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Reading Rotated Words

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Hebrew-speaking students performed lexical decisions on Hebrew letter strings that appeared at different orientations. Response times evidenced a strong interaction between string length and orientation. At angular deviations of less than 60° from the upright, neither orientation nor string length had any effect, suggesting that words were directly, and probably holistically, recognized. The results for the 60° deviation, while also exhibiting no effects of word length, yielded slower response times, suggesting a holistic rectification process. For deviations between 60° and 120°, the effects of disorientation increased sharply with increasing string length, suggesting piecemeal processing that may be due to the utilization of reading units smaller than the whole word or to piecemeal rectification. In this region, stimulus disorientation appears to impair word recognition by disrupting transgraphemic information rather than by interfering with letter identification. Extreme disorientations, 120° or more, exhibited no further impairment with increased disorientation, and all evidenced strong and similar length effects, suggesting letter-by-letter reading. The implications of the results for the reading of normal and transformed text are discussed.

This study combined a mental rotation task with a reading task in an attempt to address two separate but related issues. First, is the rectification of disoriented stimuli carried out holistically or in a piecemeal fashion? Second, are words read letter by letter or as whole units? In a previous study (Koriat & Norman, 1984) we asked subjects to perform a lexical decision task on five-letter rotated strings. Response times increased systematically with angular deviation from the upright, suggesting that words might be mentally rotated in a manner similar to that of other stimuli. In the present study we varied the number of letters in a string and examined the combined effects of degree of rotation and string length on performance.

The issue of holism in mental rotation has recently received a great deal of attention (see Robertson & Palmer, 1983; Shepard & Cooper, 1982). The question is whether a misoriented figure is mentally rotated as an integral whole with all its parts rotating simultaneously around the same point or is rotated segment by segment. If mental rotation is piecemeal and serial, the effect of disorientation might be expected to increase with the complexity of the figure or the number of "parts" it contains. Studies of this issue have yielded somewhat equivocal results, the majority leaning toward the nonholistic position (Cooper, 1975; Cooper & Podgorny, 1976; Hochberg & Gellman, 1977; Pylyshyn, 1979; Yuile & Steiger, 1982). More recently, however, Robertson and Palmer (1983) obtained data consistent with the hypothesis of holistic mental rotation. They used large (global) letters constructed from spatial arrangements of small (local) letters. Rate of mental rotation was not affected by the number of levels that were rotated, suggesting a holistic rotation process in which rotation of global and local levels occurs together.

In their recent reassessment of the holistic–nonholistic issue in mental rotation, Shepard and Cooper (1982) offered a view that appears to accommodate the divergent results. Mental rotation is assumed to be holistic when the task involves only one stimulus that is to be compared to a memory representation and when this stimulus constitutes a well-learned, integrated figure. On the other hand, mental rotation might be piecemeal when the task

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calls for the matching of two stimuli, and/or when the stimulus lacks mental integration.

When the recognition of misoriented words is examined within this framework, the following might be proposed. If familiar words constitute well-integrated wholes, they should be mentally transformed as integral units. Thus, the magnitude of the rotation effect should be the same for words of different length. On the other hand, if they are represented as composites of distinct units, they might exhibit piecemeal rotation, with "rate of mental rotation" decreasing with number of letters in the string.

This leads directly to the second issue, that of holism in word recognition (see e.g., Henderson, 1980). This issue has a far longer history than the issue of holism in mental rotation (e.g., Cattell, 1886; Huey, 1908) and has attracted a vast amount of research effort (see e.g., Henderson, 1982, for a review). The question is whether word recognition is based on the visual configuration of the word as a whole or is mediated by processes of letter identification. One experimental approach to this question has involved the use of nonstandard typographic variations, particularly those assumed to disrupt the familiar visual configuration of the word without destroying the identity or the arrangement of its constituent letters (e.g., Adams, 1979). Such orthographic variations have been found to impair performance (e.g., Coltheart & Freeman, 1974), suggesting that word recognition normally capitalizes on supraletter features (but this may also be due to the impairment of letter identification, see e.g., Paap, Newsome, & Noel, 1984). On the other hand, these variations did not reduce the size of the word superiority effect (McClelland, 1976), consistent with letter-mediated models of reading (e.g., McClelland & Rumelhart, 1981).

The rotation of word stimuli utilized in the present study is another form of visual distortion that has the advantage of allowing examination of continuously graded degrees of transformation. In the previous study we found degree of disorientation to exert strong and systematic effects on word recognition (Koriat & Norman, 1984). This effect is not easy to interpret, particularly because disorientation does not seem to affect the latency of identifying single letters (e.g., Corballis & Nagourney, 1978). One possibility is that word recognition is based on whole-word units and that disorientation disrupts the total configuration of the word. A second possibility is that word recognition does rest on letter identities and that when letters are embedded in a letter string, disorientation does impair their identities or the perception of their arrangement. The study of the combined effects of word rotation and string length on word recognition might shed some light on this issue. We know that for upright words lexical decision latency is generally indifferent to word length (Frederiksen & Kroll, 1976), suggesting the possibility of whole-word reading. If word recognition is found to be indifferent to string length throughout the entire range of orientations, this would further substantiate the idea that words are generally processed as integral units.

There is some indication, however, that visual transformations that apparently do not disrupt letter identities do yield increased length effects relative to standard format (Bruder, 1978; Navon, 1978). We may, therefore, suspect that the effect of string length should increase with increased disorientation, suggesting that some piecemeal sequential processing occurs. If such is the case, the detailed examination of the manner in which length effects emerge with increased disorientation might provide some insight into the question of holism in word recognition. Thus, in our previous study small deviations from the upright appeared to have little effects on word recognition. Perhaps, word length effects can be found only for those disorientations large enough to disrupt direct activation of whole-word codes.

The following four experiments all involved lexical decisions for letter strings presented at different angular disorientations. In the first experiment the length of the letter strings was varied systematically, with the aim of determining how the effects of disorientation might interact with those of string length in affecting performance.

Experiment 1

Method

Subjects. Twenty-four volunteers participated in the study. They were all students at the University of Haifa whose primary language was Hebrew.

Stimulus materials. Ninety-six Hebrew words were compiled, 24 of each of the 2-, 3-, 4-, and 5-letter lengths.

They contained only consonantal letters and had only one pronunciation when unpointed (see Koriat, 1984). Twelve words of each length were transformed into nonwords by replacing one letter with another consonantal letter. The order of the letter strings was the same for all subjects. This order was random except for the constraint that each block of eight successive strings included one word and one nonword of each length.

Apparatus and procedure. The experiment was controlled by a PDP 11/34 minicomputer, and the stimuli were presented on a VT-11 CRT Graphic Display Unit. The subjects sat at a viewing distance of 80 cm, with their heads resting on a chin-and-head rest, preventing head rotations. They were asked to classify letter strings as words or nonwords as quickly as they could without making errors. They responded by pressing one key labeled *word* with their right index finger or a second key labeled *nonword* with their left index finger. They were informed that the strings would appear in one of six orientations. The session began with 32 practice trials, followed by two repetitions of the 96 experimental strings in the same order. There was a 2-min break between the two presentations.

All strings appeared unpointed (see Koriat, 1984) at the center of the screen and were rotated about their center. The letter strings subtended 0.8 cm vertically (when upright) and ranged between 2 cm (two-letter strings) and 5 cm (five-letter strings) horizontally. Each string remained in view until the subjects responded, and it was replaced by the subsequent stimulus after 500 ms. String orientations were preprogrammed so that for each subject and repetition two words and two nonwords of each length appeared at each orientation, and for each repetition each string appeared equally often at each orientation across all subjects. The orientation of each letter string varied between repetitions.

