Journal of Experimental Psychology:
Human Perception and Performance
1989, Vol. 15, No. 2, 287-303

0096-1523/89/$00.75

Types and Tokens in Visual Letter Perception

Michael C. Mozer
Department of Computer Science and Institute of Cognitive Science
University of Colorado, Boulder

Five experiments demonstrate that in briefly presented displays, subjects have difficulty distinguishing repeated instances of a letter or digit (multiple *tokens* of the same *type*). When subjects were asked to estimate the numerosity of a display, reports were lower for displays containing repeated letters, for example, *DDDD*, than for displays containing distinct letters, for example, *NRVT*. This *homogeneity effect* depends on the common visual form of adjacent letters. A distinct homogeneity effect, one that depends on the repetition of abstract letter identities, was also found: When subjects were asked to report the number of *A*s and *E*s in a display, performance was poorer on displays containing two instances of a target letter, one appearing in uppercase and the other in lowercase, than on displays containing one of each target letter. This effect must be due to the repetition of identities, because visual form is not repeated in these mixed-case displays. Further experiments showed that this effect was not influenced by the context surrounding the target letters, and that it can be tied to limitations in attentional processing. The results are interpreted in terms of a model in which parallel encoding processes are capable of automatically analyzing information from several regions of the visual field simultaneously, but fail to accurately encode location information. The resulting representation is thus insufficient to distinguish one token from another because two tokens of a given type differ only in location. However, with serial attentional processing multiple tokens can be kept distinct, pointing to yet another limit on the ability to process visual information in parallel.

Despite the seemingly infinite variety in our visual world, we often encounter collections of identical objects: a bunch of bananas, rows of prefab condominiums, a stack of plates, the two *t*s in the word *letter*. If two objects are so alike, how does the human visual system distinguish one instance from another? That is, how does the visual system represent two *tokens* of the same *type*? Several anecdotes suggest that the visual system indeed has difficulty representing tokens. A colleague reported that when proofreading a letter with the New York City zip code 10003, he must scrutinize the zip code to ensure that the right number of zeros are present, that one is not missing or that an extra zero has not been inserted. In a computer program, I discovered that the source of a bug was the expression NTEST[1]+1 which should have read NTEST1[1]+1. I had stared at that line of code over and over, each time convinced it actually read NTEST1. I have experienced difficulty not just in detecting repetitions of alphanumeric characters, but even entire words: I misread the phrase *interested involves* as *interested in involves* half a dozen times before noticing the missing *in*. A popular illusion also plays upon this difficulty:

Paris in the
the spring.

When the phrase is read, the repetition of *the* often goes unnoticed. This article reports on a series of experiments examining the extent to which the human visual system has difficulty in processing simultaneously presented, repeated tokens and the conditions that give rise to such difficulties.

Pashler and Badgio (1985, 1987) have outlined a view of attentional selection in visual information processing that appears to predict a difficulty with repeated tokens. They posit that "parallel encoding processes are capable of extracting the identities present in a multielement display but not of tying those identities to locations in a centrally accessible format" (Pashler & Badgio, 1985, p. 119). Thus, if attention is not focused and several objects appear in a display, the objects may be identified in parallel, but the locations of the objects are not registered. This shall be called the *spatial uncertainty hypothesis*. Because two tokens of an object differ only in location, a representation based on identity information alone is insufficient to allow the system to distinguish one token from another.

Mozer (1987, 1988) has recently developed a computational model of multiple object perception, called MORSEL, that behaves in accord with the spatial uncertainty hypothesis.

This research was supported by Contract N00014-85-K-0450 NR 667-548 with the Personnel and Training Research Programs of the Office of Naval Research, a grant from the System Development Foundation to Donald A. Norman and David E. Rumelhart, an IBM Graduate Fellowship, and Grant 87-2-36 from the Alfred P. Sloan Foundation to Geoffrey Hinton.

This research has benefited from discussions with Harold Pashler, Nancy Kanwisher, Donald Norman, David Rumelhart, James McClelland, and Mary Potter, who suggested the manipulations in Experiment 4. Special thanks also to Rachel Mann, my self-proclaimed "goddess of experimentation," for her masterful assistance in testing untold numbers of subjects.

Correspondence concerning this article should be addressed to Michael C. Mozer, Department of Computer Science, University of Colorado, Boulder, Colorado 80309-0430.

MORSEL is capable of automatically processing information from several regions of its visual field simultaneously, but the result of such processing consists solely of identity information. This is because at early stages of processing, MORSEL has only type detectors. These detectors signal the presence of an object, regardless of its location, and do not even indicate whether they were activated by one or by several tokens. For MORSEL to recover the location associated with an object, sequential processing is required. As in Treisman and Gelade's (1980) feature integration theory, attention can be used to bind the object-type information with other attributes such as color and location, a process that serves to distinguish one token from another. Thus, with serial attentional processing multiple tokens can be kept distinct.

MORSEL and the spatial uncertainty hypothesis make a strong prediction. If several tokens of the same object are presented, differing only in display location, then to the extent that attentional processing is prevented it should be impossible to distinguish one token from another. Consequently, subjects should have greater difficulty determining how many tokens were presented when all tokens are of the same type than when each token is of a different type.

Frick (1987) observed this sort of effect, which he termed the *homogeneity effect*. Subjects were asked to count the number of digits presented in a row. In one condition, a single digit was repeated throughout; in the other, adjacent digits were distinct. Frick found that response latencies were greater for repeated than for distinct digits. However, given the latencies were on the order of 400 ms per digit, it is unclear whether the homogeneity effect observed was due to a difficulty in detecting repeated tokens or, as Frick concluded, in guiding attentional shifts and eye movements. This is especially of concern given that no homogeneity effect was observed for displays containing fewer than eight digits. A stronger test of the spatial uncertainty hypothesis would be to find a homogeneity effect for smaller displays and, preferably, an effect on accuracy with brief displays rather than response latency with displays of unlimited viewing time.

Schneider and Shiffrin (1977, Experiment 3) observed just this. On each trial of their experiment, subjects were given a *target set* containing two items. A sequence of *20 frames* was then presented in rapid succession (60–80 ms per frame), each consisting of four elements arranged in a square. Two of the elements were random dot patterns and the other two elements were selected from the set of target items or from a set of distractor items. Subjects were instructed to count the number of target items appearing across all frames. Zero, one, or two targets could occur on a given trial. On trials containing two targets, the temporal relation between the two targets was varied: Both could appear in the same frame or they could be separated by one, two, or four frames. Also, the relation between the two targets was varied: The targets were either identical or nonidentical. Schneider and Shiffrin found that with target sets composed of digits and distractor sets composed of letters, or vice versa, the correct response rate was higher for nonidentical targets than for identical targets, although no statistical tests of reliability were performed. (A correct response meant that subjects reported seeing two targets.) In addition, the effect was strong only when the two targets appeared in the same frame.

This result appears to support the notion that subjects have difficulty detecting repeated tokens. However, the multiple-frame task employed by Schneider and Schiffrin, which was designed to examine quite a different issue, complicates an interpretation of the results in terms of types and tokens. It is possible that position-specific representations are accessible following a briefly presented display, even a masked display, but when several frames arrive in succession, the position-specific representation of items in the first frame might be displaced by the representation of corresponding items in the next frame. On this account, the unavailability of token information would be due to its loss in the course of analyzing the rapid-fire sequence of frames, not to the fact that it had never been encoded in an accessible form.

The present set of experiments replicate and expand on the phenomenon using a simpler single-frame task. Experiments 1 and 2 examined stimulus displays similar to those studied by Frick (1987). The results show that the homogeneity effect in such displays was due almost entirely to the physical similarity of adjacent items. This shall be termed a *form homogeneity* effect. Experiments 3 and 4 discovered a distinct effect, one of *identity homogeneity*, that was due to the repetition of abstract letter identities in a display and was independent of the context in which they were embedded. Finally, Experiment 5 explored the relation between focal attention and the homogeneity effect.

