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Establishing Global and Local Correspondence Between Successive Stimuli: The Holistic Nature of Backward Alignment

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Reflection decisions on alphanumeric characters display systematic effects of disorientation, suggesting that subjects mentally rotate the stimulus to the upright (the uprighting process). However, response time also increases with increasing angular disparity between the current and preceding orientations. This occurs only when the current stimulus is a rotational transform of the preceding stimulus, suggesting that the current stimulus is brought into congruence with the preceding one (the backward alignment process). In the present study, we examined the hypothesis that the transformation that occurs in backward alignment is holistic even in tasks in which the uprighting process is likely to be piecemeal. Evidence supporting this hypothesis is presented on the basis of tasks requiring either classification of numbers (Experiments 1 and 3) and words (Experiment 2), or mirror image discrimination on letter pairs (Experiment 4). The results indicated that backward alignment establishes global correspondence between successive stimuli and is indifferent to local correspondence at the level of the constituent elements. The establishment of this global correspondence decreases with the number of elements in the stimulus (Experiment 5), but its effects are still observed for four-letter strings (Experiment 6).

A great deal of research has focused in recent years on the mental transformation of disoriented visual stimuli. The results have been commonly interpreted as supporting the occurrence of a "mental rotation" process in which a stimulus is imagined to rotate to a desired orientation before the required decision is reached. There has been some dispute, however, regarding the exact nature of this process. One of the questions is whether mental rotation is holistic or piecemeal. Shepard and Cooper (1982) proposed that visual stimuli are mentally transformed as unitary wholes, with all their parts simultaneously rotated about the same point. Other researchers, in contrast, argued that the transformation of visual images is carried out piecemeal, by segmenting the visual image and mentally rotating each of the parts in turn (e.g., Pylyshyn, 1979). This controversy is particularly significant because of its relevance to the general issue of whether visual information is represented and transformed in an analogical or in a propositional form (see Bethell-Fox & Shepard, 1988; Palmer, 1975; Pylyshyn, 1973). Some of the propositional accounts of mental rotation seem to imply a piecemeal transformation process, and results supporting a holistic transformation are seen as detrimental to such accounts (see Cooper & Podgorny, 1976).

One experimental paradigm used to tackle the issue of holism in mental rotation examines the dependence of rate of mental rotation on stimulus complexity. If mental rotation is piecemeal and serial, the effects of disorientation should increase with the complexity of the stimulus. Several studies examined mirror-image discriminations on Attneave-type polygons that differed in the number of vertices (Cooper, 1975; Cooper & Podgorny, 1976). They found no decrease in rate of mental rotation with increasing visual complexity, as is consistent with the holistic-and-analog view of mental rotation. These studies have been criticized on the ground that subjects in the greater complexity conditions may have found it sufficient to rotate only partial images. Indeed, Folk and Luce (1987) reported slower rotation rates for high-similarity than for low-similarity stimuli, suggesting that when the stimuli are relatively dissimilar, subjects tend to rotate partial images. Furthermore, for highly similar stimuli, rate of mental rotation did decrease with stimulus complexity. Other investigators also reported systematic effects of stimulus complexity, supporting the view of mental rotation as consisting of a series of "rotate and compare" subprocesses (e.g., Hochberg & Gellman, 1977; Pylyshyn, 1979; Yuille & Steiger, 1982), though a recent study by Bethell-Fox and Shepard (1988) suggests that these effects tend to dissipate with increased familiarity with the stimuli.

A related experimental paradigm has focused on stimuli that are composed of several discrete elements and has explored the possibility that the effect of disorientation increases with the number of elements. Presson (1982), for example, had subjects imagine how a spatial array of objects would appear if rotated about its center. The results suggested that subjects did not transform the entire array as a holistic unit but imagined a relocation of each object in turn. In an earlier study (Koriat & Norman, 1985), we had subjects perform lexical decisions on two- to five-letter Hebrew strings presented at different orientations. The effects of disorientation were found to increase systematically and strongly with the number of letters in the string. This increase was not due to

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the larger visual extent of the longer strings, because the effect of number of elements was also obtained for three- and four-letter strings that subtended the same visual angle (Experiment 3). These results suggested that letter strings are not mentally rotated as integral wholes. Further evidence that letter strings are rotated letter by letter has recently been reported by Murray and Corballis (1987), who had subjects decide whether two letters that were rotated as a unit were both normal, both reflected, or one normal and one reflected. Rate of mental rotation in this task was almost exactly half that found for normal–reflected decisions on single letters.

The studies reviewed thus far concerned the mental rotation process described by Shepard and Cooper (1982). In the present study we examine the holism–piecemeal issue with regard to a second type of visual transformation that we recently studied (Koriat & Norman, 1988). This transformation, labeled *backward alignment*, was inferred from examination of sequential effects in reflection decisions on single alphanumeric characters (see Cooper & Shepard, 1973). Such decisions normally yield a systematic increase in response time, with increases in the angular deviation from the upright (ADU). Under certain conditions, however, response time also increases systematically and strongly with the angular deviation from the preceding orientation (ADP). Such effects occur only when the current stimulus is a rotational variant of the preceding stimulus, that is, when the two stimuli in a sequence are identical except for orientation. This suggests a distinction between two types of mental rotation processes. The first, the uprighting process, is that described by Shepard and Cooper (1982), in which the stimulus is imagined to rotate to the upright and then compared with its long-term memorial representation. In the second process, backward alignment, the stimulus is brought into congruence with the short-term visual trace of the preceding stimulus. This latter process succeeds only for sequences in which the same letter is repeated in the same format (normal or reflected), that is, sequences in which the two stimuli are rotational transforms. For these sequences the backward alignment process is presumably used to establish the orientation-invariant identity of the two stimuli, thus allowing response repetition. Our results (Koriat & Norman, 1988) suggest that the uprighting process and the backward alignment process have the same rate of mental rotation and that for sequences in which the current stimulus is a rotational transform of the preceding stimulus, the two processes compete so that the response is determined by the one requiring the shortest rotational path.

In the present study we examined the hypothesis that the backward alignment transformation is holistic even in tasks and conditions where the uprighting process is presumably piecemeal. This hypothesis is based on the general assumption that the uprighting and backward alignment processes are qualitatively different (see Koriat & Norman, 1988). Whereas the uprighting process is an effortful, subject-initiated, imaginal process, backward alignment is a largely automatic, stimulus-initiated process that is induced ad hoc by the orientation-invariant correspondence between successive stimuli. This correspondence, we propose, is established at a precategorical level by the matching of the current stimulus to the short-term visual trace of the preceding stimulus. Therefore, even when the uprighting process operates on an articulated representation of the stimulus, transforming different segments in turn, the backward alignment process may be based on the unarticulated representation of the stimulus, relying on the global correspondence between successive stimuli rather than on the correspondence between their constituent elements.

To examine this hypothesis, we used stimuli consisting of rotated strings of alphanumeric characters. Although previous research has indicated that such strings are not transformed holistically, but possibly in a character-by-character fashion (Koriat & Norman, 1985, 1989; Murray & Corballis, 1987), we hypothesize that when backward alignment occurs, it is based on the global correspondence between the successive strings as unitary wholes rather than on the correspondence between their constituent elements. If this hypothesis is supported, it will lend further credence to the general proposition of a qualitative difference between the mental rotation processes of uprighting and backward alignment.[1]

Experiment 1

The results reported below are based on a reanalysis of part of the data of Experiment 2 of Koriat and Norman (1989). In that experiment subjects were required to classify either the four letters *A*, *B*, *M*, and *V* (the letter condition), or the four numbers *13*, *31*, *45*, and *54* (the number condition), which appeared in different orientations. The same stimulus was used for *B* and *13*. Strong effects of disorientation were found when that stimulus was interpreted as *13*, but none when it was interpreted as *B*. This suggested that the time to recognize a single character is indifferent to disorientation, whereas the speed of recognizing a multielement stimulus is orientation dependent. But this difference between *B* and *13* was not obtained in another experiment (Experiment 1) in which the numbers used did not have any digits in common. This, as well as other results, suggested that orientation effects are obtained mainly when order information is critical for classification, that is, when the stimulus must be analyzed into separable elements and processed as a specific permutation of these elements.

The following analyses will focus only on the results from the number condition in Experiment 2, where effects of ADU were found, apparently deriving from a piecemeal rectification process. Assuming that these effects are due to a piecemeal uprighting process, would the backward alignment process in this task also entail an element-by-element transformation or one based on the stimulus configuration as a whole? This question was examined by comparing stimulus sequences

[1] Lynn Robertson (personal communication, June, 1988) has correctly noted that our characterization of the "uprighting" process applies to any process that requires mental rotation to a specified orientation, whether it is the upright or not. Indeed, in our previous study (Koriat & Norman, 1988; Experiment 4) we have shown that the backward alignment process differs from the process underlying the preparation of the stimulus in a specified orientation. The term "uprighting" process, although narrower in connotation, conveniently applies in most mental rotation tasks where the canonical orientation is the verical.

that consisted of the same digits. If backward alignment occurs piecemeal, we should expect systematic effects of ADP both when a stimulus follows itself (e.g., *45* following *45*) and when it follows a different stimulus that contains the same digits (e.g., *45* following *54*). If, on the other hand, backward alignment is holistic, these effects should obtain only for sequences like the former, which preserve global correspondence.

Method

The method is fully described in Koriat and Norman (1989; Experiment 2). Here we report only the details of the number condition that are of interest in the present context.

Apparatus and stimuli The experiment was run on an Apollo Domain DN300 computerized graphics display unit. The stimuli were the numbers *13*, *31*, *45*, and *54*. Each subtended about 2.0 cm vertically and 1.3–1.8 cm horizontally, and appeared white on a dark background at six different orientations (0°, 60°, 120°, 240°, and 300°).