Results

Response times in excess of 5,000 ms or less than 250 ms (0.8%) were eliminated from the analyses. The two repetitions yielded very similar results and were therefore combined. Mean latencies for correct responses are shown in Figure 1, where the effects of angular disorientation are seen to vary systematically with string length. These results were analyzed in terms of the four angular deviations from upright, 0°, 60°, 120°, and 180°, (i.e., collapsing over equivalent deviations, 60° + 300°, 120° + 240°). A three-way analysis of variance (ANOVA), Angular Deviation × String

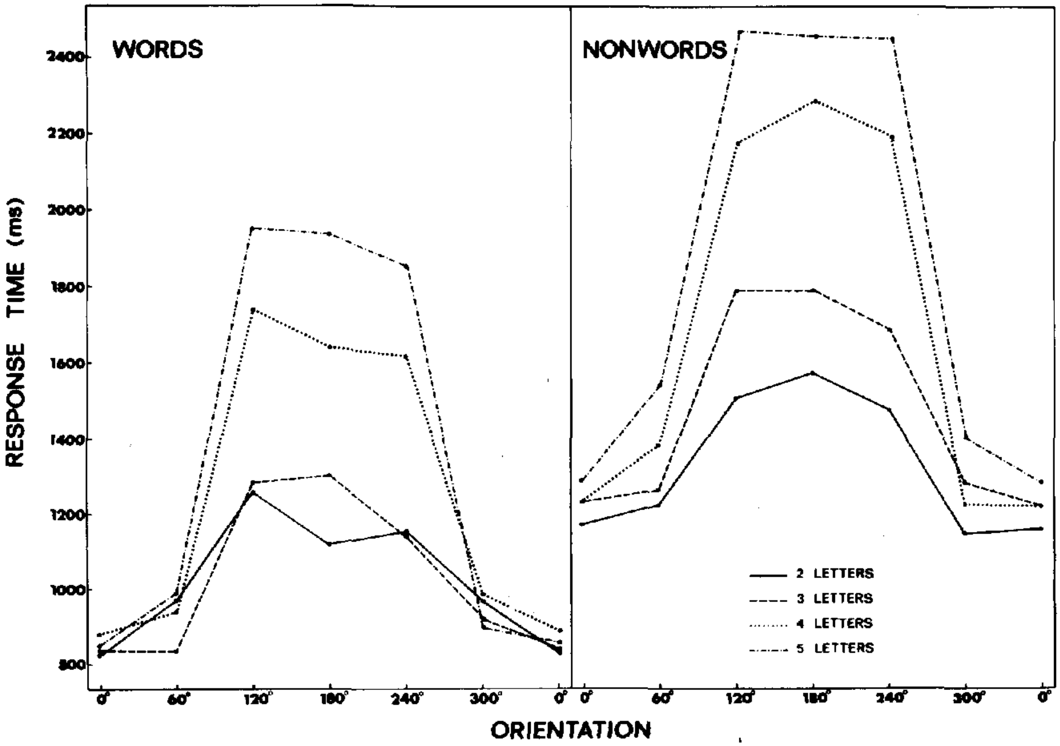

Figure 1. Response time (in milliseconds) for words and nonwords as a function of orientation with string length as a parameter (Experiment 1).

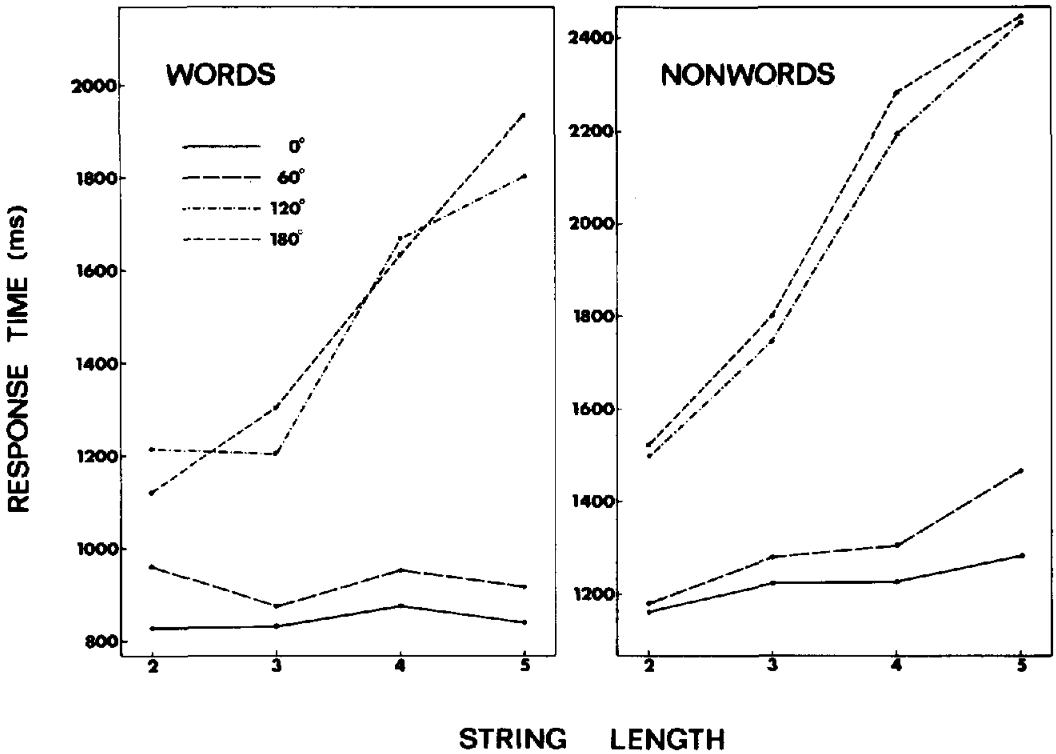

Figure 2. Response time (in milliseconds) for words and nonwords as a function of string length for different angular deviations from the upright (Experiment 1).

Length × Lexicality (words vs. nonwords) on response times yielded significant main effects for angular deviation, $F(3, 69) = 86.05$, $p < .0001$, and for string length, $F(3, 69) = 86.43$, $p < .0001$. Response times were longer for nonwords than for words, $F(1, 23) = 75.43$, $p < .0001$, and nonwords exhibited stronger effects of deviation, $F(3, 69) = 3.69$, $p < .02$, as well as stronger effects of length, $F(3, 69) = 3.81$, $p < .02$, compared with words.

The interaction between deviation and string length was highly significant, $F(9, 207) = 28.06$, $p < .0001$. The nature of this interaction may be best seen in Figure 2. For both words and nonwords the effect of string length increases substantially with increased deviation from the upright. Normally oriented words (0°) show no effect of word length ($F < 1$), consistent with previous findings, whereas for the 120° and 180° deviations response times increased by about 700 ms from two-letter to five-letter words, $F(3, 69) = 63.45$, $p < .0001$.

Interestingly, the results for the 60° deviation for words exhibit the same independence of length as found for the 0° orientation, but at the same time yield longer response times by about 85 ms. A two-way ANOVA, 0° versus 60° × String Length yielded a significant effect for the 0° versus 60° comparison, $F(1, 23) = 17.76$, $p < .0005$, but neither the effects of length nor the interaction was significant. This appears not to be the case for nonwords, where the 60° deviation yielded a significant effect of string length, $F(3, 69) = 6.56$; $p < .001$.

A three-way ANOVA on the error rates yielded significant main effects for angular deviation, $F(3, 69) = 3.24$, $p < .05$, and for string length, $F(3, 69) = 12.42$, $p < .0001$, but no effects for lexicality. Although the effects of deviation mimic those of the response times, those for string length do not. Mean percent errors for string lengths 2, 3, 4, and 5, were 15.1%, 11.4%, 8.4%, and 9.6%, respectively. The higher error rates for the shorter strings point to the possibility of a speed–accuracy trade-off for the length effects.

Discussion

In Experiment 1 we examined the question whether in reading disoriented words the transformation process is holistic, operating on the entire word pattern as an integral unit, or is conducted piecewise, with segments of the word transformed in turn. On the face of it, the results seem to suggest the operation of both types of transformation processes. First, response latency increases sharply with string length. The extent of orientation effects from 0° to 180°, calculated across words and nonwords, was 339 ms, 508 ms, 909 ms, and 1,100 ms for two- to five-letter strings, respectively. This systematic increase suggests that whatever transformation is applied to disoriented strings, it operates in a piecemeal, apparently letter-by-letter, fashion. Second, however, there is a range of orientations over which words seem to be processed as integral wholes, and when transformation is required, it operates on the word as a single unit. This is suggested by the results for word stimuli at deviations 0° and 60°. Although the 60° disorientation required significantly longer response times than did the upright (0°) orientation, this effect was independent of word length. Apparently for deviations of up to 40° or 60° from the upright, holistic transformation processes take place.