Experiment 1

In Experiment 1, displays containing between two and nine letters were briefly presented and subjects were simply asked to report the number of letters in the display. The displays could contain *n* repetitions of a single letter (the *repeated-letter* condition) or *n* distinct letters (the *distinct-letters* condition). If subjects had greater difficulty perceiving repeated tokens, estimates of numerosity would be lower for the repeated-letter condition.

Several confounding factors needed to be considered. First, if the spacing between letters was held constant, subjects could accurately estimate numerosity based on the line length. In order to avoid this possibility, the spacing between letters was manipulated. Second, in multiletter displays, there was the possibility that subjects might interpret the letters as forming words or wordlike strings. In order to avoid the complications introduced by word-level knowledge, displays contained only consonants. Third, because subjects appear to have the ability to subitize, that is, to rapidly and accurately apprehend the numerosity of the displays with fewer than seven or so items (Kaufman, Lord, Reese, & Volkmann, 1949), it would have been possible for them to accurately report the number of items present without concern for the nature of the items. Subitizing would therefore mask a homogeneity effect. Consequently, letters were presented in a linear arrangement to reduce configurational cues that appear to play a role in subitizing (Mandler & Shebo, 1982).

Method

Subjects. Sixteen University of California, San Diego, undergraduates participated in this experiment to satisfy course requirements.

Viewing conditions. Subjects were seated in front of an AED 512 Color Graphics/Imaging Terminal (manufactured by Advanced Electronic Design, Inc.) on which the letter displays were presented. Each letter was printed in upper case and was colored bright green against a dark background. A 7 × 9 dot-matrix font was used to represent each letter. When centered on the fovea, the matrix subtended .27° of visual angle in the horizontal dimension and .35° in the vertical.

Stimuli. Stimulus letters were chosen from the set of consonants excluding *Y*. The display size varied from two to nine letters. For repeated-letter trials, a single letter was repeated the required number of times; for distinct-letters trials, all letters in the display had distinct identities. Three levels of interletter spacing were examined; .5, 1.0, and 1.5, indicating the approximate proportion of the width of a letter that separated one letter from the next. More precisely, the separation between letters was 3, 7, or 11 pixels in these conditions.

A total of 192 trials was generated by crossing the following conditions: display size (2–9 letters), homogeneity condition (repeated letter vs. distinct letters), and interletter spacing (.5, 1.0, or 1.5). Letters were selected at random on each trial for each subject. The set of trials was divided into 12 blocks of 16 trials, each block containing 1 trial for each combination of display size and homogeneity condition. Allocation of trials to blocks was otherwise random, and the order of trials within a block was also random.

Twenty-four practice trials were generated in the same manner as the experimental trials.

Procedure. Subjects were tested individually. Each subject sat with the experimenter in a soundproof chamber, at a distance of 22 in. from the cathode ray tube (CRT) screen.

Throughout the experiment, a large green rectangle appeared on the screen subtending horizontal and vertical visual angles of 13.21° and 1.20°, respectively. Each trial began with the appearance of a green fixation point in the center of the rectangle. Subjects were instructed to fixate on the point and say "go" when ready. The experimenter then hit a key to initiate the trial, causing the fixation point to be replaced with a stimulus display for a controlled duration. Following the display, a random-dot mask filling the rectangle appeared for 200 ms. The mask covered a 345 × 31 pixel area, 35% of which were turned on at random. Once the mask was removed, the rectangle again became visible, at which point subjects were to report the number of letters they had seen. The experimenter recorded this response, after which the fixation point reappeared and the next trial could begin.

Each stimulus display was centered vertically within the rectangle. The horizontal position of the display, however, was selected at random such that it was equally likely that any of the *n* letters in the display would appear at the location of the fixation point. The visual angle of the letter displays ranged from .66° (for a two-letter display with interletter spacing of .5) to 5.80° (for a nine-letter display with either end anchored at the fixation point and interletter spacing of 1.5).

The initial exposure duration of the stimuli was 167 ms. The exposure duration was adjusted automatically after every 10 trials to yield a mean error magnitude (i.e., absolute value of the difference between the number of items presented and the number of items reported) of .75. The average exposure duration across all subjects and trials was 114 ms and the actual error magnitude was .70, slightly less than targeted.

Results and Discussion

The average error on each trial was computed by subtracting the number of letters reported from the number of letters presented. This error measure is shown in Figure 1, broken down by display size and homogeneity condition. In both repeated-letter and distinct-letters conditions, subjects tended to underestimate the number of letters in the display. (In fact, fewer than 4% of all incorrect responses were overestimates.) However, the underestimation error was consistently larger in the repeated-letter condition than in the distinct-letters condition (.73 vs. .58, $F(1, 15) = 19.4$, $p < .001$). Thus, subjects did have a harder time judging the numerosity of a display containing repeated tokens of a single letter than one containing single tokens of distinct letters.

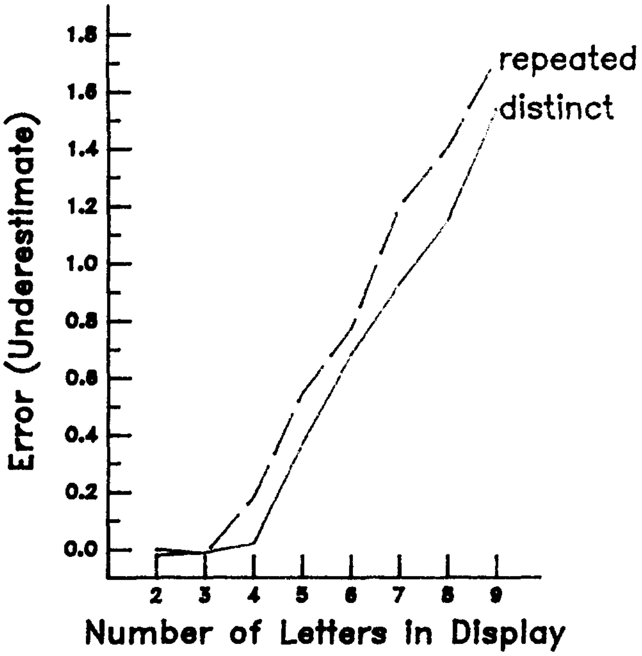

Figure 1. Error by display size and homogeneity condition in Experiment 1.

There was a Display Size × Homogeneity Condition interaction, $F(7, 105) = 2.60$, $p < .025$, most likely because of a lack of a homogeneity effect for displays containing two or three items contrasted with a consistent effect for larger displays. This interaction likely reflects a ceiling effect on performance for small displays.

Figure 2 shows the report error broken down by spacing and homogeneity conditions. Interitem spacing clearly affected performance: Error decreased with increased spacing, $F(2, 30) = 16.3$, $p < .001$. Nonetheless, the homogeneity effect was found at all three levels of interitem spacing. Although the effect appeared to be somewhat larger for the .5 spacing condition, there was no Spacing × Homogeneity condition interaction, $F(2, 30) = 1.66$, $p > .20$. This interaction was not significant even when only the .5 and 1.0 spacing levels were compared, $F(1, 15) = 2.25$, $p > .15$.