Subjects and procedure. Twelve University of Haifa students participated in the study. They sat at a viewing distance of 50 cm from the screen and were told to classify the numbers by pressing one of four keys, using the index and middle fingers of the two hands. The assignment of keys to stimuli was counterbalanced across subjects. On each trial, the stimulus appeared at the center of the screen. It remained on until the subject responded, and was replaced by the next stimulus after 500 ms. A high-pitched tone gave the subjects feedback after errors.

The experiment included one practice block and eight experimental blocks of 240 trials each. Each block included 10 replications of each of the four numbers in each of the six orientations. The order of the stimuli in each block was randomly determined so that the sequencing of the four numbers and their orientations was not controlled.

Results

Response times outside the range of 200–3,000 ms were eliminated (1.2%). All response time analyses to be reported in the present article were based on the means of subject median response times for correct responses.

As far as the effects of ADU are concerned, mean response times for 0°, 60°, 120°, and 180° ADUs were 641, 660, 721, and 736 ms, respectively, $F(3, 33) = 17.23$, $p < .0001$. This pattern of a sharp increase between ADUs of 60° or less and 120° or more is similar to that found for lexical decisions on letter strings (Koriat & Norman, 1985). The respective means for percentage of errors were 4.1%, 3.6%, 4.3%, and 4.8%, respectively $F(3, 33) = 2.33$, $p < .10$.

We shall next examine the effects of ADP. The 240 stimuli of each block of the experiment allowed for 239 prime-target sequences, with each stimulus serving both as a target and as a prime for the subsequent stimulus (except for the first stimulus, which served only as a prime). The 1,912 "sequences" of each subject were classified into 12 categories, on the basis of four levels of ADP (0°, 60°, 120°, and 180°) and three types of stimulus sequences: (a) sequences in which the same number was repeated, for example, *45* following *45* (same number); (b) sequences in which the same digits were repeated but in a different order, for example, *45* following *54* (same digits); and (c) sequences that had no digits in common, for example, *45* following *13* (different digits). It should be noted that because the order of the stimuli and their orientations was random, the number of observations per category varied markedly and also differed from subject to subject.

Figure 1 presents mean response time and percentage of errors as a function of ADP for the three types of sequences. A two-way analysis of variance (ANOVA) on response time indicated a significant interaction between ADP and sequence type $F(6, 66) = 30.24$, $p < .0001$. It is readily apparent that the same-number sequences evidence systematic effects of ADP, whereas the same-digits sequences indicate little effects, as is the case for different-digits sequences.

This conclusion was confirmed by several additional analyses. First, a two-way ANOVA comparing same-digits and different-digits sequences yielded significant main effects for sequence type $F(1,11) = 15.85$, $p < .01$, but no significant effects for ADP ($F < 1$) or for the interaction ($F < 1$). Second, a comparison including only same-number and same-digits sequences yielded a highly significant interaction $F(3, 33) = 28.77$, $p < .0001$, indicating stronger effects of ADP for same-number sequences. Third, separate one-way ANOVAs for each sequence type yielded significant effects of ADP only for same-number sequences $F(3, 33) = 50.77$, $p < .0001$, but not for same-digits ($F < 1$) or different-digits sequences ($F < 1$).

The results for percentage of errors paralleled those of response time. A significant effect of ADP was found for same-number sequences, $F(3, 33) = 4.39$, $p < .02$, but not for

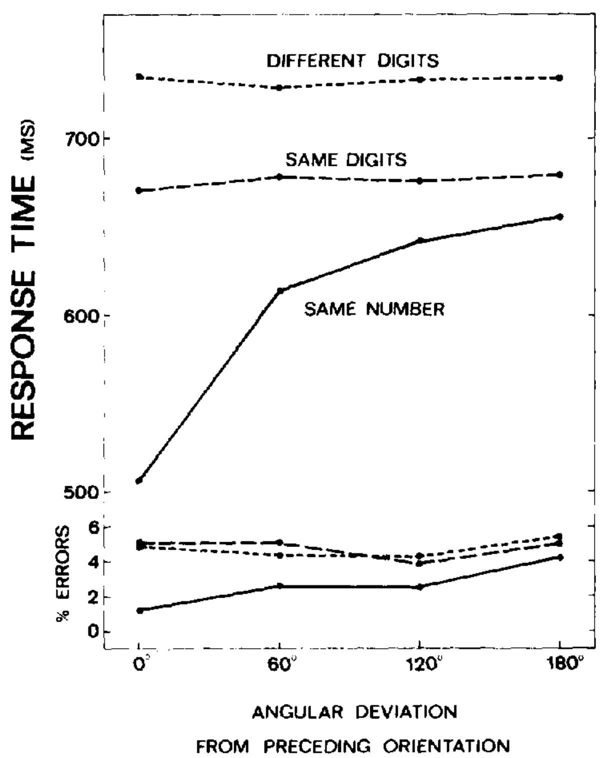

Figure 1. Response time and percentage of errors as a function of angular deviation from preceding orientation for same number, same-digits, and different-digits sequences (Experiment 1).

same-digits ($F < 1$) or different-digits, $F(3, 33) = 1.50$, *ns*, sequences.

Figure 2 presents mean response time as a function of ADP, with ADU as a parameter. The results are presented separately for different-number sequences (that is, same-digits and different-digits sequences combined) and same-number sequences. The pattern is remarkably similar to that we found for reflection decisions on single letters (Koriat & Norman, 1988), which we interpreted as suggesting a race between rotation to the upright and rotation to the preceding stimulus for shape-invariant sequences. First, same-number sequences yielded a significant ADP × ADU interaction, $F(9, 99) = 4.77$, $p < .0001$, indicating that the effects of ADP generally increase as the orientation of the current stimulus departs from the upright. Second, the effects of backward alignment are facilitatory, in that for each value of ADU mean response time for same-number sequences at ADP of 180° is close to or lower than the respective value for different-number sequences. Thus, when backward alignment occurs, it improves performance: The stronger the departure of the current stimulus from the upright, the greater the benefit.

Discussion

The results of Experiment 1 indicate that backward alignment is based on the overall configural correspondence between successive strings rather than on the correspondence between their constituent elements. When the same two-digit number appeared on two successive trials, systematic ADP effects were found. In contrast, when two consecutive stimuli contained the same digits but in a different order, no such effects were obtained, as was the case for sequences that had no digits in common. This indicates that the effects of ADP observed in the same-number condition are not due to a visual transformation that operates on each of the constituent digits separately.

Although same-digits sequences did not evidence any effects of ADP, they did yield faster response times than did different-digits sequences. We suspect that this is due to a hierarchical classification of the stimuli, where subjects first group the stimuli into two classes in terms of the constituent digits regardless of order (i.e., *13* and *31* vs. *45* and *54*) and then make use of order information to distinguish between the two members of each class (see Koriat & Norman, 1989). Thus, the faster response times for same-digits sequences may derive from the priming of the class to which the stimulus belongs. Evidence in support of this interpretation will be presented in conjunction with the next experiment.

What is the process underlying the recognition of a disoriented multidigit number when it is not preceded by the same number? We know that under the conditions of Experiment 1, stimulus recognition is strongly impaired by disorientation, apparently because disorientation disrupts order information (Koriat & Norman, 1989). Thus, if the effects of ADU are due to some sort of mental transformation, this transformation is apparently aimed at restoring order information rather than at facilitating the identification of the constituent elements. The observation that the extent of orientation effects increases systematically with the number of elements in the string (Koriat & Norman, 1985, 1989) suggests that this transformation does not operate on the entire string as a whole but is piecemeal in nature. If this conclusion is correct, then the results of Experiment 1 seem to suggest that two processes are pitted against each other in this experiment: an analytic mental transformation that compensates for the angular deviation of the stimulus from the upright and a holistic backward alignment. The latter succeeds only for same-number sequences, and for these sequences response time is generally determined by the process that requires the shortest transformational path (Figure 2).

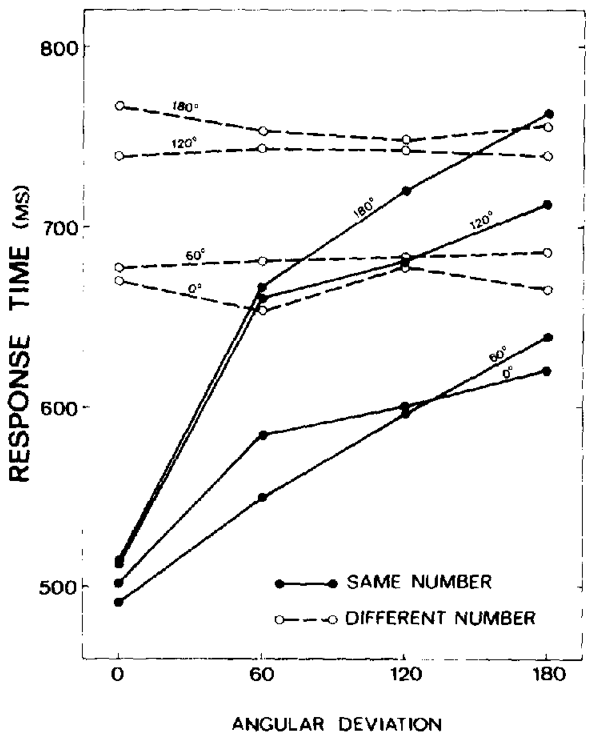

Figure 2. Response time as a function of angular deviation from preceding orientation for same-number and different-number sequences, with the angular deviation from the upright as a parameter. (Experiment 1).

Experiment 2

The data of Experiment 2 are based on the results of the experimental condition of Experiment 4 of Koriat and Norman (1989). In that condition subjects classified four rotated two-letter Hebrew words by pressing a different key for each word. In contrast to Experiment 1, in which each number was paired with another that contained the same elements in the reverse order, in the present experiment this was true for only two of the four stimuli. These two consisted of permutations of the same letters (like the English words *on* and *no*; Hebrew offers many more such pairs than English). The other two words had no letters in common with any of the other words.