The increase in response time from 0° to 60° deviations is relatively slight. A similar type of relative indifference to small disorientations from the upright has been discussed by Hock and Tromley (1978) in terms of the notion of a perceptual upright. They proposed that each stimulus has a characteristic range of orientations over which it is perceived as upright and that mental rotation need proceed only until the stimulus attains its perceptual uprightness. It is tempting to speculate that words are perceptually upright in a range of ±60° about their normal orientation, and within this range they are processed holistically. But, on the other hand, it remains unclear why the 60° deviations yield significantly longer response times than do the 0° deviations.

Cooper and Shepard (1973), using reflection decisions on single characters, found a nonlinear increase in response time with degree of disorientation, with smaller disorientations yielding relatively small effects. They suggested that the memory representation of the normal, upright character may be broadly tuned so that a response can be made for tilts of 60° or more without any need for mental rotation. This concept of broad tuning is similar to the idea of a perceptual upright but appears better fitted to accommodate findings of a small increase in response time with increasing disorientation like that found in the present study.

As a final comment, it should be noted that the results appear dichotomous, with the three smaller disorientations (0°, 60°, and 300°) yielding relatively fast responses and the three larger disorientations (120°, 180°, and 240°) yielding considerably slower responses that are quite similar in their magnitude. We shall return to this point in connection with Experiment 3.

Experiment 2

The results of Experiment 1 can be interpreted as indicating that letter strings at disorientations greater than 60° tend to be processed nonholistically. This interpretation rests on the assumption that the critical factor affecting speed of processing is the number of letters in the string.

There are, however, two additional interpretations. The first is that longer strings are visually more complex, and complex figures might require slower rotation rates than do simple figures. This account is hard to refute, though it does not seem likely in view of the fact that word length did not have any effects at the 0° and 60° deviations. If complexity were the critical factor, it would have been expected to affect performance at all orientations. The second account involves another factor that is correlated with string length, namely, the visual extent of the stimulus. It might be argued that longer strings are rotated more slowly than shorter strings simply because they are larger. Indeed, Shwartz (1979; see Kosslyn, 1980, pp. 290–292) found the size of a visual image to affect rotation rate.

Subjects were presented with an Attneave-type polygon and were asked to rotate its image until it reached a specified orientation and to press a button when the desired orientation was attained. Larger polygons were found to yield slower rotation rates than smaller polygons.

In Experiment 2 we varied number of letters in a string while holding its visual extent constant. The stimuli were three- and four-letter strings that subtended the same visual angle. If the two string lengths exhibit similar effects of rotation, the results obtained in Experiment 1 might be interpreted in terms of the size effect of Shwartz (1979), namely that the slower "rate of rotation" obtained for longer strings stems from a slower but holistic rotation process, rather than from a nonholistic, piecemeal process.

Method

Subjects. Twelve University of Haifa students participated in the study for course credit. None had participated in Experiment 1.

Stimulus materials. Seventy-two three-letter and 72 four-letter Hebrew words were compiled, containing only consonantal letters and possessing only one pronunciation. Half of the words of each length were transformed into nonwords by replacing one letter by another consonantal letter. Strings of both lengths subtended 4.3 cm horizontally (when upright) and 1.4 cm vertically. In the three-letter strings letters subtended 1.3 cm maximally with about 0.2 cm between letters. The respective values for the four-letter strings were 1.0 and 0.1 cm. Hebrew readers judged the two types of strings to be equally similar to normal printed Hebrew.

Apparatus and procedure. The apparatus and general procedure were the same as in Experiment 1. Each subject was presented with four blocks, each block homogeneous with respect to string length. Half the subjects received the four blocks in the order three-, four-, four-, and three-letter strings, and the other half in the order four-, three-, three-, and four-letter strings. Each block included 72 experimental trials preceded by 12 practice trials. The third and fourth blocks were replications of the second and first blocks, but the string orders were different, randomly determined for each subject and for each block. In each block six words and six nonwords appeared in each of the six orientations—0°, 60°, 120°, 180°, 240°, and, 300°—and each string appeared equally often in each orientation across all subjects.

Results and Discussion

Responses in excess of 5,000 ms or less than 250 ms were discarded (0.3%). Figure 3 presents mean response times for correct responses for words and nonwords as a function of orientation and string length. The effect of disorientation on response time is clearly stronger for four-letter strings than for three-letter strings. A three-way ANOVA yielded significant main effects for string length, $F(1, 11) = 99.87$, $p < .0001$; for orientation, $F(5, 55) = 31.77$, $p < .0001$; and for lexicality, $F(1, 11) = 53.23$, $p < .0001$. The orientation effects were larger for the four-letter strings than for the three-letter strings, $F(5, 55) = 12.27$, $p < .0001$, and larger for nonwords than words, $F(5, 55) = 4.22$, $p < .002$. The other interactions were not significant.

When the results were analyzed in terms of angular deviation from the upright, mean response times for 0°, 60°, 120°, and 180° deviations were 690 ms, 735 ms, 1,125 ms, and 1,125 ms for three-letter words and 725 ms, 789 ms, 1,378 ms, and 1,426 ms for four-letter words, respectively. Percent errors for these four deviations were 1.4%, 2.8%, 6.6%, and 7.6% for the three-letter words, and 0.7%, 0.3%, 10.1%, and 6.9% for the four-letter words.

It is interesting to note that, as in Experiment 1, although words at 60° deviations yielded significantly longer response times than at the 0° deviation, $F(1, 11) = 25.63$, $p < .0005$, the interaction between this comparison and word length was not significant ($F < 1$). The same was true for nonwords: The 0° versus 60° comparison yielded $F(1, 11) = 7.08$, $p < .05$, but the interaction was not significant, $F(1, 11) = 1.65$.

All in all, the results of Experiment 2 indicated significantly larger orientation effects for the four-letter strings than for the three-letter strings even when they subtended the same visual angle.

Experiment 3

Taken together, the results of Experiments 1 and 2 indicate stronger orientation effects for longer letter strings, and the critical factor is the number of the letters in the string rather than its visual extent. These results suggest nonholistic processing beyond 60° angular deviation from the upright.

Experiment 3 was designed to obtain a more fine-grained picture of the combined effects of angular disorientation and string length by sampling a larger number of orientations. Specifically, the results of Experiment 1 suggest the following trends that deserve detailed examination. First, there appears to be a range of orientations over which