The main effect of spacing, as shown in Figure 2, represented a well-studied phenomenon known as *lateral masking* or *lateral interference*, in which the perceptibility of an item in a multiitem display is systematically related to the spatial separation among items (Estes, 1982; Townsend, Taylor, & Brown, 1971; Wolford & Hollingsworth, 1974). Whereas most studies of lateral masking have shown that spatial separation affects the identifiability of an item, the present study also demonstrated an effect on detectability. Further, spatial sep-

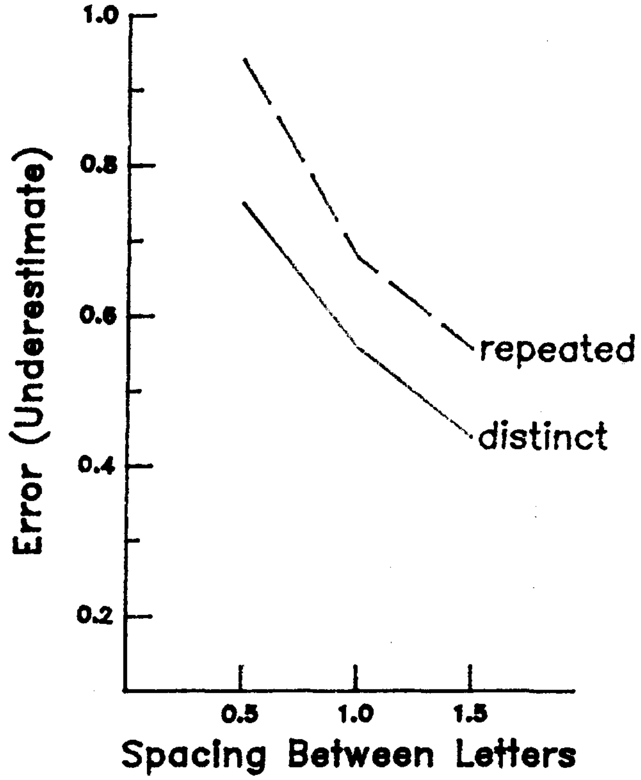

Figure 2. Error by spacing and homogeneity conditions in Experiment 1.

aration affected detectability in a comparable manner for visually similar (repeated letter) and dissimilar (distinct letters) displays, as evidenced by the lack of an interaction in Figure 2. This result is entirely compatible with Estes's (1982) conclusion that lateral interactions are not influenced by the similarity of adjacent items and thus do not appear to be of the sort assumed in models based on the notion of feature-specific inhibition (Bjork & Murray, 1977; Estes, 1972; Krumhansl & Thomas, 1977). It would seem inappropriate, therefore, to attribute the observed homogeneity effect to feature-specific lateral interference among the repeated letters.

Experiment 1 clearly showed that repeated tokens are often confused, but permitted no conclusions as to the nature of the tokens. Two tokens of a given letter share both a common letter *identity* and a common visual *form.* Experiment 2 attempted to unconfound these two kinds of similarity by studying responses to displays containing a mixture of upper- and lowercase letters, where repeated letters shared a common identity but not necessarily a common form.

Experiment 2

As in Experiment 1, subjects were asked to estimate the numerosity of displays containing either repetitions of a single letter or a set of distinct letters. In addition, the case of the letters was manipulated. On some trials, stimulus letters were uniform in case (the *uniform-case* condition), either all uppercase, as in Experiment 1, or all lowercase. On other trials, the case of adjacent letters was alternated (the *alternating-case* condition); a sample repeated-letter display on these trials might be *gGgGg,* and a distinct-letters display *NdFb.* Note that adjacent letters were never visually similar, but in the repeated-letter condition, they were conceptually similar. If the homogeneity effect obtained in Experiment 1 depended on the repetition of letter identities, then case alternation should not matter; on the other hand, if the effect depended on the visual form of letters, then case alternation should be disruptive.

In pilot experiments using repeated-letter alternating-case displays, subjects often adopted the strategy of grouping pairs of upper- and lowercase letters together, thereby dividing in half the effective number of display items. However, in the distinct-letters alternating-case display, there was no subjective impression of an alternating uppercase–lowercase pattern. This greatly simplified the counting task in the repeated-letter condition, and could mask a homogeneity effect. In order to equalize difficulty in repeated and distinct displays, a font was designed in which uppercase and lowercase letters were of the same height (Figure 3). Apparently, size cues were largely responsible for the grouping effect, because subjects reported that size matching eliminated their ability to group by pairs.

A further problem with the alternating-case displays was that if subjects identified the cases of the extreme letters in the display, they could then deduce whether an even or odd number of digits was present. On the basis of this knowledge, subjects might be able to correct their estimate if it was off by only one (which was the mean deviation in Experiment 1). Consequently, a third type of trial was presented in which letter case was alternated for each pair of letters (the *paired-case* condition), for example, *rrRRrrR* or *MLhg.* When these trials were intermixed with the uniform and alternating case trials, it was no longer possible to predict evenness or oddness on the basis of the cases of the extreme letters.

In Experiment 1, the homogeneity effect was not influenced by interletter spacing. However, the range of interletter spacings varied only from .12° to .42° of visual angle (approximately .5 to 1.5 letter widths). This is a small range, considering that a separation of at least 1% is required to achieve perceptual independence of neighboring items (Collins & Eriksen, 1967). Perhaps larger spacings would weaken the homogeneity effect. In order to examine this issue, interletter spacing in Experiment 2 was varied over a wider range, from

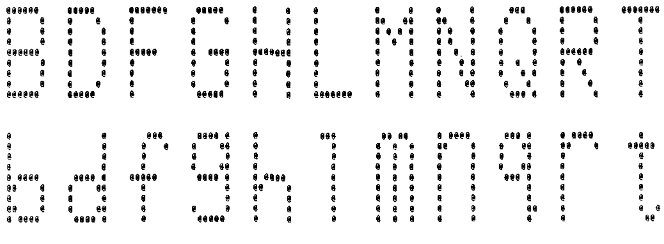

Figure 3. Font used in Experiment 2. Each letter is formed from a 7 × 9 pixel array such that uppercase and lowercase letters are the same height.

.12° to 1.20° of visual angle (approximately .5 to 4.5 letter widths).

Method

Subjects. Twenty University of California, San Diego, undergraduates participated in this experiment to satisfy course requirements.

Stimuli. The set of stimulus letters was slightly smaller than the set used in Experiment 1: *B, D, F, G, H, L, M, N, Q, R,* and *T.* This was the complete set of consonants whose uppercase form was visually dissimilar from the lowercase. A special font was devised in which the dimensions of each uppercase and lowercase letter was 7 × 9 pixels. These were the same dimensions as the uppercase letters used in Experiment 1, although the actual uppercase font was modified slightly to accentuate differences between uppercase and lowercase letters.

A total of 252 trials was generated by crossing the following conditions: display size (three–nine letters), homogeneity condition (repeated letter vs. distinct letters), case condition (uniform, alternating, or paired), case of first letter in string (uppercase vs. lowercase), and interletter spacing (.5, 2.5, or 4.5 letter widths, corresponding to .12°, .66°, or 1.20° of visual angle, respectively). Letters were selected at random on each trial for each subject.

The set of trials was divided into 18 blocks of 14 trials. Each block contained 1 trial for each combination of display size and homogeneity condition. Allocation of trials to blocks was otherwise random, and order of trials within a block was also random.

Fourteen practice trials were generated, one of each display size and homogeneity condition.

Procedure. The procedure was nearly the same as that of Experiment 1. Subjects were told that displays would contain between two and nine upper- and/or lowercase letters, but that letter case was irrelevant and their task was simply to count the number of letters in the display.

In order to accommodate the larger interletter spacings, the size of the rectangle enclosing stimulus displays was increased to subtend a visual angle of 18.6° in the horizontal. The horizontal position of each stimulus display was selected at random, as in Experiment 1. However, in order to fit each display within the bounds of the rectangle, several of the leftmost and rightmost presentation positions were eliminated for eight- and nine-letter displays.

Unlike Experiment 1, each trial was initiated automatically: Once the subject's response to the previous trial had been entered, the large green rectangle would immediately go blank for 500 ms, the fixation star would appear for 500 ms, and the next stimulus display would appear immediately thereafter.

The initial exposure duration of the stimuli was 167 ms. As in Experiment 1, the exposure duration was adjusted after every 10 trials to yield a mean error magnitude of .75. The mean exposure duration across all subjects and trials was 92 ms, and the mean error magnitude obtained was .62.