One of the original aims of this experiment was to see if subjects can evolve different strategies of pattern recognition for different stimuli within the same ensemble, depending on the criticality of order information. Confusable words (whose classification depends on letter order) did indeed yield longer response times and stronger effects of ADU than did nonconfusable words. Apparently, subjects can utilize the identity of the constituent letters to decide whether an order-restoring rectification is needed.

Here we examine the effects of ADP on the confusable and nonconfusable words. As in Experiment 1, the results for the confusable words will indicate whether in backward alignment the word is transformed as a unitary whole or letter by letter. The results for nonconfusable words should also be enlightening. Because a nonconfusable word contains no elements in common with the other words and can be recognized on the basis of subword features, perhaps its visual trace cannot serve as a referent for the holistic backward alignment of its repetition. If such is the case, a repetition of a nonconfusable word might facilitate the response but not necessarily in a manner that depends on the angular disparity between the two stimuli. We expect, however, that a holistic backward alignment will also occur with nonconfusable words even if these can be recognized on the basis of their constituent letters rather than on the basis of their overall global pattern.

Method

Subjects. Twelve University of Haifa students whose primary language was Hebrew participated in the experiment.

Stimuli. The stimuli were drawn from a set of four pairs of two-letter Hebrew words. In each pair, one partner had the reversed letter sequence of the other word (e.g., *on* and *no* represent one such "confusable" pair) and had no letters in common with any of the other words in the set. Each subject received four words, two of which were confusable partners and two were nonconfusable, that is, drawn from different pairs. Each of the words appeared equally often as confusable and nonconfusable across all subjects. A word subtended 2 cm vertically and 2.2–2.5 cm horizontally, and appeared on the screen white on black in six orientations (as in Experiment 1).

Apparatus and procedure. The apparatus and viewing distance were the same as in the previous experiment. The procedure was also the same except that the assignment of keys to words was randomized (rather than counterbalanced) across subjects. As in Experiment 1, there were 240 practice trials and 1,920 experimental trials.

Results

Response times outside the range of 200–5,000 ms were eliminated (0.8%).

The results were analyzed separately for trials in which the current target was one of the two confusable words and for trials in which it was one of the two nonconfusable words. In each case, the effects of ADP were evaluated for three types of sequences: (a) those in which the same word was repeated (same word), (b) those in which the successive words differed but both belonged to the same class, either both confusable or both nonconfusable (same class), and (c) those in which the two words belonged to different classes and therefore had no letters in common (different class). It should be noted that in same-class confusable sequences, the two successive words had the same letters but in a different order, whereas same-class nonconfusable words had no letters in common.

Figure 3 presents mean response time and percentage of errors as a function of ADP for the three types of sequences for confusable and nonconfusable targets.

The results for confusable words closely replicated those of Experiment 1. First, same-word sequences evidenced systematic effects of ADP, $F(3, 33) = 30.34$, $p < .0001$. Response times for these sequences were significantly faster than for same class sequences, $F(1, 11) = 71.32$, $p < .0001$. This was true even for ADP of 180°, $F(1, 11) = 8.04$, $p < .05$, suggesting that the global correspondence between two successive visual stimuli can be established even over the maximal angular disparity (see Koriat & Norman, 1988). Second, in contrast to same-word sequences, same-class sequences (i.e., same letters in a different order) yielded no effects of ADP, $F(3, 33) = 1.03$, *ns*. The effects of ADP were significant for different-class sequences, apparently because of the higher mean response time for ADP of 180°, $F(3, 33) = 4.67$, $p < .01$. Third, same-class sequences yielded faster overall response times than did different-class sequences, $F(1, 11) = 22.34$, $p < .001$, similar to what was seen in Experiment 1.

Percentage of errors yielded significant effects of ADP for same-word sequences, $F(3, 33) = 4.04$, $p < .05$, but not for

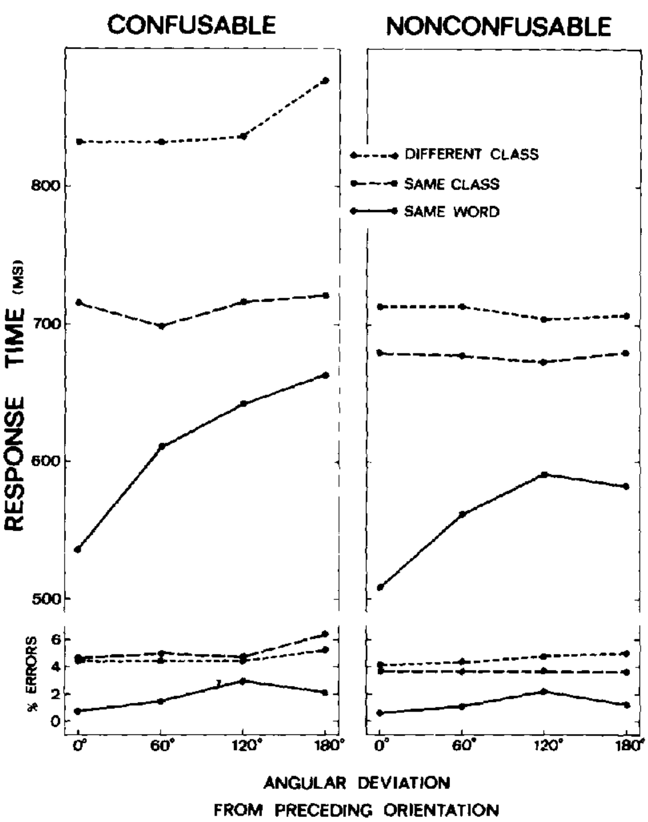

Figure 3. Response time and percentage of errors as a function of angular deviation from preceding orientation for same-word, same-class, and different-class sequences. The results are plotted separately for confusable and nonconfusable words (Experiment 2).

same-class, $F(3, 33) = 1.13$, or different-class sequences ($F < 1$). Mean percentage of errors was significantly smaller for same-word than for same-class sequences, $F(1, 11) = 9.53$, $p < .05$.

The results for the nonconfusable words (Figure 3: right panel) were very similar to those for the confusable words except that all the effects were somewhat weaker. Same-word sequences evidenced significant effects of ADP, $F(3, 33) = 27.05$, $p < .0001$. Mean response time for these sequences was faster than that of the same-class sequences, $F(1, 11) = 34.20$, $p < .0001$, and this was true even for the 180° ADP, $F(1, 11) = 48.47$, $p < .0001$. The effect of ADP was not significant either for same-class sequences ($F < 1$) or for different-class sequences ($F < 1$), but the former sequences yielded overall faster response times than the latter sequences, $F(1, 11) = 8.93$, $p < .02$. Percentage of errors was smaller for same-word than for same-class sequences, $F(1, 11) = 8.07$, $p < .05$, but there were no significant effects of ADP for any of the sequence types.

An analysis of the combined effects of ADU and ADP revealed a similar interactive pattern to that displayed in Figure 2 for both confusable and nonconfusable words. The strongest difference in the effects of ADP for same-word sequences was between ADUs of 0° and 60°, on the one hand, and those of 120° and 180°, on the other.

Discussion

The results of Experiment 2 were consistent with those of Experiment 1 in indicating a systematic effect of ADP for same-word sequences. This was true for both confusable and nonconfusable words. It suggests the operation of a backward alignment process that facilitates performance by allowing repetition of the same response. The nature of this process is clarified by the observation that the same-class confusable sequences in which the same letters were repeated in a different order yielded no effects of ADP, as was the case for sequences in which no letter was repeated. On the basis of these results, it seems that backward alignment utilizes the global correspondence between two successive visual patterns rather than the correspondence between their constituent elements.

In our previous report (Koriat & Norman, 1989) we noted that confusable words yielded significantly stronger effects of ADU than did nonconfusable words. We interpreted this as an indication that subjects can evolve different strategies for the recognition of disoriented multielement strings, depending on the criticality of order information, and can do so even when the two types of strings are intermixed. Apparently, nonconfusable words can sometimes be classified on the basis of some of their constituent elements, and such classification is equally fast irrespective of orientation (see e.g., Corballis & Nagourney, 1978). The recognition of confusable words, in contrast, requires a preceding rectification process that restores the element-position mapping. This presumed differential processing of confusable and nonconfusable words might have been expected to result in ADP effects only, or mostly, for confusable words. However, significant effects of ADP were obtained for the nonconfusable words as well. This result suggests that the same type of backward alignment process underlies the effects of ADP for same-word sequences of both types. Thus, although nonconfusable words may be recognized on the basis of subword features, they still undergo holistic backward alignment.

The results for nonconfusable words may also help in the interpretation of the relatively faster response times for same-digits than for different-digits sequences in Experiment 1 and for same-class confusable words than for different-class confusable words in Experiment 2. These effects could be attributed to a correspondence at the local, elemental level. However, the finding of a similar effect for nonconfusable words in Experiment 2 is consistent with the interpretation offered earlier: Apparently, the classification task included a preliminary stage in which the strings were sorted into different classes according to their constituent elements. This sorting could help to narrow down the response alternatives. Presumably, it is this preliminary stage that was facilitated when a target stimulus was preceded by a stimulus from the same class.

Experiment 3

Experiments 1 and 2 yielded evidence for the occurrence of backward alignment in the classification of multielement stimuli when two successive visual strings preserved orientation-invariant global correspondence. This was not the case when the two strings included the same elements in the reverse order. This observation indicates that the backward alignment transformation is holistic even in tasks where the uprighting rectification appears to derive from a piecemeal, analytic process (Koriat & Norman, 1985, 1989).