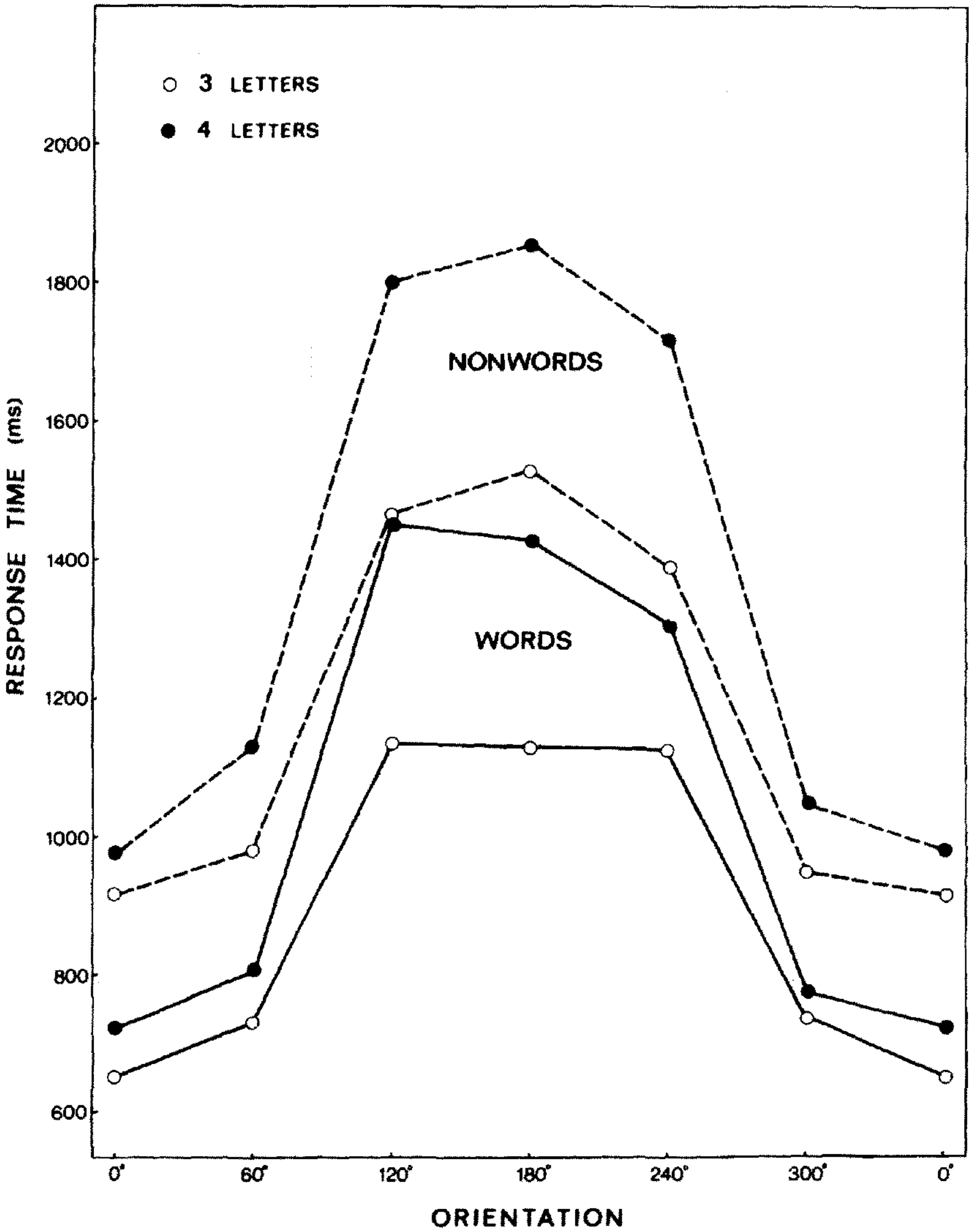

Figure 3. Response time (in milliseconds) as a function of orientation for three- and four-letter words and nonwords (Experiment 2).

words are processed and transformed holistically, as suggested by the length-independent increase in response time from 0° to 60° deviations. In Experiment 3 we hope to delimit the boundaries of this range of orientations. Second, the results for words (Figure 2) suggest a sharp dichotomy between the 0° and 60° deviations, which evidence no length effects at all, and the 120° and 180° deviations, which evidence strong and nearly identical length effects. The inclusion of intermediate deviations might help determine whether the transition between these two regions is sharp or gradual. Third, the comparison between the 180° and the 120° deviations suggests that beyond a certain degree of disorientation there is no further decrement in performance and no further increase in the size of the length effect with increasing angular deviation. In order to examine these trends, 18 different orientations were employed in Experiment 3, 0° to 340° in 20° steps, yielding a total of 10 different deviations from the upright.

Subjects. Eighteen students at the University of Haifa, whose primary language was Hebrew, took part in the experiment for course credit. None had participated in Experiments 1 or 2.

Stimulus materials. Two hundred and eighty-eight 2- to 5-letter Hebrew strings were used. These represented an equal number of words and nonwords of each of the four lengths. The selection of words and the construction of nonwords were according to the same criteria as used in Experiment 1.

Apparatus and procedure. The apparatus was the same as in Experiment 1. The procedure was also the same except for the following. The strings appeared in 18 different orientations, 0° to 340° in 20° steps. The session began with 36 practice trials, followed by two repetitions of the 288 experimental strings. There was a short break after each block of 144 trials and a 2-min break between the two repetitions. Each block began with four filler items to allow warm-up. String orientations were preprogrammed so that for each subject and repetition two words and two nonwords of each length appeared at each orientation, and for each repetition each string appeared equally often at each orientation across all subjects. The orientation of each letter string varied between repetitions. The order of the stimuli was randomly determined for each subject and for each repetition.

Results

Response latencies in excess of 5,000 ms and less than 250 ms were discarded (0.3%). The two repetitions yielded similar results and were therefore combined.

First, we shall examine in some detail the main effects of rotation, after which we shall turn to the combined effects of orientation and string length. The curves for strings of different lengths were all quite similar in shape, and Figure 4, which presents response times and percent errors averaged across string lengths, seems to best convey the major trends.

One noteworthy feature of the curves presented in Figure 4 is their noticeable departure from linearity. Although response time generally increases with angular deviation from the upright, the shapes of the functions are different from those obtained for mental rotation of block figures (Shepard & Metzler, 1971) or single letters (Cooper & Shepard, 1973) and are not consistent with the notion of a constant rate of mental rotation. In terms of angular deviation from the upright (regardless of direction), the curves appear to be S-shaped, with the range between the 60° and 120° accounting for the bulk of the rotation effect. Outside this range, that is, for disorientations of less than 60° or more than 120°, response time is relatively indifferent to the extent of angular deviation.

In the lower range, 0°, 20°, and 40° deviations, rotation appears to have little effect, with rotation effects emerging at around 60°. Comparing only the five orientations between ±40°, a one-way ANOVA yielded $F < 1$ for words and $F(4, 68) = 1.70$, *ns,* for nonwords. These results are consistent with the notion of a perceptual upright and suggest that words that are disoriented up to about ±40° need not be mentally rotated or rectified before recognition.

The upper range of disorientations, 120°–240°, represents perhaps the largest departure from what is customarily found for single-letter mental rotation tasks. Response times for the 180° orientation are far lower than would have been expected. In fact, further increases in angular deviation beyond 120° do not result in any additional impairment in performance.

Three additional features deserve mention: the word–nonword differences, the asymmetry effects, and the upside-down effect, all previously noted by Koriat and Norman (1984). First, nonwords exhibited stronger rotation effects than did words: The increase in response time from 0° to 180° was 550 ms for words and 800 ms for nonwords, $t(17) = 4.63$, $p < .001$. This is consistent with the results of Experiment 1 (see Figure 1) and might suggest that the transformation and recognition processes partly interact.

Second, the curves for both words and nonwords exhibit a certain degree of asymmetry that is most evident in the upper range