Results

The average error is shown in Figure 4, broken down by display size and homogeneity condition for each of the three letter-case conditions. As in Experiment 1, subjects tended to underestimate the number of letters in the display, and the amount of underestimation increased with display size. The underestimation error was consistently larger in the repeated-letter condition than in the distinct-letters condition for uniform-case displays, $F(1, 19) = 11.4$, $p < .01$, but not for alternating-case or paired-case displays, $F(1, 19) < 1$ for each. This resulted in a Homogeneity Condition × Case Condition interaction, $F(2, 38) = 6.4$, $p < .01$.

The effect of interletter spacing can be seen in Figure 5. Error varied inversely with interletter spacing, replicating the finding of Experiment 1. The homogeneity effect in uniform displays was evident at all spacings, but in alternating and paired displays, the effect was not consistent. In uniform displays, the homogeneity effect was more than three times as large for .5 spacing as for 2.5 or 4.5 spacing, but there was little disparity between 2.5 and 4.5 spacing (.5 spacing: .24 difference between repeated and distinct; 2.5 spacing: .068; 4.5 spacing: .061). The Spacing × Homogeneity Condition interaction was significant for uniform displays, $F(2, 38) =$

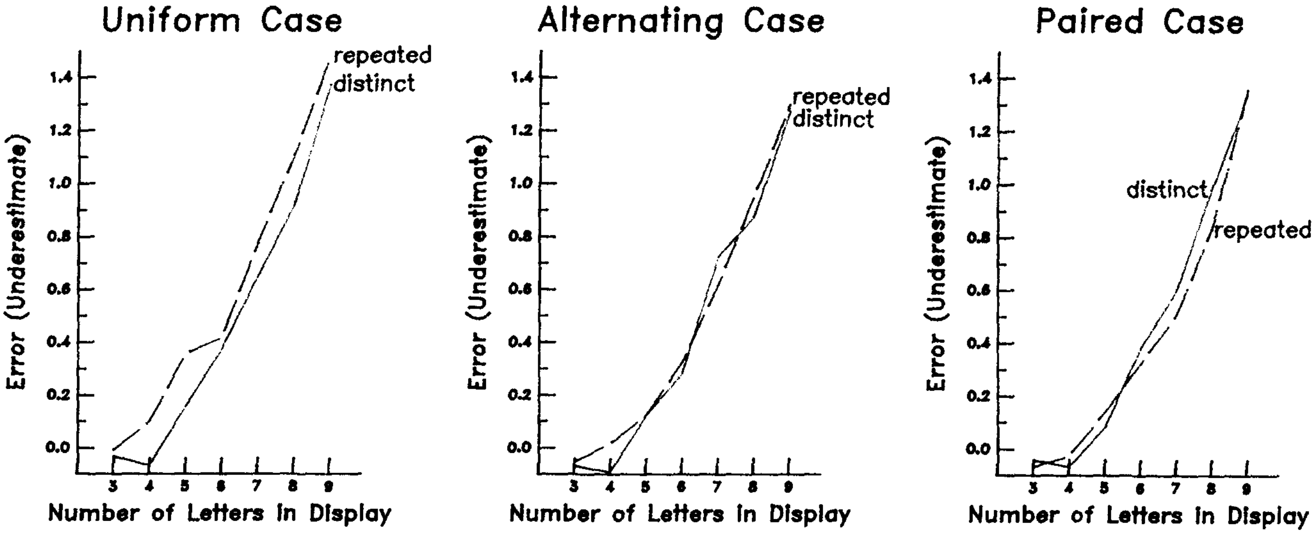

Figure 4. Error by display size and homogeneity condition for each letter-case condition in Experiment 2.

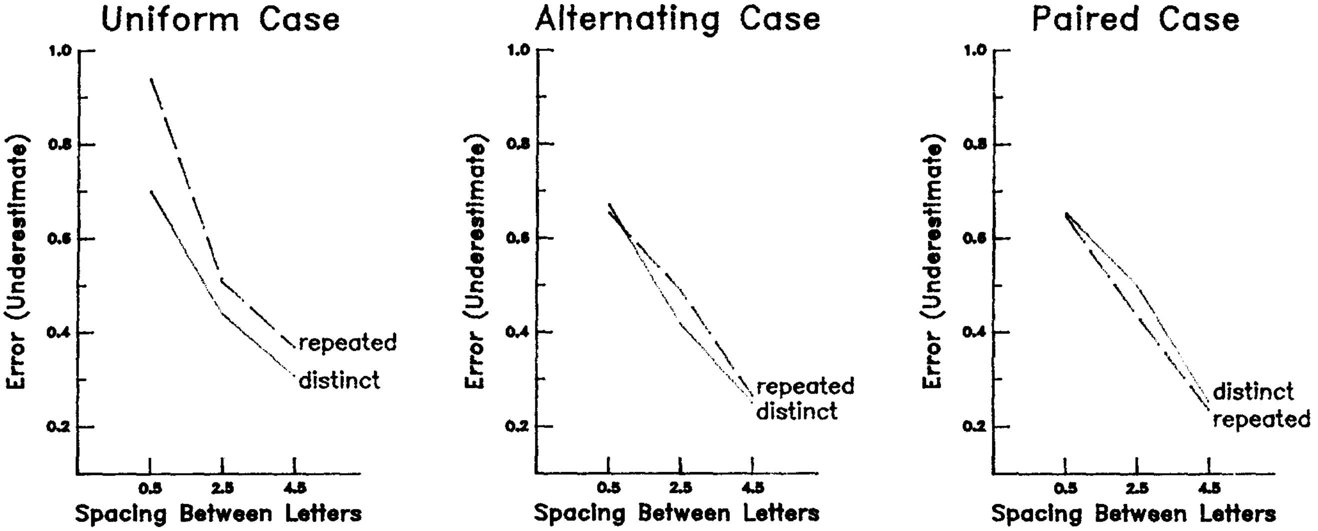

Figure 5. Error by interletter spacing and homogeneity condition for each letter-case condition in Experiment 2.

4.34, $p < .025$. This result contrasts with Experiment 1, where smaller interletter spacings were studied. One possible cause of such an interaction might be that magnitude of the homogeneity effect was simply proportional to the total error. However, this does not appear to be the case: The total error for 2.5 spacing was much larger than for 4.5, yet 2.5 and 4.5 spacing showed comparable homogeneity effects.

The most striking data point in Figure 5 is that of uniform-case repeated-letter displays at .5 spacing. Indeed, it looks like this point was solely responsible for elevating the error in the uniform-case condition (mean error for uniform case was .54; paired case, .45; and alternating case, .46; $F(2, 38) = 9.69$, $p < .001$), although the Spacing × Homogeneity Condition × Case Condition interaction did not reach significance, $F(4, 76) = 1.93$, $p > .10$. Nonetheless, this point is reliably higher than its neighbors: uniform repeated displays at 2.5 spacing, $F(1, 19) = 39.0$, $p < .001$; uniform distinct displays at .5 spacing, $F(1, 19) = 24.4$, $p < .001$; and both alternating and paired repeated displays at .5 spacing, $F(1, 19) = 35.8$, $p < .001$, $F(1, 19) = 55.2$, $p < .001$.

Discussion

Subjects had more trouble judging numerosity in repeated-letter displays than in distinct-letters displays when letter case was uniform across the display, but not when case alternated from one letter to the next or from one pair of letters to the next.[1] Thus, the homogeneity effect depended on letters' sharing a common visual form. This result suggests that tokens of a letter are confused at a fairly early stage of visual perception, before letter identification has occurred. Letter identification, by definition, requires that abstract identity information be represented distinct from information about visual appearance. Such an abstract representation did not come into play here, because the homogeneity effect was not observed in alternating-case displays.