This interpretation of the results of Experiments 1 and 2 suffers from the fact that in these experiments a different response was required when the elements appeared in one order than when they appeared in the reverse order. Thus, in sequences in which the same elements were repeated, the same response could be repeated only when the elements also appeared in the same order. We have argued that the backward alignment process is aimed at establishing the orientation-invariant identity of successive shapes, and it thus allows response repetition (Koriat & Norman, 1988). In the tasks of Experiments 1 and 2, this process would obviously be beneficial only for sequences that reserve global correspondence, but not for those that do not. Although the results of Experiments 1 and 2 indicate that backward alignment can be used to establish global correspondence, they do not rule out the possibility of backward alignment at the local level. Thus, subjects might choose to rely either on global correspondence or on local correspondence, depending on whichever of these is expedient for the task at hand. Or, perhaps, both types of alignment processes occur in parallel, but only the one calling for response repetition is allowed access to the response mechanism.

In Experiments 3 and 4 we examined this issue by using tasks requiring the same response to different spatial arrangements of the same elements. Thus, if backward alignment of constituent elements occurs at the local level, it could manifest itself in response repetition. Experiment 3 was similar to

Experiment 1. Subjects were presented with the numbers *37, 73, 45,* and *54,* and asked to classify them into two groups on the basis of the constituent digits regardless of order. If subjects are able to take advantage of visual congruence at the local level, then we should expect significant effects of ADP for both same-number (e.g., *37* following *37*) and same-digits sequences (e.g., *37* following *73*).

Method

Subjects. Twelve University of Haifa students participated in the study for course credit. None had participated in the previous experiments.

Stimuli. The stimuli were the numbers *37, 73, 45,* and *54.* Each subtended about 2.0 cm vertically, and 2.1 cm horizontally, and appeared at six orientations, as in Experiment 1.

Apparatus and procedure. The apparatus was the same as in Experiment 1. The procedure was similar except for the following. Subjects classified the numbers by pressing one key for the numbers *37* and *73,* and a second key for the numbers *45* and *54.* They used the right and left index fingers, balancing the finger assignment across subjects. When the experiment was completed, the subjects filled out a brief questionnaire on the strategy they used in performing the task.

Results

Response times outside the range of 200–3,000 ms were eliminated (0.3%).

A one-way ANOVA on response time yielded $F(3, 33) = 3.41$, $p < .05$, for ADU. A similar ANOVA on percentage of errors yielded $F(3, 33) = 2.37$, $p < .10$. Mean response times for ADUs of 0°, 60°, 120°, and 180° were 471, 473, 478, and 476 ms, respectively. The respective means for percentage of errors were 3.7%, 4.1%, 4.5%, and 3.6%.

In the analyses of ADP effects, the stimulus sequences were divided into three types: same number (e.g., *54* following *54*), same digits (e.g., *54* following *45*), and different digits (e.g., *54* following *37*). This classification is the same as that used in Experiment 1, except that here same-digits sequences entailed a repetition of the same response. Figure 4 presents mean response times and percentage of errors for the three types of sequences as a function of ADP.

A two-way ANOVA on the response time data of Figure 4 yielded $F(2, 22) = 28.68$, $p < .0001$, for sequence type; $F(3, 33) = 7.52$, $p < .001$, for ADP; and $F(6, 66) = 9.77$, $p < .0001$, for the interaction. A similar ANOVA on percentage of errors yielded $F(2, 22) = 9.02$, $p < .005$, for sequence type; $F(3, 33) = 1.96$, *ns* for ADP; and $F(6, 66) = 8.85$, $p < .0001$, for the interaction. It may be seen that the interaction in both cases apparently derives from the fact that only for same-number sequences response time and percentage of errors increase with increasing ADP. Same-digits and different-digits sequences, in contrast, manifest little systematic effects of ADP.

This conclusion was substantiated by several additional comparisons. First, a two-way ANOVA on response times including only same-digits and different-digits sequences yielded significant effects for sequence type, $F(3, 33) = 33.45$, $p < .0001$, but not for ADP ($F < 1$). The interaction was significant, $F(3, 33) = 3.21$, $p < .05$, apparently deriving from nonsystematic effects. A similar ANOVA on percentage of errors indicated fewer errors for same-digits (3.3%) than for different-digits (5.3%) sequences, $F(1, 11) = 4.91$, $p < .05$. There were also significant effects for both ADP, $F(3, 33) = 3.20$, $p < .05$, and the interaction, $F(3, 33) = 3.27$, $p < .05$.

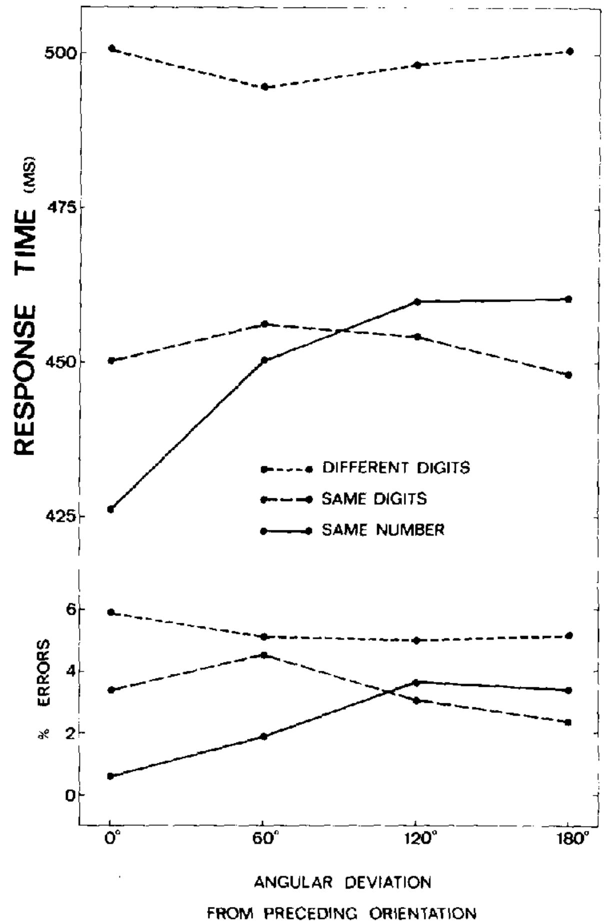

Figure 4. Response time and percentage of errors as a function of angular deviation from preceding orientation for same-number, same-digits, and different-digits sequences (Experiment 3).

Second, a two-way ANOVA contrasting same-number and same-digits sequences on response time yielded $F < 1$ for sequence type, but significant effects for ADP, $F(3, 33) = 10.31$, $p < .0001$, and for the interaction, $F(3, 33) = 9.41$, $p < .0001$. One-way ANOVAS indicated that the effect of ADP was significant for same-number sequences, $F(3, 33) = 14.60$, $p < .0001$, but not for same-digits sequences, $F(3, 33) = 1.24$. Similar analyses on percentage of errors indicated that same-number sequences yielded a lower error rate than same-digits sequences, $F(1, 11) = 8.12$, $p < .05$, as well as a stronger effect of ADP, $F(3, 33) = 10.33$, $p < .0001$. The increase in percentage of errors with increasing ADP was significant for same-number sequences, $F(3, 33) = 14.90$, $p < .0001$, but the nonsystematic variation observed for the same-digits sequences was also significant $F(3, 33) = 4.54$, $p < .01$.

In the postexperimental questionnaire, subjects were specifically asked whether they had focused on only one digit in each of the stimulus pairs for making the discrimination. Four subjects reported using this strategy. These subjects evidenced somewhat faster response times than did the remaining subjects, but they had a very similar pattern of results to that depicted in Figure 4.

Discussion

The results of Experiment 3 are quite similar to those of Experiment 1. Most important, same-digits sequences evidenced no systematic effects of ADP, as was also the case for different-digits sequences. In contrast, same-number sequences yielded a systematic increase in both response times and errors with increasing ADPs.

The effects of ADP for same-number sequences suggest that backward alignment occurs in these sequences. These effects are not as strong as those observed in the previous experiments, possibly because response time was overall much faster in Experiment 3 than in the previous experiments. Same-digits sequences, in contrast, yielded little effects of ADP, although response times for these sequences were as fast as those of same-number sequences. In fact, at the 180° ADP, response time was significantly faster for same-digits than for same-number sequences, $F(1, 11) = 8.12$, $p < .05$, hinting that, perhaps, backward alignment may sometimes delay response time.

Altogether, as far as the effects of ADP are concerned, the results obtained for same-digits sequences are not different from what was found in Experiment 1, despite the fact that in Experiment 3 same-digits sequences entailed response repetition. This result clearly indicates that backward alignment does not occur at the level of the constituent elements or at least is not manifest in response speed and accuracy.

Experiment 4

Experiment 4 extends the results of the present study to a task requiring reflection decisions rather than stimulus classification. When presented with pairs of letters that were rotated as a pair into different orientations, subjects had to determine whether the letters were both normal, both reflected, or one normal and one reflected. This task was used by Murray and Corballis (1987), who found response time to yield the typical mental rotation function, with rate of mental rotation almost exactly half that found for reflection decisions on single-letter stimuli. These results were taken to suggest that subjects were "unable to treat the letter pairs as single units for the purpose of mental rotation, but instead rotated them letter by letter" (p.1).

As in Experiment 3, this two-letter task is indifferent to the order of the elements in the pair, so that, in principle, the response can benefit from backward alignment at the local level. We shall examine the possibility that even in this task the backward alignment is more likely to be based on global correspondence than on local correspondence.

Method

Subjects. Twelve Hebrew-speaking subjects participated in this study for course credit.

