) and image rotation processes.

Second, the results indicate a nonlinear increase in response time with increasing ADP even when ADU = 180°. This suggests either that the likelihood of resorting to backward alignment generally decreases with increasing ADP for any given value of ADU, or that the rate of backward alignment is not constant.

Apart from these minor modifications, we have left open the question of how response selection is determined. The results are consistent with three versions of the backward alignment model, which should be contrasted in subsequent research. The first assumes that normally an uprighting process takes place, but this may be preempted by backward alignment for shape-preserving sequences. In order for this to occur we must postulate some early preattentive process by which the rotation-invariant identity of S1 and S2 can be determined. As in the case of apparent rigid motion, this process may involve both the establishment of the correspond-

ence between the two stimuli as well as a selection of the transformational path to be implected by backward alignment. The finding of marked ADP effects even under speed instructions (Experiment 2) suggests that this implection is not simply a checking operation, but is probably necessary for proper response selection.

The second version assumes that the two processes occur in parallel and that the response is determined by the first to be completed. Backward alignment would be assumed to rest on an automatic search for possible transformational variants of S2, a sort of spread of activation which originates from S1 and diffuses in all directions.

A third version also assumes that the two processes occur in parallel, but that backward alignment operates in an all-or-none manner. On each SLSF sequence the shape identity of S1 and S2 may be detected, with a probability that increases with decreasing ADP. When detection occurs it allows immediate response repetition. The predictions from this model are similar to those of the previous versions, except that the latency-ADP function is seen to reflect only the changes in the probability mixture of the two processes and not mental rotation time. This version is somewhat less appealing in view of the impressive findings suggesting that even the occurrence of apparent motion is highly dependent on processes that take time.

Frames or Images?

In our previous report (Koriat & Norman, 1984) the strong ADU effects were seen to indicate an image rotation process, but the weaker effects of ADP suggested that a frame rotation process is also occurring. The results of the present study, in contrast, indicated that both of these effects are due to image transformation processes, but that one involves alignment with the upright whereas the other involves alignment with the preceding orientation. The failure to obtain stronger evidence for frame rotation processes is difficult to reconcile with the commonly accepted view regarding the pervasive role that intrinsic frames of reference play in perception (Rock, 1973). One possibility is that there is a qualitative difference between visual stimuli for which the intrinsic frame is data driven, that is, determined solely by their visual characteristics, and those (e.g., alphanumeric characters) in which it is conceptually driven, that is, defined by their known canonical orientations. It may be the case that intrinsic frames of the latter type are not as automatically activated as those of the former type. Some findings by Simion et al. (1982) and Bagnara et al. (1984) suggest that this distinction is worth pursuing.

Our conclusions are also difficult to reconcile with those of Robertson et al. (1987). Although there is a great deal of similarity in the methods used and in some of the findings, they interpreted their results as favoring the transformation of reference frames rather than the transformation of template-like representations. Like the present study they obtained systematic and strong ADP effects for SLSF sequences, but they also found similar, though somewhat weaker, effects for DLSF sequences. We intentionally used letters that are very different in shape, whereas, in three of

their experiments, Robertson et al. used two rather similar letters, F and R. This might explain why they obtained sequential effects for DLSF sequences while we did not. However, in their fourth experiment dissimilar letters were also included. Although these yielded relatively longer mean response times, they displayed the same sequential effects as those shown by similar letters.

Another possibility is that conditions exist that are particularly amenable to the occurrence of frame rotation. Robertson et al. (1987), for example, used very short response-stimulus intervals (100 ms), and perhaps these are necessary to capture the effects of a preceding frame of reference. Two other conditions that also seem to yield frame rotation effects are suggested by our results. First, is the evidence in Experiment 2 suggesting that the intrinsic frame of a preceding stimulus may affect the response to the current stimulus. In that experiment sequential orientational disparity had systematic effects on percent errors and on response repetition even for different-letter sequences, provided they shared the same format. The ADP effects on percentage of errors were not found in the other experiments, but they were also obtained in a recent study of ours using brief stimulus presentations. Thus, conditions might exist (e.g., those requiring speed) in which the present stimulus tends to be interpreted in terms of the intrinsic frame of the previous stimulus. The observation that in Experiment 2 these effects were not obtained for response times suggests that they might depend on an all-or-none process, with the likelihood of frame matching increasing with decreased ADP.

Second, there is an indication in Experiment 4 of frame rotation in the sense of perspective change. Significant and marked ADP effects were obtained even for sequences that preserve neither shape nor format. These results suggest that subjects may prepare for a specified orientation in the absence of identity information. In our interpretation of this effect we proposed the possibility that this preparation is aided by the availability of a stimulus whose orientation coincides with the prepared orientation. This possibility deserves further investigation. It should be stressed that a similar manipulation to that of Experiment 4 was not effective in a task involving lexical decisions on letter strings at different orientations (Koriat & Norman, 1984, Experiment 4), but this task may involve more complex processes than those underlying the ordinary task of mental rotation (see Koriat & Norman, 1985b). Subsequent research must further explore the specific conditions that allow frame rotation.

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Received July 9, 1986

Revision received October 2, 1986

Accepted October 17, 1986 ■