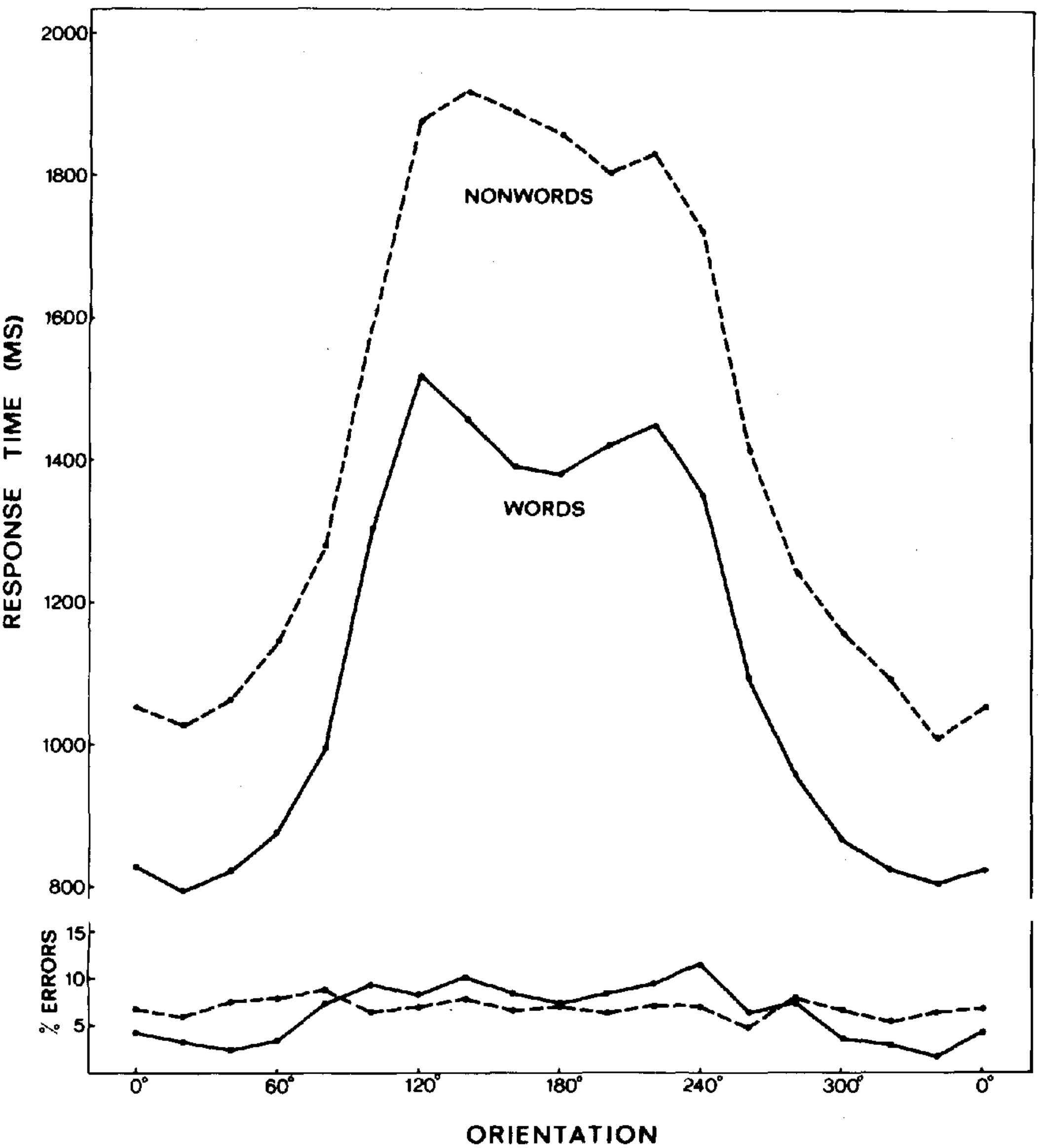

Figure 4. Response time (in milliseconds) and percent errors as a function of orientation for words and nonwords (Experiment 3).

of disorientations. Performance on the 120° orientation is considerably poorer than that on the 240° orientation, both being of equal angular disparity from the upright, $t(17) = 4.54$, $p < .001$. One explanation is that, because Hebrew is printed from right to left, at the 120° orientation strings are read in an upward direction whereas at the 240° orientation they are read in a downward direction. Reading in a downward direction might be easier than reading in an upward direction. A second explanation is that mental rotation in a clockwise direction might be easier than rotation in a counter-clockwise direction. Robertson and Palmer (1983) reported a similar asymmetry for compound Latin letters, a finding that is inconsistent with the first explanation. However, because there are major differences between their study and the present one, it is not clear that the same processes are involved.

Third, note the relative ease of processing upside-down words in comparison to all other orientations in the 120° to 240° range. The 140-ms drop from 120° to 180° was significant, $t(17) = 3.36$, $p < .005$. This effect was found to hold for each of the four word lengths. The respective drops (from 120° to 180°) for words of lengths 2 to 5, were 136 ms, 189 ms, 113 ms, and 229 ms, respectively. A similar trend appears in the error data (Figure 4). This upside-down effect, previously reported by Koriat and Norman (1984), seems consistent with other findings on the reading of misoriented text.

Turning to the effects of string length, Figure 5 presents evidence for very strong interactions between string length and angular

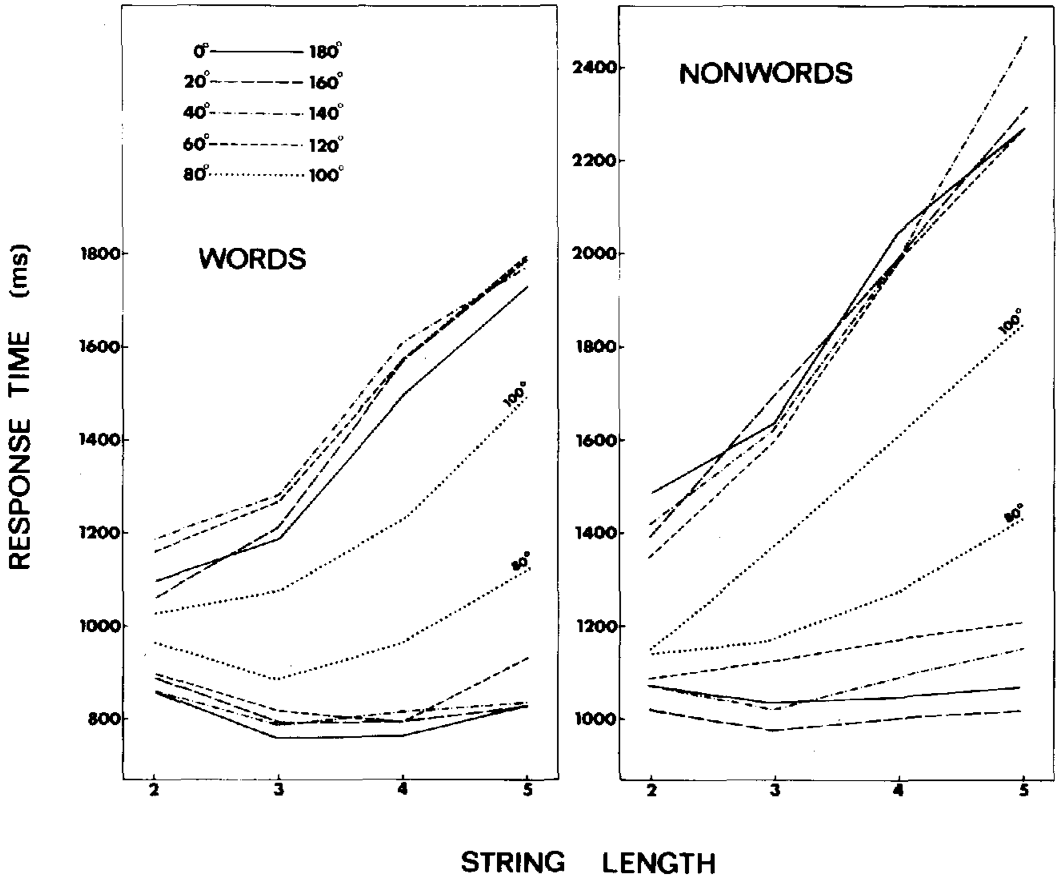

Figure 5. Response time (in milliseconds) for words and nonwords as a function of string length for different angular deviations from the upright (Experiment 3).

disorientation, for words, $F(27, 459) = 11.68$, $p < .0001$, and for nonwords, $F(27, 459) = 15.51$, $p < .0001$. The results presented in this figure are very similar to those of Figure 2 with respect to the four values in common, 0°, 60°, 120°, and 180°. The smallest angular disorientations, 20° and 40°, evidence little increase in response time with word length, the curves virtually overlapping that of the upright position (0°). Thus, word recognition appears to be indifferent to either word length or angular disorientation for deviations of 40° or less from the upright position.

As for the error data, a two-way ANOVA yielded significant effects of word length, with percent errors for two- to five-letter words being 9.6%, 4.0%, 6.0%, and 5.7%, respectively. The somewhat high error rate for two-letter words may be due to the inclusion of two very rare two-letter words. This may also explain the slight increase in response times for two-letter words (see Figure 5), as well as the small but significant interaction between length and angular deviation found for percent errors. Neither of these effects was significant for nonword errors: The percent errors for two- to five-letter strings were 9.5%, 5.6%, 5.2%, and 7.0%, respectively. Thus, the suspicion of a speed–accuracy trade-off for length effects seen in Experiment 1 is not corroborated here.