Stimuli. The stimuli were composed of the two Hebrew letters, he and mem, which appeared one above the other. The letters appeared in either one of two arrangements (he above mem or mem above he), and each letter could be either normal or mirror-reflected, yielding eight different patterns. The size of each letter was about 0.9 × 0.9 cm, and the two letters were 0.5 cm apart. Each pattern was displayed at each of the same six orientations used in the previous experiments.

While in the study of Murray and Corballis (1987) the letters appeared side by side, we used a vertical arrangement because we thought that it is less likely to activate readinglike processes.

Procedure. The experiment was controlled by a PDP11/34 minicomputer, and the stimuli were presented on a VT-11 graphic display unit. Viewing distance was 80 cm. The subjects were instructed to decide whether both letters were normal, both reflected, or one normal and one reflected. They pressed one key on a computer keyboard with their right index finger for "both normal," another key with their left index finger for "both reflected," and the space bar for "mixed."

There were two sessions separated by a short break. Each session included a practice block of 40 trials, followed by four blocks of 145 trials each. These were programmed to produce 144 sequences (with the first stimulus serving only as a prime for the first sequence), representing four replications of each combination of Current Orientation (6) × Preceding Orientation (6), randomly ordered. All stimulus patterns appeared equally often in each of these orientation combinations across all four blocks. This resulted in the mixed pairs being twice as likely as either of the other two pair types. On each trial, the stimulus remained on until the subject responded; then it was replaced after 500 ms by the next stimulus.

Results

Response times outside the range of 250–5,000 ms were eliminated (0.5%).

We shall first examine the effects of ADU for the three types of pairs: normal, reflected, and mixed. Response times for these pair types averaged 938 ms (3.3% errors), 1,299 ms (5.6%), and 1,151 ms (3.1%), respectively. These differences were significant for both response time, $F(2, 22) = 12.39$, $p < .0001$, and percentage of errors, $F(2, 22) = 3.59$, $p < .05$. Response times increased with increases in ADU, $F(3, 33) = 40.51$, $p < .0001$, and the extent of this effect differed for the three types of pairs, $F(6, 66) = 5.37$, $p < .0001$. Mean response times for ADUs of 0°, 60°, 120°, and 180° were 938, 996, 1,183, and 1,401 ms, respectively. The extent of the ADU effect, from 0° to 180°, amounted to 460, 640, and 290 ms, for the normal, reflected and mixed pairs, respectively.

In analyzing the sequential effects, we classified the sequences in a manner that closely parallels the previous experiments: sequences in which exactly the same orientation invariant stimulus is repeated (same patterns), sequences in which the individual letters match each other in identity and format (normal vs. reflected) but appear in different arrangements (same elements), and all other sequences combined (other). Figure 5 presents response time as a function of ADP for these three types of sequences. A two-way ANOVA on these data yielded $F(2, 22) = 4.82$, $p < .05$, for sequence type; $F(3, 33) = 8.46$, $p < .001$, for ADP; and $F(6, 66) = 6.25$, $p < .0001$, for the interaction. Same-elements and other sequences evidenced only a slight effect of ADP. In fact, a two-way ANOVA comparing the results for these two sequence types yielded no significant effects for ADP, $F(3, 33) = 1.77$, or the interaction ($F < 1$). In contrast, same-pattern sequences

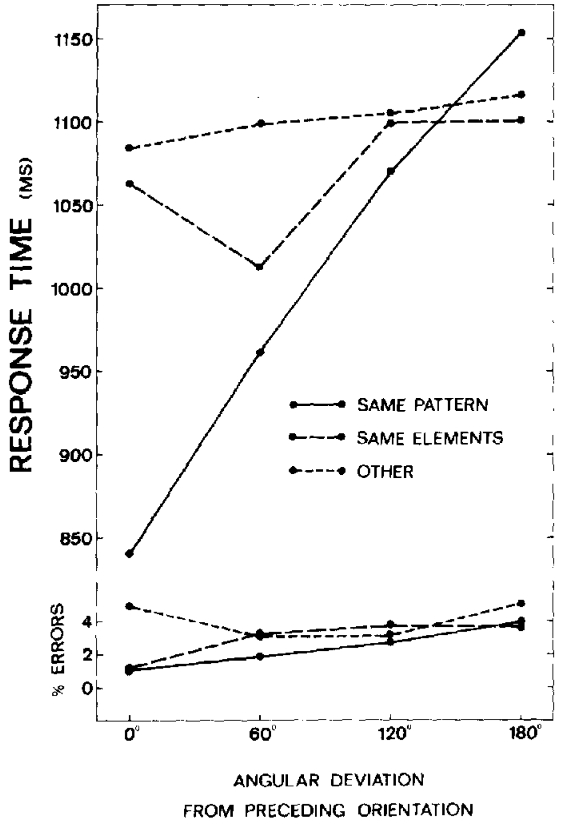

Figure 5. Response time and percentage of errors as a function of angular deviation from preceding orientation for same-pattern, same-elements, and other sequences (Experiment 4).

yielded a highly significant effect of ADP, $F(3, 33) = 15.78$, $p < .0001$, and the extent of this effect was significantly stronger than that of the same-elements sequences, $F(3, 33) = 7.41$, $p < .001$.

A sequence type × ADP ANOVA on percentage of errors yielded a significant effect only for sequence type, $F(2, 22) = 3.97$, $p < .05$.

The pattern depicted in Figure 5 was obtained for each of the three pair types—normal, reflected, and mixed. For same-pattern sequences, the extent of the ADP effects, from 0° to 180°, for these three types of pairs amounted to 295, 448, and 167 ms, respectively. It may be noted that the three types of pairs were similarly ranked in terms of the size of the effects of ADU.

In the classification of sequence types used above, several different types of sequences were lumped together in the "other" category. Two deserve special attention. In both only one letter is repeated in the same format, but in one it is in the same location (top or bottom) in the two successive patterns, whereas in the other it is in the other location. Mean response times for ADPs of 0°, 60°, 120°, and 180° were 1,120, 1,137, 1,120, and 1,110 ms, respectively, for the same-location sequences ($F < 1$), and 1,160, 1,147, 1,145, and 1,137 ms, respectively, for the different-location sequences ($F < 1$). These results suggest that individual elements are not rotated into congruence with each other even when they occupy the same relative position in two successive visual patterns.

Discussion

In Experiment 4 we extended the findings of the present study to a task requiring reflection decisions on two alphanumeric characters. The results of Murray and Corballis (1987) suggest that this task is performed piecemeal, so that each letter is transformed in turn to the upright. The question was whether this is also the case for the backward alignment transformation. If it is, then we should expect backward alignment based on correspondence at the local level. Thus, because the spatial arrangement of the two letters in a pair was immaterial, perhaps the effects of ADP should be found for sequences containing the same elements but in different arrangements.

The results were quite clear-cut. Strong and systematic effects of ADP were found only for sequences preserving global correspondence. All other sequences failed to evidence any such effects, including sequences consisting of exactly the same visual elements in the reverse arrangements, and sequences in which one element was repeated in the same or in a different location. These results clearly indicate that backward alignment does not utilize local correspondences even when these could speed up the response.

Experiment 5

The issue of holism in uprighting mental rotation has generally been studied by examining the dependence of rate of mental rotation on such factors as stimulus complexity (e.g., Folk & Luce, 1987), number of stimulus elements (e.g., Koriat & Norman, 1985), or the number of levels to be processed (e.g., Robertson & Palmer, 1983). In contrast, the preceding experiments examined the issue of holism in backward alignment by comparing sequential effects for successive stimuli possessing either global or local correspondence. Experiment 5 applied a rate of mental rotation paradigm to a task known to evidence backward alignment. The question is whether the effects of ADP increase with the number of elements in a string as was found to be the case for ADU (Koriat & Norman, 1985). If backward alignment is holistic, its speed might be indifferent to the number of elements to be rotated. But, on the other hand, global correspondence might be more difficult to establish for stimuli containing more elements, and this might result in weaker ADP effects for these stimuli.

In Experiment 5 subjects had to classify four stimuli, two two-letter words, and two single letters. Because it has already been established that the effects of ADP are proportional to the effects of ADU (Koriat & Norman, 1988), it was necessary to use stimuli for which the effects of ADU are likely to be equivalent for both one-character and two-character strings. Therefore, following the results of Koriat and Norman (1989), we used a set of stimuli that had no characters in common.

Method

Subjects. Sixteen Hebrew-speaking subjects participated in the experiment for course credit. None had participated in the previous experiments.

Stimuli. The stimuli for each subject consisted of two two-letter Hebrew words and two single-letter stimuli with no letter repeated throughout the set. These were constructed from a base set of four two-letter Hebrew words and their constituent letters. For each group of four subjects, two different Hebrew words were used plus two of the letters of one of the other words. All stimuli were equally represented across all subjects.

Procedure. The procedure was similar to that of Experiment 1. The assignment of each stimulus to the four response keys was counterbalanced across each of the 4 subjects receiving the same set of stimuli.

Results

Response times outside the range of 200–3,000 ms were eliminated (1.8%).

Focusing first on the effects of ADU, response time for ADUs of 0°, 60°, 120°, and 180° averaged 616, 621, 623, and 629 ms, respectively, for single letters, and 610, 606, 625, and 628 ms, respectively, for two-letter stimuli. A two-way ANOVA on these means yielded $F < 1$ for number of letters (1 vs. 2), $F(3, 45) = 4.86$, $p < .01$, for ADU, and $F(3, 45) = 2.71$, $p < .10$ for the interaction. Thus, response time increased only very slightly with ADU. Percentage of errors averaged 3.5% and did not increase with increasing ADU ($F < 1$).