One low-level account for the homogeneity effect follows by assuming that the visual system is bounded in its ability to represent location information. For example, suppose that there is a limited number of visual information processing channels, and that features coming from locations sufficiently close together in the visual field use the same channel (Estes, 1972, 1975). If location information is not maintained within a channel, some positional uncertainty will arise. This explains the finding that locations of neighboring items are often confused (Estes, Allmeyer, & Reder, 1976; Mewhort & Campbell, 1978). Further, if the items are identical, that is, if they differ only on the basis of location, one such item will be indistinguishable from another within a processing channel, and multiple instances will be perceived as one.

This account also predicts the effects of interletter spacing. At small spacings, neighboring letters are likely to be processed within the same channel. Consequently, a large homogeneity effect is expected (for uniform-case displays), and the magnitude of the effect should decrease as interletter spacing is increased. This general pattern of results was obtained in Experiment 2. However, there is a problem. One might expect that channel band width is about 1° of visual angle, because this is the minimum spacing required to achieve perceptual independence of two *centrally presented* stimuli (Collins & Eriksen, 1967). At spacings of this order, no more than one

---

[1] At first glance, it seems odd that paired-case displays produced no hint of a homogeneity effect, and in fact produced a slight reverse effect. After all, in terms of the visual similarity of neighboring letters, these displays were intermediate between uniform case, where the case of each letter was the same as both neighbors, and alternating case, where the case of each letter was different than either neighbor. However, as Figures 1 and 4 show, sequences of fewer than four identical letters, even in the uniform-case condition, did not produce a sizeable homogeneity effect. Perhaps the effect would become visible for paired-case displays, as well as for smaller uniform-case displays, had briefer stimulus exposure durations been studied.

letter should fall into a given channel, and the homogeneity effect should disappear. This did not occur in Experiment 2: A residual effect was found even at the widest spacing, 1.2° of visual angle. Peripheral channels could have been less densely distributed than central ones, so the residual effect could have been due to items presented in the periphery.

Other data from Experiment 2 are also consistent with the conclusion that spatial proximity is a critical factor. Consider the alternating- and paired-case conditions. If the spatial positions of letters were irrelevant, displays such as *BbBbBbBb* or *BBbbBBbb* should have produced effects similar to a display such as *BBBBbbbb*. Rearranging the letters in this manner approximates two uniform-case displays of four letters. Whereas there was a reliable effect of repetition for four-letter uniform displays, there was no effect for alternating and paired displays of seven or more letters. This suggests that proximity is important, not only in terms of absolute spatial distance between letters but in the adjacency relations of letters.

Experiment 2 raised the issue of whether the homogeneity effect is due to repeated tokens of letter *form* or letter *identity*. The results showed a homogeneity effect for letter form. Of course, it is not altogether surprising that letter identity per se was unimportant: The task did not require subjects to analyze identity information. In tasks demanding responses based on abstract stimulus properties, identity information has been shown to play a significant role (McClelland, 1976; Rudnicky & Kolers, 1984). Thus, the results of Experiment 2 should not exclude the possibility of homogeneity effects based on identity tokens. Experiment 3 aimed at uncovering such a homogeneity effect.

Experiment 3

In Experiment 3, subjects were required to *identify*, not just count, stimulus items. Pairs of vowels were presented in a pattern-masked display, one printed in uppercase and the other in lowercase, and subjects were instructed to report the number of *A*s or *E*s that appeared (the *target letters*). On some trials, two instances of the same target letter were presented—*A* and *a*, or *E* and *e*; on other trials, one instance of each target letter was presented—*A* and *e*, or *E* and *a*. If a homogeneity effect were found, it would depend on the common identity of the two targets, not a common visual form, and would suggest the existence of an *identity homogeneity effect*, distinct in nature from the *form homogeneity effect* observed in Experiments 1 and 2.

Now suppose that each target letter was embedded in a three-letter string, e.g., *bec MES*. Is there still a repetition in this display? In terms of the individual letters, there is a repetition of the *E*; however, in terms of the strings, there is no repetition because *bec* is distinct from *MES*. Thus, if abstract letter identities function as perceptual units, this display contains a repetition and may induce a homogeneity effect. But if the perceptual units are of a higher order, for example, letter clusters, the display contains no repetition and should not induce a homogeneity effect; instead, displays containing higher order repetitions would be necessary to obtain an effect. Thus, by manipulating the nature of the repeated elements, the psychological reality of certain perceptual units could be studied in Experiment 3.

In order to explore this issue, each of the two vowel stimuli was in fact presented with two flanking consonants (the *context* letters) printed in the same case as the vowel. In addition, the relation between the context letters of the two strings was varied. In the *different-context* condition, the context letters of one string were different from those of the other; for example, a two-target repeated-letter display might be *BEC mes*, a two-target distinct-letters display *ner TAL*. In the *same-context* condition, the context letters of the two strings were identical, for example, *BEC bec* and *ner NAR*. To the degree that perceptual units are of a higher order than single letters, the homogeneity effect could be expected to be larger in the same-context than in the different-context condition.

Embedding the vowels in a context served a second function: It separated one vowel from another. In Experiment 2, form homogeneity effects were found to be dependent on the adjacency relations among display items: A sequence of uppercase letters produced a homogeneity effect, as did a sequence of lowercase letters, but when the two sequences were alternated, the effect disappeared. This dependency is not surprising; the form homogeneity effect appears to be closely tied to the physical arrangement of the display. However, the hypothesized identity homogeneity effect, being relatively abstract, should be less likely to depend on the exact display format. If a homogeneity effect was found in Experiment 3 despite the nonadjacency of repeated letters, it would be a further dissociation between the form and identity homogeneity effects, suggesting all the more strongly a qualitative difference between the two.

Method

Subjects. Twenty-five University of California, San Diego, undergraduates participated in this experiment to satisfy course requirements. All were native English speakers.

Stimuli. The stimuli were three-letter strings. Each string was made up of a vowel surrounded by two consonants. The vowels used were *A*, *E*, *I*, *O*, and *U*; the consonants were all other letters except *Y*. All possible consonant–vowel–consonant (CVC) strings were generated, but two types were eliminated: those forming words and those occurring infrequently in English words (e.g., *VIX* or *QAD*). Frequency was measured by computing the number of English words containing each CVC string, weighted by the word frequency count of Kucera and Francis (1967); all strings with net frequency of occurrence less than 10 were discarded.

The remaining set of CVC strings was used to generate experimental trials. No CVC string was used more than once. Each trial was made up of a pair of strings. Four types of trials were generated on the basis of the number of target letters—*A* or *E*—in the pair of strings. The types of trials were as follows: (a) *zero-target* trials, among which approximately one third had the same nontarget vowel repeated twice; (b) *one-target* trials, roughly divided between *A* targets and *E* targets; (c) *two-target repeated* trials, in which the same target letter appeared twice, evenly divided between *A* and *E* targets; and (d) *two-target distinct* trials, in which one string contained an *A* and the other an *E*.

The trials were further generated in two context conditions. In the *same-context* condition, corresponding outer letters of the two stimulus strings were identical. In the *different-context* condition, corresponding letters of the two strings could not be identical.

Trials were collected into blocks of eight, consisting of 1 trial for each target and context condition. Twenty-six blocks of trials were assembled, resulting in a total of 208 experimental trials. The assignment of trials to blocks and the ordering of trials within a block were performed at random for each subject.

Twenty-four practice trials, composed of three blocks, were generated in the same manner as the experimental trials.

Procedure. Subjects were instructed to report the number of target letters that appeared in the display. They were told that the target could appear only in the center position of each string, the number of targets would range from zero to two, and that they should be conservative in their responses, it being better to underestimate than to overestimate. The purpose of this last instruction was to minimize guessing in the absence of perceptual information.