In comparison to 0°–40° deviations, the 60° deviation, although evidencing a slight increase in response time overall—the difference between 60° and the average of the three smallest deviations yielded $F(1, 17) = 15.86$, $p < .001$ for words and $F(1, 17) = 22.36$, $p < .0002$ for nonwords—shows little increase in the effects of string length (the interaction between the previous comparison and length yielded $F < 1$ for both words and nonwords). This is similar to what was found for words in Experiments 1 and 2. If mental rotation occurs in this region, it would appear to be holistic in nature (or piecemeal but parallel, see Funt, 1983).

The results for the extreme disorientations yield very similar effects of string length for the four deviations between 120° and 180°. For these deviations, the overall increase in response time for each extra letter is about 220 ms for words and about 315 ms for nonwords.

The two intermediate deviations, 80° and 100°, evidence intermediate effects of string length. For words, the slopes of response time on string length are 55 ms per letter and 145 ms per letter for 80° and 100°, respectively. The respective values for nonwords are 109 ms per letter and 236 ms per letter.

Discussion

The results of Experiment 3 corroborate and extend the findings of Experiments 1 and 2. When the effects of both rotation and string length are examined conjointly, the angular orientations included in Experiment 3 appear to be roughly divided into three regions. These regions are clearly evident in Figures 4 and 5. First, there is a region in which neither angular deviation nor string length affects word recognition latency. It includes the upright (0°) orientation and extends to disorientations of up to 40° or 60°. For the second region, from about 60° to 120° deviations, marked orientation effects occur that are strongly dependent on string length. To illustrate, orientation effects in the 60°–120° region (for words and nonwords combined) increase by about 220 ms for each additional letter. The third region includes deviations in excess of 120°. These yield no further increases in response time nor an Orientation × String Length interaction.

In addition to the three regions mentioned above, the results for word stimuli at 60° deviations represent an interesting case in their own right. In Experiment 3, as in Experiments 1 and 2, they yielded significantly slower response times while at the same time indicating no effects of word length.

In sum, the results are inconsistent with the idea that words are processed and transformed as integral units over the entire range of disorientations. If we assume that the recognition of rotated words indeed involves a mental rotation process like that discussed by Shepard and Cooper (1982), the results suggest that, except for a narrow zone (around 60° deviation) in which words are rotated as integral wholes, in all other orientations in which mental rotation occurs, it is by and large piecemeal. In fact, for the range of angular deviations between 60° and 120° the systematic decrease in "rate of mental rotation" with increasing string length agrees rather well with a model in which single letters are mentally rotated in turn at a constant rate.

These results contrast those of Robertson and Palmer (1983), who, using hierarchically structured patterns (large letters made up of many small letters), found rotation rate to be unaffected by the number of levels that had to be rotated. In their task, however, decisions at the local level could be carried out on the basis of a single element, which, of course, is not possible with the lexical decision task. Our results are also not consistent with Shepard and Cooper's (1982) assumption that mental rotation is holistic in tasks involving the matching of a single, well-integrated familiar figure to an internal representation. Alternatively, we may conclude that in fact words do not constitute "well-integrated familiar figures" in the sense used by Shepard and Cooper.

It should be stressed, however, that the rotation function obtained (Figure 4) is notably different from that normally observed in mental rotation studies. This raises the question whether the recognition of rotated words involves the same sort of mental rotation process observed with other stimuli. At the least, it would seem that additional processes must be postulated to account for the results obtained over the entire range of orientations, and these processes might be specific to word recognition and reading.

From the point of view of reading processes, the region of intermediate orientations poses a difficult problem when contrasted with the other two regions. In the first region of relatively small deviations, words appear to be recognized directly, that is, with no need for additional processes over and above those required by upright words. We may assume that word recognition in this region is holistic or else that it rests on the processing of all its elements in parallel. Following Hock and Tromley (1978), we shall label this region the *region of the perceptual upright in word recognition.*

At the other extreme, beyond 120° deviations, there is no increased impairment with increased angular deviations but a strong effect of word length. This pattern suggests a process in which words are read letter by letter. If letter identity is not disrupted by disorientation (e.g., Corballis & Nagourney, 1978; however, see Jolicoeur & Landau, 1984), such a process should indeed result in orientation-independent length effects.

What, then, happens in the middle region? Word recognition in this region apparently involves neither whole-word reading nor letter-by-letter reading. Experiment 4 was designed to examine what type of visual information is lost or disrupted in this region. If visual transformation does occur in this region, we may assume that it is intended to recover some of this information.

Experiment 4

If we assume that disorientations beyond the upright impair letter identification, the results for the intermediate region of angular deviations can be interpreted in terms of a letter rotation model: Words in this region must be rotated letter by letter in order to be recognized. In this model, mental rotation is assumed to recover letter orientation. This simple and appealing model encounters the difficulty that at least as far as single-letter identification is concerned, it is not clear that letters must be rotated to be recognized (see Corballis & Nagourney, 1978; Jolicoeur & Landau, 1984). A further difficulty is that this model fails to distinguish between the second and third regions, both of which apparently involve some piecemeal processing.

An alternative model stresses the role of transgraphemic features in word recognition. It has been proposed that familiar visual patterns tend to be processed as a unit, with global word shape features dominating word processing (Haber & Schindler, 1981; Lawry, 1980). Accordingly, we may assume that within the perceptual upright, word recognition capitalizes on configurational, transgraphemic features (Garner, 1981; Monk & Hulme, 1983). These features are disrupted when the word is tilted beyond the perceptual upright. If a transformation process does occur in the intermediate region, then its function might be that of recovering some of the supraletter orthographic features.

Experiment 4 evaluated the two models by contrasting two types of stimulus transformations. In the global transformation, letter strings were rotated in their entirety about their center (as in the previous experiments), whereas in the letter-upright transformation, only the string-array direction was rotated, but each letter remained upright. If the letter rotation model is correct, the global transformation should prove the easier within the perceptual upright, whereas the letter-upright transformation should prove the easier beyond the perceptual upright. This prediction assumes that within the perceptual upright it is the orientation of the entire string that counts, whereas beyond the perceptual upright it is the orientation of the letters that matters. The second model stressing transgraphemic features, on the other hand, predicts an advantage for the global transformation even beyond the perceptual upright.

Method

Subjects. Eighteen University of Haifa students participated in the study for course credit. Hebrew was their primary language.

Stimuli. Two hundred and eighty eight words were selected. Half of the words were transformed into nonwords. An additional practice list consisted of 18 words and 18 nonwords. They appeared at one of five orientations—0°, 30°, 70°, 290°, and 330° (labeled in a clockwise direction as in Cooper & Shepard, 1973). When the strings were misoriented, they appeared in either one of two formats—global, with the entire string rotated as in the previous experiments, or letter-upright, with each letter occupying the same location as in the global format but presented upright.

Apparatus and procedure. The apparatus was the same as that used in the previous experiments. The procedure was also the same except that the subjects were instructed about the stimuli and were shown examples of the different formats and orientations. The session began with 36 practice trials, followed by two repetitions of the 288 experimental strings in different random orders. There was a short break after each block of 144 trials and a 2-min break between the two repetitions. Each block began with four filler items to allow warm-up. String orientations were preprogrammed so that for each subject and repetition 16 words and 16 nonwords appeared at the upright orientation and in each of the eight Disorientation × Format combinations. Each string appeared equally often in each of these nine arrangements across all subjects. The arrangement of each letter string varied between repetitions. The order of the stimuli was randomly determined for each subject and for each repetition. Each letter was about 1.0 × 1.0 cm, with a 0.1 cm gap between letters (in the global format).

Results

Response latencies in excess of 5,000 ms and less than 250 ms were discarded (0.4%). The two repetitions yielded similar results and were therefore combined.