Turning next to sequential effects, Figure 6 presents mean response time and percentage of errors as a function of ADP

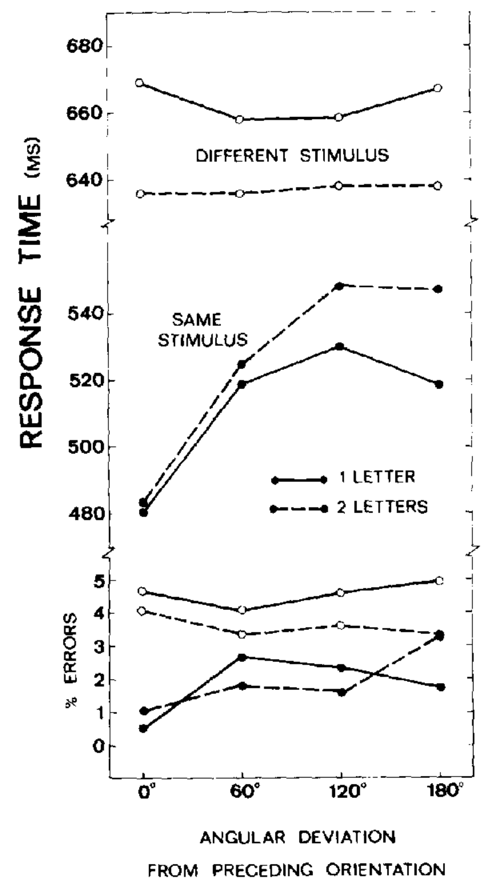

Figure 6. Response time and percentage of errors as a function of angular deviation from preceding orientation for same-stimulus and different-stimulus sequences for single-letter and two-letter stimuli (Experiment 5).

for single-letter and two-letter stimuli that followed either the same stimulus or a different stimulus. ADP affected response time for same stimulus sequences but not for different stimulus sequences, $F(3, 45) = 33.07$, $p < .0001$. Response time was faster for repeated than for nonrepeated stimuli, $F(1, 15) = 189.66$, $p < .0001$, and this effect was slightly stronger for single-letter than for two-letter stimuli, $F(1, 15) = 4.32$, $p < .10$.

The results were also analyzed separately for same-stimulus and different-stimulus sequences. Same-stimulus sequences yielded significant effects for ADP, $F(3, 45) = 43.09$, $p < .0001$, and these effects were stronger for two-letter than for single-letter stimuli, $F(3, 45) = 3.19$, $p < .05$. It may be seen that for same-stimulus sequences, number of letters had no effect at ADPs of 0° and 60°. However, at larger ADPs single-letter stimuli enjoyed a stronger benefit from stimulus repetition than did two-letter stimuli. In fact, when the analysis was confined only to ADPs of 120° or more, a Stimulus Repetition (same stimulus vs. different stimulus) × Number of Letters ANOVA yielded $F(1, 15) = 123.97$, $p < .0001$, for stimulus repetition, $F < 1$ for number of letters, and $F(1, 15) = 6.80$, $p < .05$, for the interaction. Different stimulus sequences, in contrast, yielded no significant effects for either ADP or the number of letters in the string.

Percentage of errors increased significantly with ADP for same-stimulus sequences, $F(3, 45) = 4.88$, $p < .01$, but not for different-stimulus sequences, $F(3, 45) = 1.32$.

Discussion

The results of Experiment 5 indicated stronger effects of ADP for repeated two-letter stimuli than for repeated single-letter stimuli. This difference was coupled with an overall stronger advantage of stimulus repetition for single letters than for two-letter stimuli, which was particularly evident for larger ADPs. This pattern suggests that backward alignment is more beneficial for single-letter than for two-letter stimuli.

The finding that backward alignment is sensitive to the number of elements in the string may appear inconsistent with the conclusion that this process is holistic in nature. In fact, previous researchers who argued that the uprighting mental rotation process is piecemeal based this claim primarily on the observation that the estimated rate of mental rotation decreased with stimulus complexity or with the number of elements to be rotated (e.g., Folk & Luce, 1987; Koriat & Norman, 1985; Murray & Corballis, 1987). In the present context, however, because backward alignment was found to be sensitive to the global correspondence between successive stimuli, the effect of number of elements is better attributed to either or both of the following factors. First, longer strings may be rotated more slowly than shorter strings, and second, there is a lesser likelihood of detecting visual correspondence for longer than for shorter strings. As for the former factor, Shwartz (1979), for example, found that larger images took longer to rotate than smaller images. It is possible that either visual size and/or visual complexity similarly affect the speed of backward alignment. With regard to the second factor, we should note that for same-stimulus sequences, response times for 0° ADP did not differ for single-letter and two-letter stimuli, suggesting that a comparison of exactly the same stimuli was not affected by number of elements. The observation that increasing ADP had more adverse effects on longer strings may therefore imply that in the process of backward alignment longer or more complex strings lose more of their visual details, leading to a greater difficulty in establishing visual correspondence.

In sum, we have previously shown that backward alignment is based on the global correspondence between successive stimuli. The results of the present experiment further indicate that backward alignment is also sensitive to the number of elements in the stimulus. Perhaps these two characteristics are related. It is exactly because backward alignment is based on global correspondence that the speed and/or likelihood of establishing this correspondence should vary with the number of elements in the stimulus. This implies that there should exist some upper bound on the number of elements that can be simultaneously rotated and compared in backward alignment.

Experiment 6

The results of Experiment 5 suggest that there must be an upper bound on the number and complexity of the elements that can be mapped onto each other in backward alignment. This is why in the experiments presented thus far we confined ourselves to words or numbers that contained no more than two elements. In Experiment 6 we utilized the data from an exploratory study to examine whether the effects of relative orientation might still be evidenced for four-letter strings. That study examined the possibility that word recognition may become indifferent to orientation with extensive practice. Only 1 subject participated, making target–nontarget classifications on a four-letter Hebrew word (see inset in Figure 7). The nontargets consisted of all the other 23 possible permutations of the same four letters.

Method

The same apparatus was used as in Experiment 4. The strings were about 1.0 × 4.0 cm, and appeared on the screen in 18 different orientations, 0° to 340° in 20° steps. The experiment consisted of six sessions on 6 successive days. Each session included one practice block of 36 trials followed by six blocks of 148 trials each. These included four warm-up trials followed by 144 experimental trials. The experimental trials included four targets and four nontargets in each of the orientations, randomly ordered.

Results and Discussion

Response times outside the range of 250–5,000 ms (1.2%) were eliminated. The median response time was 538 ms for targets and 528 ms for nontargets; it increased, across both types of stimuli, from 475 ms (with 1.4% errors) for 0° ADU to 594 ms (with 6.6% errors) for 180° ADU.

Figure 7 presents median response time as a function of ADP for sequences in which the same target or nontarget string was repeated and for those involving different strings. It should be stressed that because all strings, both targets and nontargets, were composed of the same four letters, the same-string and different-string sequences did not differ in local correspondence. Nevertheless, it can be clearly seen that different-string sequences exhibit a flat function, whereas same-string sequences evidence a systematic increase in response time with relative disorientation that obtains throughout the entire range of ADPs. In sum, although these results were based only on a single subject, they clearly show that a holistic backward alignment can occur for alphanumeric strings containing as many as four elements.

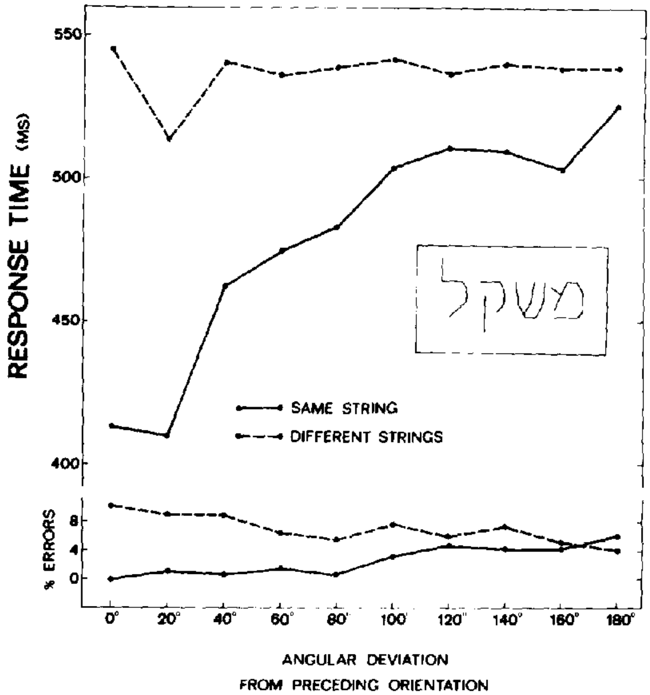

Figure 7. Response time and percentage of errors as a function of angular deviation from preceding orientation for same-string and different-string sequences (Experiment 6). (Inset: The Hebrew word used in the experiment.)

General Discussion

The present study examined the hypothesis that backward alignment is holistic, operating on the visual template as a whole. In all the experiments we used stimuli consisting of several spatially discrete elements. Previous research suggested that the constituent elements of these stimuli were treated as separate units when rotated to the upright. The question was whether they were treated as unitary wholes for the purpose of backward alignment or were also transformed piecemeal. Specifically, we sought to determine whether the effect of angular disparity between two successive stimuli (ADP) depends on their global congruence or on the local congruence between their constituent elements. The results of all six experiments indicated systematic effects of ADP only for sequences in which exactly the same pattern was repeated at varying orientations. Sequences in which the same elements were repeated but in different arrangements produced no stronger effects of ADP than those in which the two successive stimuli had no elements in common. Similar results were consistently found when the task required stimulus classification (Experiments 1, 2, 3, 5, and 6) or mirror-image discriminations (Experiment 4). These also occurred when the spatial arrangement of the elements was critical (Experiments 1, 2 and 6) or when it was irrelevant (Experiments 3 and 4). These results suggest that backward alignment operates on the overall visual congruence between successive stimuli and is indifferent to the local congruence between their constituent elements. Evidence suggesting the occurrence of such holistic backward alignment was found for alphabetic strings that contained as many as four characters (Experiment 6), but the speed and/or likelihood of backward alignment appeared to decrease with increasing number of elements in the string (Experiment 5).