Throughout the experiment, a large green rectangle appeared on the display, subtending a visual angle of 8.47° horizontally and 1.54° vertically. At the start of each trial, a fixation point appeared in the center of the display. As in Experiment 1, subjects indicated verbally when they were ready for stimulus presentation, and the experimenter pressed a key to expose the stimuli. One string was presented to the left of fixation and the other to the right. Each letter subtended a horizontal visual angle of .54°. The space between letters within a string corresponded to .23° and between strings .77°. The net horizontal visual angle subtended by the stimulus display was 4.93°.

One string was printed in uppercase, the other in lowercase, chosen at random for each trial. String presentation position was balanced so that in the one-target condition, the target appeared equally often on the left and on the right, and in the two-target distinct condition, the *A* target appeared on the left and *E* on the right as often as the other way around.

The stimulus strings were presented for a controlled duration and at a controlled intensity. Immediately following stimulus offset, a pattern mask, consisting of pound signs (#) in the six letter positions, was presented for 200 ms. The rectangle then went blank and subjects were allowed to respond.

The 24 practice trials came first, followed by successive blocks of 8 experimental trials. Initially, stimuli were presented for 100 ms, but the exposure duration and/or stimulus intensity were adjusted after every block of trials to control the overall error rate. The AED terminal had the capability of displaying 256 intensity levels, but the intensity was not allowed to go below level 100 because, in the judgment of the experimenter, the visual quality of the display deteriorated below this point. Intensity was adjusted if possible, but when intensity fell outside the allowed range, exposure duration was adjusted. Adjusting both intensity and exposure permitted finer control over the error rate.

The desired error rate, that is, the magnitude of the difference between the actual and reported number of target letters, was .40. The rate achieved was .39, and the average stimulus exposure duration was 90 ms.

Results

Figure 6 shows performance on two-target trials. The error was computed by subtracting the reported number of targets from the actual number—two in this case. Error was greater on trials containing two repetitions of the same target than on trials containing two distinct targets, $F(1, 24) = 13.2$, $p < .001$). Error was also greater on different-context than on same-context trials, $F(1, 24) = 14.5$, $p < .001$. However, there was no hint of a Homogeneity × Context interaction, $F(1, 24) < 1$.

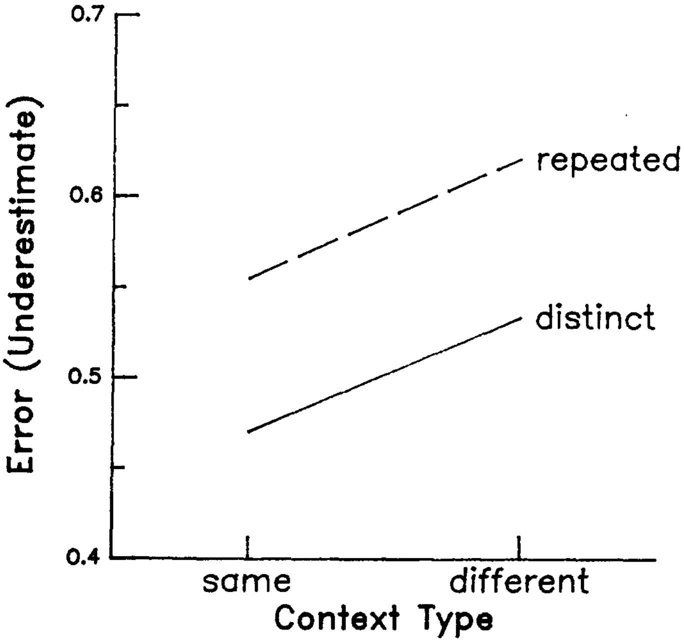

Figure 6. Mean error for two-target trials by context and homogeneity condition in Experiment 3.

A further analysis was performed with the dependent variable being the percentage of responses in which the display numerosity was correctly reported, adjusted for guesses and false alarms (a measure suggested by Schneider & Shiffrin, 1977, Appendix K). This measure did not affect the pattern of results or outcomes of statistical tests (same context: 41.2% correct for repeated, 51.8% for distinct; different context: 34.9% for repeated, 43.7% for distinct).

Interestingly, a homogeneity effect was also observed in a post hoc analysis of the zero-target condition: On trials in which the nontarget vowel was repeated, for example, *bil DIC*, subjects *overestimated* by a mean of .30 compared with trials in which the two nontarget vowels were distinct, for example, *COM hin*, where the error was only .21, $F(1, 24) = 10.9$, $p < .01$. Although this appears to be a *reverse* homogeneity effect, it is entirely consistent with the homogeneity effect observed in the two-target condition. Both effects imply decreased accuracy on repeated-letter trials. In the two-target condition, decreased accuracy is necessarily reflected by underestimation (the displays never contained more than two targets, so subjects were not permitted to overestimate); in the zero-target condition, decreased accuracy is necessarily reflected by overestimation (subjects could not underestimate, because doing so would involve reporting fewer than zero targets).

Discussion

Subjects were less able to perceive two instances of a target letter in a display than two distinct target letters. This effect was due to the repetition of a common letter identity, not a common visual form, because one target was printed in uppercase and the other in lowercase. This identity homogeneity effect contrasts with the form homogeneity effect observed in Experiment 2 not only in that it was independent of the targets' physical characteristics, but also in that it was obtained despite the interposition of extraneous letters between the repeated tokens. Thus, there is strong evidence for two qualitatively different homogeneity effects.

Experiment 3 also demonstrated that the context in which a target letter is embedded is irrelevant: same- and different-context trials produced homogeneity effects of virtually identical magnitude. This result can be expected when the functional units of perception are abstract single letter identities. If the units had been of a higher order than single letters, surrounding the two targets by different contexts would have helped to distinguish one repetition from another, and consequently, the homogeneity effect would have been attenuated or eliminated.

This result draws mixed support from the literature. On the other hand, there is evidence that letters in a trigram can function as independent perceptual units (Treisman & Souther, 1986) and, further, that familiar letter-cluster units do not facilitate encoding (McClelland & Johnston, 1977). On the other hand, the nature and frequency of perceptual errors in multiword displays depend strongly on the number of letters shared by the words (McClelland & Mozer, 1986; Mozer, 1983). Thus, before concluding that context played no role, it seemed worthwhile to seek further confirmation.

Experiment 4

In Experiment 3, only the center position of each string was relevant. Knowing this, subjects may have been able to suppress the processing of the extraneous context. This explanation is somewhat unlikely in that there was a main effect of context similarity, so the context could not have been suppressed entirely. In order to definitively rule out this explanation, however, the position of the target letter was varied from trial to trial in Experiment 4. This manipulation was expected to prevent subjects from tuning out the context in advance.

Experiment 4 differed from Experiment 3 in one other respect: Stimulus strings were two letters long, of either the form CV or the form VC. It was thought that reducing the number of letters in the display from six to four might allow a more thorough analysis of the context and consequently, might provide greater opportunity for the context to exert an effect on processing.

Because the position of the targets within a string was varied in Experiment 4, it was possible to examine a further issue of representation: whether the encoding of stimulus displays preserves relative letter position. Consider two displays, one containing two strings with target letters in corresponding positions, for example, *re CE*, and the other with target letters in noncorresponding positions, for example, *er CE*. In the first case, the two *E*s are indistinguishable in terms of both their identities and within-string positions, and hence a homogeneity effect should be observed; however, in the second display, the two *E*s are distinct by virtue of their different within-string positions and therefore may not induce a homogeneity effect. To see if relative position would indeed influence the homogeneity effect, Experiment 4 compared displays containing corresponding and noncorresponding targets.

It would seem necessary for letters to be encoded with respect to their position within a string, even if the conclusion of Experiment 3—that abstract letter identities serve as the basic units of perception—holds up. Otherwise, it would be impossible to determine the relative ordering of letters. This hypothesis is supported by the experimental findings of strong effects of position-specific single-letter frequency (Mason, 1975; McClelland, 1976; McClelland & Johnston, 1977) and position-specific effects in letter migration experiments (Shallice & McGill, 1978), and by the success of models of word perception that make use of position-specific letter analysis channels (McClelland, 1985; McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982).