Figure 6 presents mean response times for words and nonwords as a function of orientation and format. It may be readily seen that the results do not conform to the letter rotation hypothesis. For both the 30° and 70° angular deviations the letter-upright format yields longer response times than does the global format, and in fact this difference is more pronounced for the 70° than for the 30° deviations. Considering only the 30° and 70° angular deviations and combining words and nonwords, a three-way ANOVA on response times, Deviation × Direction of Rotation (clockwise, 30° and 70° vs. counterclockwise, 290° and 330°) × Format, yielded significant effects for format, $F(1, 17) = 105.96$; $p < .0001$; for deviation, $F(1, 17) = 104.52$; $p < .0001$; and for the Format × Deviation interaction, $F(1, 17) = 57.56$), $p < .0001$. The results also indicated a significant effect of direction, $F(1, 17) = 77.83$; $p < .0001$, which interacted with the effects of deviation, $F(1, 17) = 40.33$; $p < .0001$, and with the effects of format, $F(1, 17) = 29.31$, $p < .0001$. The effects of direction are probably due to the same type of asymmetry found in Experiment 3, and this asymmetry is stronger for the letter-upright format than for the global format, and for the 70° deviations than for the 30° deviations. It should be recalled that since Hebrew is read from right to left, the direction of reading is downward in the 290° orientation and upward in the 70° orientation. The triple interaction was also significant, $F(1, 17) = 23.31$; $p < .0001$.

The error data indicated a similar pattern to that found for the response time data, but a similar ANOVA yielded no significant effects apart from that due to angular deviation.

Discussion

The results of Experiment 4 indicate that stimulus transformations that disrupt whole word features while leaving letters upright impair word recognition to a greater extent than do global transformations in which some of the transgraphemic features are spared. This appears to be true within the perceptual upright and even more so beyond it.

These findings seem to argue against the idea that in the intermediate angular deviations, words are read letter by letter, with each letter first rotated to an upright orientation. If this were the case, the letter-upright format should have yielded better performance (in the 70° deviation) because in this format letters need not be rotated. Rather, the results are consistent with the view that even in the intermediate angular deviations, word recognition tends to capitalize, to some extent, on supraletter features.

This conclusion can lead to two rather different interpretations of the results for the intermediate region. The first assumes that beyond the perceptual upright some transformational process is applied to letter strings in an attempt to recover some of the supraletter features disrupted by string disorientation. The nature of this process is not clear, except that it appears to involve some piecemeal processing and that its duration depends on the extent of angular deviation from the upright.

A second account does not postulate any visual transformation process. It assumes that as a word departs from perceptual uprightness more of its transgraphemic features are lost, rendering it more difficult to recognize. Thus,

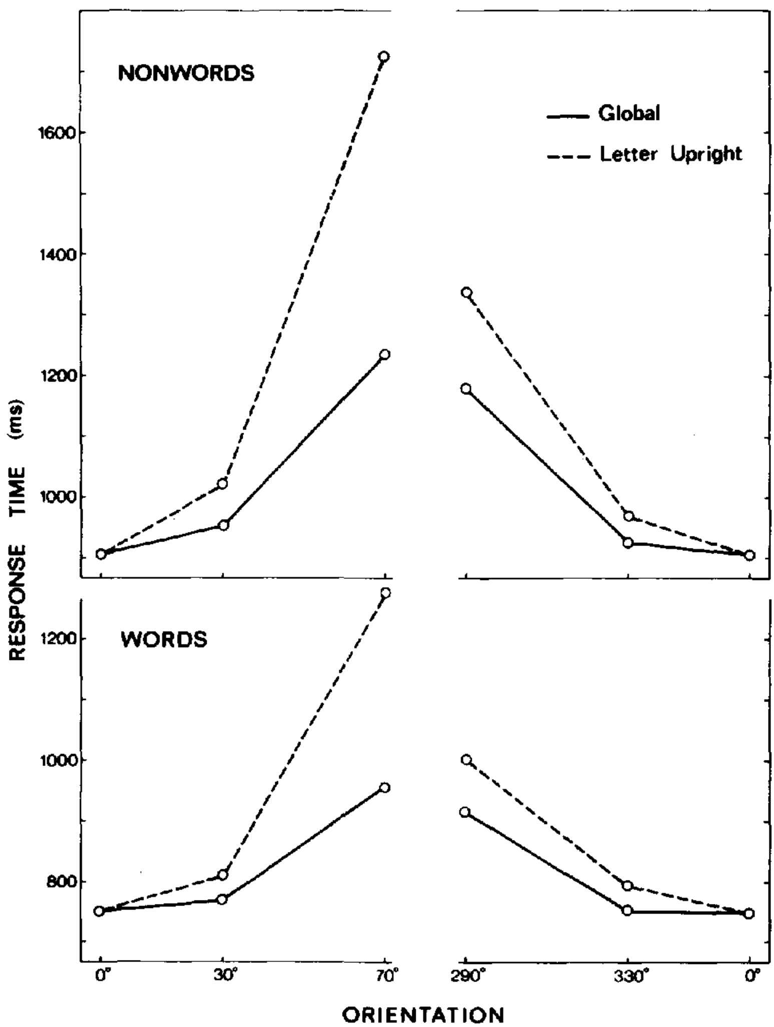

Figure 6. Response time (in milliseconds) for words and nonwords for letter-upright and global transformations as a function of disorientation (Experiment 4).

orientation effects in the intermediate region simply reflect the extent to which word recognition takes advantage of whole-word features. This account must, of course, make additional assumptions to explain why orientation effects are length dependent.

The observation that beyond the 120° deviation there is no increased impairment of performance with increased disorientation may be accommodated by both these accounts. Apparently, transgraphemic features are lost at extreme disorientations, and word recognition must rely solely on letter-by-letter reading.

General Discussion

The research reported in this article combined a reading task with a mental rotation task with the aim of obtaining information relevant to two different theoretical issues—first, whether disoriented visual stimuli are "mentally rotated" as integral wholes or piecemeal and, second, whether words are read holistically or in a letter-by-letter fashion. It was proposed that if words are processed and transformed as integral wholes, the effects of rotation should be the same for words of different length, but if they are transformed piecemeal, the effect should increase with increasing word length.

The results of Experiments 1 and 3 indicated that the effects of angular disorientation vary strongly with word length, and those of Experiment 2 suggested that these effects are not due to the physical extent of the longer strings but to the greater number of letters they contain. On the basis of these results we may safely reject the hypothesis that words are processed and transformed as integral units over the entire range of orientations.

Apart from this general conclusion, however, it is difficult to offer a complete account of the complex pattern of results obtained. Most important, it is not clear whether the reading of rotated words involves the same sort of mental rotation process envisioned by Shepard and his colleagues or any other rectification process, for that matter. The rotation functions obtained depart considerably from linearity. They are also quite different from those found for single-letter reflection decisions, especially in the region of extreme deviations. The results, on the whole, present a rather nonuniform pattern with regard to the effects of increased disorientation both on mean response time (Figures 1, 3, and 4) and on the extent of string length effects (Figures 2 and 5). Consequently it is difficult to propose an interpretation of the results in terms of one unitary principle.

In what follows we shall examine possible accounts for the results obtained relying on the subdivision into three regions discussed above. Because in the first and third regions there was no effect of rotation, we shall first examine the results for these two regions, relying solely on what is known about mechanisms of reading and word recognition.

The results for the first region of relatively small tilts about the upright are the most pertinent to normal reading. It is of considerable theoretical interest that word recognition is largely indifferent to disorientations of up to 40° or 60° from the upright and that within this range it is also indifferent to word length. The indifference of lexical decision latencies to word length has been reported for upright words (e.g., Frederiksen & Kroll, 1976; Koriat, 1984), and the present study extends this finding to words tilted up to 60° in either direction. The relative indifference to small disorientations has been reported by Cooper and Shepard (1973) for reflection decisions on single letters. Furthermore, Koriat and Norman (in press) found that this is true only for normal letters, whereas reflected letters evidence a remarkably linear increase in response time across the entire range of orientations. This was seen to suggest that the memory representations of familiar visual patterns (e.g., normal letters) are characterized by broad orientation tuning, allowing direct recognition despite small tilts. The indifference of word recognition to both word length and word orientation in the present study may similarly suggest, first, that word recognition in this region is based on the direct activation of whole-word visual patterns (see Johnson, 1975, 1981), and, second, that the internal visual representation of a familiar word is broadly tuned and can be efficiently activated even when the visual stimulus departs rather noticeably from its upright orientation. Following Hock and Tromley (1978), we label this range of orientation indifference the region of perceptual uprightness in word recognition. Thus, as long as a word is perceptually upright, it appears to be recognized holistically.