We shall examine these results in terms of four general issues: the distinction between the uprighting and backward alignment processes, the issue of holism in mental rotation, the frame rotation versus image rotation hypotheses, and the nature of *same* versus *different* judgments.

Uprighting and Backward Alignment Processes

We have distinguished between two types of mental rotation processes, uprighting and backward alignment (Koriat & Norman, 1988). The uprighting process is that originally investigated by Cooper and Shepard (1973): A disoriented character is imagined to rotate to the upright and matched to the long-term memorial representation of the normal, upright character. In the backward alignment process, in contrast, the character is brought into congruence with the short-term visual trace of the preceding character. These two processes represent two alternative mechanisms for recovering the identity of a disoriented stimulus by relating it to a familiar representation. Some of the evidence we have reported (Koriat & Norman, 1988) suggests that the two processes differ not only in the representation that is used as a referent but also in the quality of the transformational process itself. The uprighting process appears to be an imaginal, subject-initiated process that is relatively effortful (Shepard, 1984). Although there is evidence suggesting that the actual execution of mental rotation need not compete for attentional resources, the initiation and termination of mental rotation appear to be controlled (Corballis, 1986). In contrast, the backward alignment process is a stimulus-induced, perceptual process that responds to the visual congruence between successive stimuli.

In the present study we explored the possibility that the two types of mental rotation processes also differ along the holistic-nonholistic continuum, with backward alignment being more holistic. We deliberately focused on those conditions for which there is some indication that the uprighting process is nonholistic and examined the possibility that even for these conditions backward alignment operates on the visual pattern as a whole. This is based on the idea that the uprighting process often requires that the stimulus be identified before the mental rotation operation is undertaken (see Shepard & Cooper, 1982). Such is not the case for backward alignment, which is designed to detect transformational invariance over successive visual events without necessarily establishing their identities. Like apparent motion, it can rely strictly on the visual correspondence between successive stimuli. In fact, the ADP effects obtained for same-stimulus sequences indicate that even if the first stimulus must be mentally rotated to the upright, the second stimulus is brought into congruence with the raw (disoriented) visual representation of the first stimulus, not with the image of the uprighted stimulus. Thus, even if the first stimulus must be analyzed, segmented, and identified for the purpose of the uprighting process, it is presumably the unarticulated visual representation of the stimulus that serves as a referent representation in backward alignment.

In our previous study (Koriat & Norman, 1988), the evidence concerning backward alignment was based solely on experiments requiring reflection decisions on single alphanumeric characters. The results of the present study, as well as those of Koriat, Norman, and Kimchi (1988) indicate that backward alignment also occurs in tasks requiring stimulus identification or classification. This is important because these tasks sometimes fail to evidence any effects of angular deviation from the upright (ADU). Thus, although response time for the identification of single alphanumeric characters is indifferent to ADU (e.g., Corballis & Nagourney, 1982), it evidences systematic effects of ADP for same-character sequences (Koriat et al., 1988). Similarly, in some of the experiments reported in the present article, there was no evidence that letter strings had to be normalized to be classified, and yet there was evidence for the occurrence of backward alignment for same-string sequences in these tasks.

Normally, however, the classification of an alphanumeric string exhibits marked and systematic effects of disorientation that increase with increasing number of characters in the string (e.g., Koriat & Norman, 1985). In our recent study (Koriat & Norman, 1989) we suggested that this has to do with the criticality of order information: Although disorientation may not impair the identities of the constituent letters of a word, it does disrupt letter order, and mental transformation is apparently needed to restore this order. For example, the time to classify the number *13* increased markedly with ADU when the set of numbers to be classified included the number *31* but was indifferent to ADU when the set did not include *31*. This clearly suggests that the transformation of the two-digit number to the upright was not holistic but was mediated by an analysis of the number into its constituent elements.

In classification tasks where element order is critical, we should expect evidence for the operation of both the uprighting and the backward alignment processes, and the interplay between these processes then takes on particular interest. Our previous results with the reflection decision task suggested that when the current stimulus is a rotational transform of the preceding stimulus, there is competition between the uprighting and backward alignment processes, and the response is determined by the process that requires the shortest transformational path (Koriat & Norman, 1988). The same appears to hold in the present study in tasks requiring the classification of letter strings when order information was critical (and therefore, some uprighting rectification was apparently needed; see Figure 2). Thus, in same-stimulus sequences, the second target may be "identified" by matching it either with the long term memorial representation of the normal, upright stimulus or with the short-term visual trace of the preceding stimulus, whichever of these requires the shortest rotational path.

Holism in Mental Rotation

The above discussion implies that in those classification tasks where order information is critical, competition exists between two image rotation processes: a holistic backward alignment process that operates on the visual stimulus as a whole and a nonholistic uprighting process that operates on its component elements. But this conclusion must be qualified because the holistic nature of backward alignment and the nonholistic nature of the uprighting process were inferred from different aspects of performance. Nonholistic processing was inferred from the observation that for stimuli consisting of spatially discrete elements, rate of mental rotation decreases systematically with the number of elements in the stimulus (e.g., Koriat & Norman, 1985, 1989; Murray & Corballis, 1987). Also, the dependence of ADU effects on the criticality of element order (Koriat & Norman, 1989) further suggests that the strings are analyzed into the constituent components for the purpose of the transformation to the upright. The holistic nature of backward alignment, in contrast, was inferred from the dependence of this process on the configural correspondence between successive stimuli, with local correspondence being inconsequential. This suggested that the stimulus is not parsed into separate units that are treated independently for the purpose of the matching to the preceding stimulus but is apparently processed as a unitary whole.

The question still remains whether the two methods used in addressing the issue of holism in mental rotation—the rate of rotation and the visual congruence methods—are equivalent. That they are not necessarily so is strongly suggested by the results of Experiment 5. These indicated that the effects of ADP were obtained only for stimuli preserving configural congruence, but still these effects were stronger for two-letter stimuli than for single letters. This finding calls into question the common assumption that the dependence of rate of mental rotation on stimulus complexity is evidence for piecemeal rotation. At the least, it must be conceded that such dependence may simply derive from a slower-but-holistic rotation of the more complex stimuli. In the present article we tentatively conclude that although backward alignment is sensitive to configural correspondence, the speed of the transformation process and/or its success in establishing this correspondence may decrease with increasing number of elements in the string. Thus, perhaps, there is a limit on the number and complexity of elements that can be simultaneously transformed and compared in backward alignment.

The experimental method used in the present study is similar to a paradigm employed by Robertson and Palmer (1983), though their paradigm appears to imply a somewhat different definition of the issue of holism in mental rotation. They used hierarchically structured stimuli consisting of large (global) letters constructed from spatial arrangements of small (local) letters (see Navon, 1977), and they had subjects make reflection decisions on the global and/or local letters. Their results indicated that rate of mental rotation did not depend on the number of levels to be rotated, suggesting that rotation to the upright of local and global levels occurred together rather than sequentially.

The stimuli employed by Robertson and Palmer allow an independent manipulation of the local and global levels. In the present study the term *global correspondence* was used to designate the type of correspondence that is necessary to bring one stimulus into perfect alignment with the other through a single rotation of the entire stimulus array as a whole. Global correspondence in this sense implies local correspondence. It would be of interest to study the backward alignment process with the type of stimuli used by Robertson and Palmer in order to determine whether subjects can selectively tune either to congruence of the elements or to congruence of their spatial arrangement for the purpose of backward alignment. The results of Experiments 3 and 4 suggest that they cannot do so: No evidence was found for backward alignment at the local level, even when such alignment was sufficient to guarantee response repetition. Nevertheless, it is possible, of course, that backward alignment does occur at the level of the constituent elements but fails to modulate the effects of ADP, either because it is relatively slow or because it does not gain access to the response mechanism.

In discussions of holism in mental rotation, several factors were claimed to affect the use of a holistic or a nonholistic transformation. Can these factors explain our results? It has been argued, for example, that tasks requiring the matching of two simultaneously presented figures do not induce the rotation of complete images, and subjects may resort to a piecemeal comparison of figure segments (see Folk & Luce, 1987). Similarly, Shepard and Cooper (1982) proposed that mental rotation is holistic when a well-learned, integrated stimulus is compared with a memory representation but may be piecemeal when the task requires the matching of two stimuli. When our results are examined in this perspective, they seem to display just the reverse pattern. Backward alignment is similar in many respects to the task of comparing two visual stimuli, but we found it to be holistic in the present study. This is so despite the fact that the stimuli consisted of several spatially discrete units. In contrast, it is the uprighting process, which involves a comparison of a single stimulus with a memorial representation, that has been found to be nonholistic for such stimuli (e.g., Koriat & Norman, 1985).

Frame Rotation Versus Image Rotation

Originally, the study of sequential effects in mental rotation was aimed at answering the question of what is rotated in mental rotation (see Hintzman, O'Dell, & Arndt, 1981; Koriat & Norman, 1984; Robertson, Palmer & Gomez, 1987). Two alternative hypotheses were entertained: an image rotation hypothesis, where a disoriented stimulus is interpreted by imagining it rotated to the upright (see Shepard & Cooper, 1982), and a frame rotation hypothesis, where a disoriented stimulus is interpreted by rotating the entire perceptual frame of reference into alignment with the coordinates of the stimulus. It has been argued that if the frame rotation hypothesis is correct, response time in a mental rotation task should increase with increasing ADPs. This is so because if subjects adjust their perceptual frames of reference to each incoming stimulus in turn, the time to readjust this frame should vary with the angular disparity between successive stimuli. The results of several experiments yielded systematic effects of ADP, consistent with the frame rotation hypothesis (Koriat & Norman, 1984; Robertson et al., 1987). However, our detailed analyses of these results (Koriat & Norman, 1988) indicated that these effects are obtained only under very specific conditions, namely those in which the same alphanumeric character appears in the same format (normal or unreflected) in two successive trials. The effects of ADP were practically absent in all other conditions. This stimulus-bound character of the effects of ADP has convinced us that these effects were not due to the rotation of an abstract frame of reference but derived instead from a second type of image rotation, one in which the current stimulus is brought into alignment with the preceding stimulus rather than with the upright. When such backward alignment succeeds, the same response may be repeated.