Method

Subjects. Twenty University of California, San Diego, undergraduates participated in this experiment to satisfy course requirements.

Stimuli. Each stimulus string was composed of a consonant and a vowel. The set of consonants excluded *Q*, X, and *Y*. An attempt was made to eliminate all words from the set of allowed strings; three words, *NO*, *WE*, and *BE*, were inadvertently allowed, but they appeared with approximately equal frequency in each experimental condition. Because of the relatively small number of stimulus strings, it was necessary to allow a given string to appear more than once over the course of the experiment; however, no string was allowed to appear more than six times total.

Two strings were presented on each trial, one printed in uppercase, the other in lowercase. The context condition determined how one string was paired with another. In the *same-corresponding context* (*S–C*) condition, the two consonants were identical and appeared in corresponding positions of the two strings, for example, *ig AG* or *gi GA*. In the *different-corresponding context* (*D–C*) condition, the two consonants were different but appeared in corresponding positions, for example, *ig AC* or *gi CA*. In the *different-noncorresponding context* (*D–NC*) condition, the two consonants were different and appeared in noncorresponding positions, for example, *ig CA* or *gi AC*.

Within each of these three context conditions, there were four target conditions (zero target, one target, two-target distinct, and two-target repeated). Twenty trials were generated for each target condition crossed with context condition, amounting to a total of 240 experimental trials. The vowel appeared in Position 1 as often as in Position 2, and this factor was counterbalanced across conditions. The trials were collected into 20 blocks of 12, with 1 trial of each type per block. The assignment of trials to blocks and the ordering of trials within a block were performed at random for each subject.

Twenty-four practice trials were generated in the same manner as the experimental trials.

Procedure. The procedure was identical to that of Experiment 3, except that the spacing between strings, 1.23° of visual angle, was slightly larger, resulting in a net horizontal visual angle of 3.86° from one end of the stimulus display to the other.

Results

Figure 7 shows performance on two-target trials for the three context conditions. Separate analyses were conducted

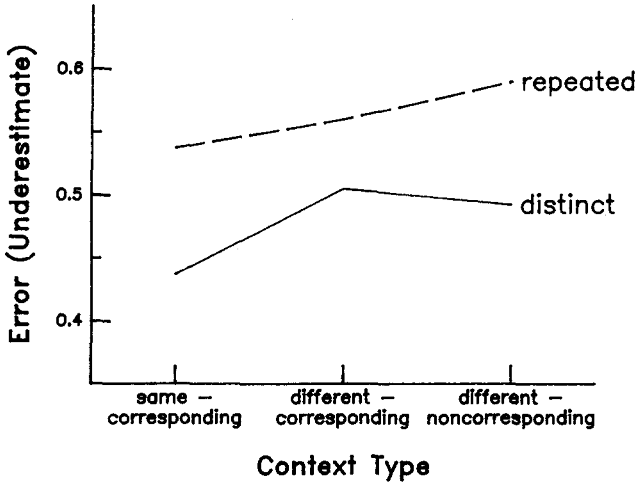

Figure 7. Mean error for two-target trials by context and homogeneity condition in Experiment 4.

for S–C versus D–C conditions and for D–C versus D-NC conditions.

First, consider S–C versus D–C (the leftmost two conditions in Figure 7). Error was consistently larger for repeated-target trials than for distinct-targets trials, $F(1, 19) = 10.2$, $p < .01$, and error was consistently larger for different-context than for same-context trials, $F(1, 19) = 6.3$, $p < .025$. The homogeneity effect was somewhat larger for same-context trials, but the Context × Homogeneity interaction was not significant, $F(1, 19) < 1$. These results thus replicate the findings of Experiment 3.

Incidentally, error was about twice as large for targets appearing in the second letter position as for targets appearing in the first position (.66 vs. .36, $F(1, 19) = 26.8$, $p < .001$), but this factor did not interact with any other.

Turning now to D–C versus D–NC trials (the rightmost two conditions in Figure 7), error was consistently larger for repeated-target trials than for distinct-targets trials, $F(1, 19) = 5.33$, $p < .05$, but there was no reliable difference in overall error between corresponding and noncorresponding trials, $F(1, 19) < 1$. The homogeneity effect was slightly larger for noncorresponding trials, but the Context × Homogeneity interaction was not significant, $F(1, 19) < 1$.

Examining the D-NC trials in isolation, the homogeneity effect was smaller for trials in which the target appeared in the outer two positions, for example *AB ra*, than in the inner two positions, for example *BA ar* (.05 vs. .14), but this difference was not significant (Proximity × Homogeneity interaction, $F(1, 19) = 2.00$, $p > .15$). Even if this difference were real, its source would be indeterminate: Two factors, spatial separation of the targets and the absolute distance of the targets from fixation, were confounded in this manipulation.

All data were reanalyzed using Schneider and Shiffrin's (1977) adjusted percentage correct measure as the dependent variable. Significance results were unaffected.

Discussion

The S–C and D–C conditions of this experiment were designed to replicate Experiment 3, with the exceptions that the stimulus strings were composed of two letters instead of three and the position of the target letter was varied across trials. It was postulated that these manipulations might allow the context to be more fully processed, leading to an influence of the context on the homogeneity effect. However, this argument was not borne out by the results: although the homogeneity effect was slightly smaller for different contexts, there was no reliable influence of context.

A further issue addressed by Experiment 4 was whether a homogeneity effect would be obtained if the repeated letters appeared in noncorresponding within-string positions. The homogeneity effect turned out to be at least as large for noncorresponding displays as for corresponding displays, indicating that relative letter position within a string could not be used to distinguish one instance of a letter from another.

Summarizing the findings of Experiments 3 and 4, it appears that to the extent that viewing time is limited, letter strings are encoded in terms of the identities of the individual letters. This encoding fails to preserve absolute position in the display, which is the cause of the homogeneity effect, as well as the relative position of one letter with respect to another. The implications of these findings are considered in the General Discussion.

Experiment 5

Experiment 5 attempted to strengthen the link between attention and the homogeneity effect. The spatial uncertainty hypothesis, as stated in the introduction, claims that attention is critical in detecting multiple tokens: With serial attentional scanning, each token can be bound to its location and hence distinguished from the others. Thus, to the extent that attentional processing is possible, the homogeneity effect should be weakened.

In the previous experiments, focal attention on individual items was restricted by brief exposures and large numbers of items in the display. Experiment 5 reduced the load on attention by increasing the exposure duration by a factor of 5, but kept the overall task difficulty the same by degrading the quality of the stimulus display. The aim of this manipulation was to obtain a change from resource-limited to data-limited processing (Norman & Bobrow, 1975). The prediction was simply that, if attention is indeed crucial to the homogeneity effect, the effect should disappear because attention can be accurately focused on individual items. Errors should result only from inadequate feature registration, which will have a comparable effect on repeated-letter and distinct-letters conditions.

In addition to this data-limited (DL) condition, an attention-limited (AL) condition comparable to the conditions of Experiments 3 and 4 was included. Stimuli were presented for 333 ms in the DL and 67 ms in the AL condition, but overall performance was matched between conditions by degrading the quality of the DL stimulus displays.

The task in Experiment 5 used digits instead of letters. Subjects were presented with displays consisting of between two and four digits positioned on the corners of an imaginary square. Their task was to report the number of odd digits present, which varied from zero to three. When two odd digits were present, they could be two repetitions of a given digit or two distinct digits. When three were present, they could be three repetitions of a given digit, two repetitions and a third distinct digit, or three distinct digits. The display types were characterized in terms of (a) the number of items in the display, (b) the number of targets (odd digits), and (c) the number of repetitions of a target. The notation xi–yt–zr was used to indicate a display containing x items, y targets, and z repetitions of the target. (For zero- and one-target displays, the number of repetitions was simply dropped from the notation.) Figure 8 shows several sample displays.