It should be noted, though, that the indifference of word recognition to word length is also consistent with the view that word recognition involves parallel processing of single letters (e.g., McClelland & Rumelhart, 1981). It is not clear, however, why such parallel processing should hold only within the confines of the perceptual upright and not beyond.

The finding that words at the 60° deviation evidenced length-independent orientation effects in all of the first three experiments deserves particular attention. It suggests the existence of a transitional zone on the fringe of the perceptual upright where words appear to be transformed holistically. This phenomenon lends further support to the idea that within the perceptual upright, word recognition is based on whole-word patterns.

Turning next to the results for the third region (beyond 120° deviations), these seem to suggest a rather different reading strategy in which words are processed letter by letter without mental rotation or transformation. Single letters are identified serially and the strings unitized before (or partly in unison with) lexical access. If the speed of identifying single letters is indifferent to their orientation, a process of this sort should yield no effect of word orientation but strong effects of word length as was found to be the case. It would seem that these nearly horizontal inverted letter arrays induce serial scanning and result in the type of processes investigated by Kolers and Perkins (1975). This serial processing is reminiscent of the reading disorder referred to as *word-form dyslexia* (Warrington & Shallice, 1980) or *letter-by-letter* reading (Patterson & Kay, 1982). Indeed, the most distinctive characteristic of this syndrome is that reading time increases monotonically with word length. This syndrome has been assumed to reflect the inaccessibility of visual word forms that normally allow whole-word recognition. The patient is forced to reconstruct the word from the names of the letters (Warrington & Shallice, 1980). It is not clear, however, whether the letter-by-letter reading of the present study also relies on phonemic codes (see Shallice, 1981).

Summing up at this point, when the first and third regions are compared, they appear to involve two contrasting reading strategies, whole word and letter by letter. Because in both response time does not increase with increased disorientation, this may suggest direct activation of the respective codes, whole-word codes or letter codes.

Before examining the results for the intermediate region, let us note that the contrast between the two reading strategies presented above may help resolve the paradox noted by Corballis, Zbrodoff, Shetzer, and Butler (1978): Although stimulus disorientation has a negligible effect on the identification of single letters (e.g., Corballis & Nagourney, 1978), it has considerable disruptive effects on the reading of longer strings (Kolers & Perkins, 1975). Why would an upside-down letter be identified as quickly as an upright letter, whereas an upside-down word takes longer to recognize than an upright word? In terms of the propositions offered above, this occurs because reading an upright word involves the activation of a single, whole-word code, whereas reading an upside-down word involves the processing of several units in sequence. If this interpretation is correct, the recognition of single-letter words should be indifferent to orientation. The results of Experiments 1 and 3 suggest that this might indeed be the case: If we were to extrapolate the curves depicted in Figures 2 and 5, they would intersect at a value nearly equivalent to a one-letter word. The same is true for nonwords as well. No single-letter words exist in Hebrew, but it would be instructive to see whether lexical decision times for single-letter English words are indeed indifferent to disorientation (but see Samuel, van Santen, & Johnston, 1982). The interesting question, however, still remains: Why are words recognized directly only within the perceptual upright, whereas single letters (and probably single-letter words) are recognized directly over the entire range of disorientations?

We shall turn now to the intermediate region involving length-dependent orientation effects. The interpretation of these effects must take into account the results of Experiment 4, where the global transformation was easier than the letter-upright transformation at 70° angular deviations. This suggests that the reading of rotated words in the intermediate region can take advantage of information pertaining to units that are larger than a letter. Thus, although reading in this region appears to involve piecemeal processing, it differs from the letter-by-letter reading characteristic of the third region.

The major difficulty in explaining the results for the intermediate region is that it is not clear whether the piecemeal processing that apparently takes place in this region derives from mechanisms of visual transformation, from mechanisms of word recognition, or from both. One type of interpretation relies solely on principles of word recognition. In terms of the contrast between the two reading strategies that seem to characterize the first and third regions, perhaps the simplest account of the results for the intermediate region is that they reflect either a probabilistic mixture of the strategies of whole-word and letter-by-letter reading, or better, a reliance on units of intermediate size. Consistent with the idea of multiple units in word recognition (cf. Santa, Santa, & Smith, 1977), the increase in length effects with increasing angular deviations may be assumed to stem from the size of the unit involved in word recognition: For small disorientations, the unit is the whole word, for extreme disorientations it is the single letter, and for intermediate disorientations it is letter clusters, the size of which decreases with increasing disorientation. In this interpretation, orientation and length effects are seen to reflect the same process: Increased disorientation reduces the size of the perceptual unit, and thus the number of effective units becomes a joint function of disorientation and word length. If this interpretation is correct, it may help explain the difference between words and nonwords. Nonwords exhibited stronger orientation effects in Experiments 1, 2, and 3, and stronger length effects in Experiments 1 and 3. These differences may be accommodated by assuming that at any given orientation, words require fewer units than nonwords of the same length.

A second type of interpretation attributes the length-dependent orientation effects to rectification processes. The best candidate for such a process is some sort of piecemeal mental rotation in which letters are rotated in turn at a constant rate. This model fits the data because it is conjointly sensitive to both number of letters and degree of disorientation. The results of Experiment 4 suggest that the aim of letter rotation is not simply to aid in letter identification but to assist in recovering transgraphemic features, thus allowing word recognition to capitalize on larger units, even whole words. The weaker effects of orientation and length found for words than for nonwords may result from the interplay between activations at the letter and word levels (see McClelland & Rumelhart, 1981; Rudnicky & Kolers, 1984). We should point out that the emphasis on transgraphemic features is open to several objections (see Henderson, 1982), among them its inconsistency with the finding that word superiority is rather immune to the disruption of supraletter features (e.g., Adams, 1979; McClelland, 1976).

An alternative account emphasizes the importance of letter-order permutations. Several letter-based theories of word recognition (e.g., McClelland & Rumelhart, 1981; Paap, Newsome, McDonald, & Schvaneveldt, 1982) assume position-specific parallel activation of the appropriate codes for all the letters in a word. Perhaps disorientation beyond the perceptual upright disrupts the letter-position mapping, and it is this mapping that is restored by the rectification process.

In conclusion, this study of the reading of rotated words has yielded a rather complex pattern of results pertaining to the issue of holism in mental rotation and word recognition. As far as mental rotation is concerned, the results do not generally conform to the hypothesis that word stimuli are mentally rotated as integral units. This is inconsistent with Shepard and Cooper's assumption concerning the rotation of well-integrated, familiar stimuli. Thus, we must either reject the hypothesis of holistic mental rotation altogether, admit that words do not constitute well-integrated wholes, or conclude that rotated letter strings induce different types of processes than those normally observed for other disoriented visual stimuli. The results for words at 60° deviations do hint, however, at the possibility of holistic mental rotation, and this deserves further research scrutiny.

As for the issue of holism in word recognition, the results appear to indicate that within the perceptual upright (±60° about the upright), word recognition relies on whole-word units, whereas at extreme disorientations (120°–240°) it appears to be mediated by sequential letter identification. The interpretation of what occurs in the intermediate region of deviations (60°–120°) is more difficult, though it appears that word recognition in this region may rely on units larger than single letters. Further research is needed to determine whether the length-dependent orientation effects in this region are best interpreted in terms of mechanisms of visual rectification, mechanisms of word recognition, or both.

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Psychological Documents to Be Discontinued

At its February 2–3, 1985, meeting, the Council of Representatives voted to cease publication of *Psychological Documents* (formerly the Journal Supplement Abstract Service) as of December 31, 1985, with the publication of the December 1985 issue of the catalog. Continued low submissions, decreasing usage, and rising costs for fulfillment of paper and microfiche copies of documents were reasons given for discontinuing publication of the alternative format publication, which was begun in 1971 as an "experimental" publication.

Authors who wished to submit documents for publication consideration in 1985 were required to do so by July 1. Authors revising documents were required to complete all revisions and submit them for final review no later than July 1. Fulfillment of orders for paper and microfiche copies of documents presently in the system and of those documents entered during 1985 will continue through December 31, 1986.