Clearly, we do not deny the possibility of frame rotation occurring under certain circumstances. The question is whether this process is responsible for the observed ADP effects. In our previous studies (Koriat & Norman, 1988; Koriat et al., 1988) the effects of ADP were either entirely absent or else very small when the two successive stimuli were not rotational transforms. Robertson et al. (1987) also observed stronger ADP effects for same-pattern than for different-pattern sequences, but their results also indicated systematic and significant ADP effects for the latter sequences. Thus, perhaps in their study the ADP effects derived from two different types of processes: an automatic backward alignment and a controlled mental rotation process, where the current stimulus is interpreted relative to the frame of reference of the preceding stimulus.

As far as the present study is concerned, the results, on the whole, are entirely consistent with the backward alignment interpretation of the ADP effects. Not only are these effects practically absent for sequences in which the two successive stimuli have no elements in common, but they are also not observed for sequences that contain exactly the same elements but in different spatial arrangements. These results are difficult to accommodate to the frame rotation interpretation. Rather, the stimulus-bound nature of the ADP effects suggests that they derive from a particular form of image rotation.

Judgments of Sameness and Difference

Finally, we shall comment on possible implications of the present work for the research on the nature of *same* versus *different* judgments in stimulus comparison tasks (see Farell, 1985, for a review). The conditions assumed to give rise to backward alignment have much in common with those underlying *same* judgments: Subjects presumably detect the orientation-invariant correspondence between two successive stimuli, and this allows repetition of the same response, thus circumventing the need to make an independent classification of the second stimulus. Indeed, in several *same–different* comparison studies in which the two stimuli varied along some continuous irrelevant dimension of disparity (e.g., size or orientation), *same* response times evidenced systematic effects of this dimension, suggesting that the irrelevant disparities were normalized before comparison. These effects were generally absent in the case of *different* responses (e.g., Dixon & Just, 1978; Simion, Bagnara, Roncato, & Umiltà, 1982). These results are analogous to those that gave rise to the concept of backward alignment. But note that the backward alignment results were obtained in a task that did not explicitly require the comparison of stimuli.

The different pattern of effects observed for *same* and *different* judgments, as well as the surprising observation that *same* judgments are generally faster than *different* judgments, suggested the hypothesis that judgments of sameness are mediated by qualitatively different comparison operations than are judgments of difference. One model that incorporated this assumption centers on the notion of the identity reporter (Bamber, 1969). The identity reporter is a postulated fast processor that allows only the detection of a match but not of a mismatch. This is in contrast to a different, slower processor that operates serially and allows the detection of mismatches as well. On *same* trials, the output of the identity reporter preempts that of the slow serial processor, resulting in fast *same* responses.

One hypothesis is that the two processors differ in their mode of operation, the identity reporter being more holistic, operating in terms of an overall template match, and the slower processor being analytic and serial (see e.g., Cunnigham, Cooper, & Reaves, 1982; Hock, 1973). According to this view, the identity reporter that mediates *same* judgments operates on the global or template congruence between stimuli, whereas the slower processor underlying *different* judgments is based on a serial, self-terminating comparison of stimulus features or components.

If the backward alignment process is assumed to utilize the identity reporter said to mediate *same* responses in stimulus comparison tasks, then our results appear to offer some support for the proposed holistic mode of this reporter. What is more, the results of Experiments 3 and 4 would then imply that this reporter cannot detect local congruence even when this congruence is sufficient to guarantee repetition of the same response. Obviously, subjects are able to match multiletter strings irrespective of the order of the letters (e.g., Proctor & Healy, 1987), suggesting that *same* judgments in this task can be mediated by different processes than those underlying the effects of ADP observed in the present study. Also, it is not clear that the identity reporter can initiate a *same* response only when the two stimuli have the same overall appearance (e.g., Bamber & Paine, 1973). In fact, as Farell pointed out (1985), "the identity reporter remains a black box" (p. 436). So, perhaps the line of research illustrated in the present article can help further explore the utility of this concept by relating it to the phenomena that we have subsumed under the concept of backward alignment.

References

Bamber, D. (1969). Reaction times and error rates for "same"–"different" judgments of multidimensional stimuli. *Perception &*

Psychophysics, 6, 169–174.

Bamber, D., & Paine, S. (1973). Information retrieval processes in "same"–"different" judgments of letter strings. In S. Kornblum (Ed.), *Attention and performance IV* (pp. 477–495). New York: Academic Press.

Bethel-Fox, C. E., & Shepard, R. (1988). Mental rotation: Effects of stimulus complexity and familiarity. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 12–23.

Cooper, L. A. (1975). Mental rotation of random two dimensional shapes. *Cognitive Psychology, 7,* 20–43.

Cooper, L. A., & Podgorny, P. (1976). Mental transformations and visual comparison processes: Effects of complexity and similarity. *Journal of Experimental Psychology: Human Perception and Performance, 2,* 503–514.

Cooper, L. A., & Shepard, R. N. (1973). Chronometric studies of the rotation of mental images. In W. G. Chase (Ed.), *Visual information processing* (pp. 75–176). New York: Academic Press.

Corballis, M. C., & Nagourney, B. A. (1978). Latency to categorize disoriented alphanumeric characters as letters or digits. *Canadian Journal of Psychology, 32,* 186–188.

Corballis, M. C. (1986). Is mental rotation controlled or automatic? *Memory & Cognition, 14,* 124–128.

Cunninghan, J. P., Cooper, L. A., & Reaves, C. C. (1982). Visual comparison processes; Identity and similarity decisions. *Perception & Psychophysics, 32,* 50–60.

Dixon, P., & Just, M. A. (1978). Normalization of irrelevant dimensions in stimulus comparisons. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 36–46.

Farell, B. (1985). "Same"–"different" judgments: A Review of current controversies in perceptual comparisons. *Psychological Bulletin, 98,* 419–456.

Folk, M. D., & Luce, R. D. (1987). Effects of stimulus complexity on mental rotation rate of polygons. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 395–404.

Hintzman, D. L., O'Dell, C. S., & Arndt, D. R. (1981). Orientation in cognitive maps. *Cognitive Psychology, 13,* 149–206.

Hochberg, J., & Gellman, L. (1977). The effect of landmark features on "mental rotation" times. *Memory & Cognition, 5,* 23–26.

Hock, H. S. (1973). The effect of stimulus structure and familiarity on same–different comparison. *Perception & Psychophysics, 14,* 413–420.

Koriat, A., & Norman, J. (1984). What is rotated in mental rotation? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 10,* 421–434.

Koriat, A., & Norman, J. (1985). Reading rotated words. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 490–508.

Koriat, A., & Norman, J. (1988). Frames and images: Sequential effects in mental rotation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 14,* 93–111.

Koriat, A., & Norman, J. (1989). Why is word recognition impaired by disorientation while the identification of single letters is not? *Journal of Experimental Psychology: Human Perception and Performance, 15,* 153–163.

Koriat, A., Norman, J., & Kimchi, R. (1988). *The recognition of disoriented characters: Evidence for backward alignment.* Unpublished manuscript.

Murray, J. E., & Corballis, M. C. (1987). *Mental rotation of pairs of letters.* Unpublished manuscript.

Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology, 9,* 353–383.

Palmer, S. E. (1975). Visual perception and world knowledge: Notes on a model of sensory–cognitive interaction. In D. A. Norman & D. E. Rumelhart (Eds.), *Explorations in cognition* (pp. 279–307). San Francisco: Freeman.

Presson, C. C. (1982). Strategies in spatial reasoning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 8,* 243–251.

Proctor, R. W., & Healy, A. F. (1987). Task-specific serial position effects in comparisons of multiletter strings. *Perception & Psychophysics, 42,* 180–194.

Pylyshyn, Z. W. (1973). What the mind's eye tells the mind's brain. *Psychological Review, 80,* 1–24.

Pylyshyn, Z. W. (1979). The rate of "mental rotation" of images: A test of a holistic analogue hypothesis. *Memory & Cognition, 7,* 19–28.

Robertson, L. C., & Palmer, S. E. (1983). Holistic processes in the perception and transformation of disoriented figures. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 203–214.

Robertson, L. C., Palmer, S. E., & Gomez, L. M. (1987). Reference frames in mental rotation. *Journal of Experimental Psychology: Learning, Memory and Cognition, 13,* 368–379.

Shepard, R. N. (1984). Ecological constraints on internal representation: Resonant kinematics of perceiving, imagining, thinking, and dreaming. *Psychological Review, 91,* 417–447.

Shepard, R. N., & Cooper, L. A. (1982). *Mental images and their transformation,* Cambridge, MA: MIT Press.

Shwartz, S. P. (1979). *Studies of mental image rotation: Implications for a computer simulation of visual imagery.* Unpublished doctoral dissertation, Johns Hopkins University, Baltimore.

Simion, F., Bagnara, S., Roncato, S., & Umiltà, C. (1982). Transformation processes upon the visual code. *Perception & Psychophysics, 31,* 13–25.

Yuille, J. C., & Steiger, J. H. (1982). Nonholistic processing in mental rotation: Some suggestive evidence. *Perception & Psychophysics, 31,* 201–209.

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