In a pilot experiment, all displays contained exactly four digits, but some subjects reported using a strategy of searching for even digits and then computing the number of odd digits by subtracting the number of even digits from four. The display size manipulation was intended to prevent the use of this alternative strategy.

Method

Subjects. Fifty University of California, San Diego, undergraduates participated in this experiment to satisfy course requirements. Twenty-five subjects were assigned to the AL condition, and 25 to the DL. One subject in the AL condition had to be replaced because he could not perform the task; he was unable to perceive stimuli at even the highest display intensity setting.

Stimuli. The target set consisted of the odd digits 1, 3, 5, 7, and 9. Eighteen different trial types were used, representing all valid combinations of two–four item displays, zero–three targets, and one–three repetitions: 2i–0t, 2i–1t, 2i–2t–1r, 2i–2t–2r, 3i–0t, 3i–1t, 3i–2t–1r, 3i–2t–2r, 3i–3t–1r, 3i–3t–2r, 3i–3t–3r, 4i–0t, 4i–1t, 4i–2t–1r, 4i–2t–2r, 4i–3t–1r, 4i–3t–2r, and 4i–3t–3r. Twelve trials of each type were generated, amounting to a total of 216 trials. Target and distractor digits were selected at random for each trial for each subject; in conditions having two, three, or four distractors, repetitions of the distractor digits occurred with the same frequency distribution as the target digit repetitions.

In two- and three-item displays, the unoccupied display locations were left blank. Stimulus sets were balanced so that each possible arrangement of distractor and target digits occurred with equal frequency, and blank spaces occurred equally often in each position. For example, with 4i–3t–2r trials, the two repeated targets could appear in 6 arrangements, and the other target could appear in either of 2 arrangements, for a total of 12 possible arrangements; with 3i–0t trials, the three distractors could appear in any of 4 arrangements, each leaving a different corner empty.

Trials were sorted into 12 blocks of 18, with 1 trial of each type per block. Within a block, the order of stimuli was randomized. Twenty-four practice trials were generated with equal numbers of trials for zero, one, two, and three targets.

In the experimental trials, there were twice as many three- and two-target trials as one- and zero-target trials. This distribution could bias subjects to report two or three targets more frequently, but the bias should affect repeated- and distinct-target conditions comparably.

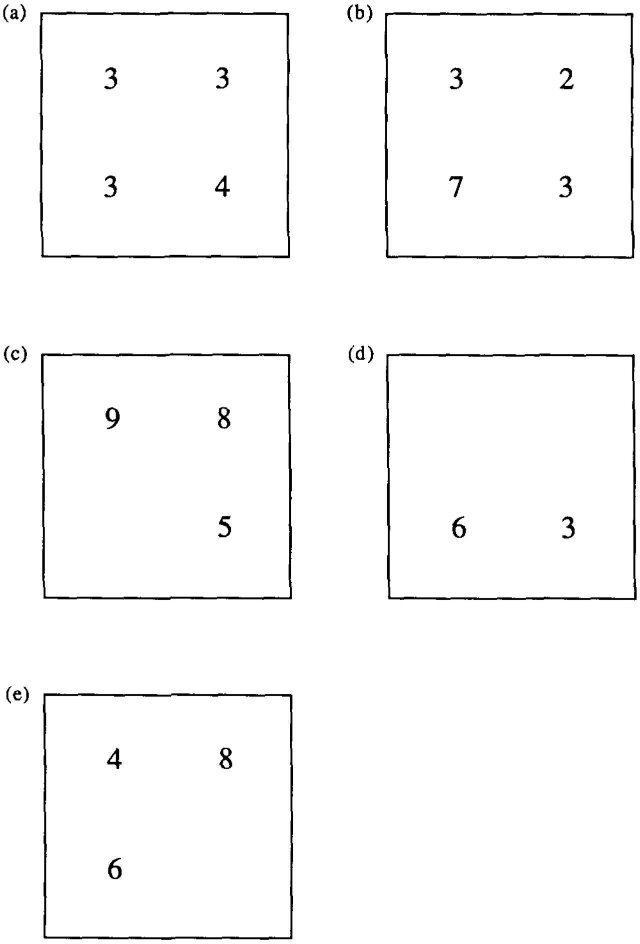

Figure 8. Sample displays from Experiment 5: (a) 4i–3t–3r, (b) 4i–3t–2r, (c) 3i–2t–1r, (d) 2i–1t, and (e) 3i–0t. (In the preceding notations, i = items, t = targets, and r = repetitions of the targets.)

Procedure. Throughout the experiment, a green square appeared on the screen subtending a visual angle of 3.66° in each dimension. Each trial began with the appearance of a green fixation point in the center of the square. Initiation of the trial proceeded as in Experiment 3 and caused the fixation point to be replaced with two to four digits positioned on the corners of an imaginary square inside the green square. The empty space between either horizontally or vertically aligned digits subtended a visual angle of 1.54°; the net visual angle including the digits was 2.08°. The stimulus display was exposed for 67 ms in the AL condition and 333 ms in the DL, followed by a pattern mask for 200 ms. The pattern mask consisted of #s appearing in the four possible stimulus locations. Once the mask was removed, the screen went blank except for the green square, at which point subjects were to report the number of targets that they had observed. Subjects were instructed to be conservative in their reports, that is, to only report on the digits that they were fairly certain about and not to guess.

The intensity of the stimulus display was adjusted after every 10 trials to yield an average error magnitude of .75 for each subject. The actual error magnitude achieved for AL subjects was .67 and for DL subjects .72. The mean stimulus intensities were 165 for AL and 59 for DL in a range of 0 to 255.[2]

Results

Performance on two- and three-target trials is summarized in Figure 9. In the AL condition, shown in the left-hand panel, error increased monotonically with the number of repetitions for both two- and three-target trials (two targets: $F(1, 24) = 7.51, p < .025$; three targets: $F(2, 48) = 15.7, p < .001$). This held across the various display sizes: The interaction between display size and number of repetitions was nonsignificant (two targets: $F(2, 48) < 1$; three targets: $F(2, 48) = 1.97, p > .15$).

In the DL condition, however, quite a different pattern of results was observed. There was no reliable effect of number of repetitions for either two- or three-target trials (two targets: $F(1, 24) < 1$; three targets: $F(2, 48) = 1.69, p > .15$). The Display Size × Number of Repetitions interaction was not significant for two-target trials, $F(2, 48) < 1$, but was for three-target trials, $F(2, 48) = 3.18, p = .05$. Thus, at best, a homogeneity effect was observed in the DL condition for 4i–3t trials, in contrast to the consistent effect in the AL condition for 2i–2t, 3i–2t, 4i–2t, 3i–3t, and 4i–3t trials.

Interactions involving the AL versus DL factor were consistent with this finding: The AL–DL × Number of Repetitions interaction was marginally significant for two-target trials, $F(1, 48) = 3.84, p = .056$. Although the AL–DL × Number of Repetitions interaction was not significant for three-target trials, $F(2, 96) = 1.67, p > .15$, the three-way AL–DL × Display Size × Number of Repetitions interaction was, $F(2, 96) = 4.11, p < .02$.

Discussion

The robust homogeneity effect obtained in the AL condition was not obtained in the DL condition, although overall error rates were approximately matched between conditions. Thus, the homogeneity effect appears to be dependent on attentional limitations; mere degradation of stimulus quality is insufficient to induce an effect. This finding is predicted by the spatial uncertainty hypothesis, which claims that attentional processing is required to distinguish repeated tokens of an object.

The elimination of the homogeneity effect in the DL condition rules out one conceivable explanation of the effect proposed by Schneider and Shiffrin (1977). They suggested that it is simply a memory error, not a perceptual error: Subjects have no problem perceptually encoding repetitions of an item, but they do have more trouble remembering repetitions of an item than distinct items. This account is exactly the reverse of that suggested by the spatial uncertainty hypothesis. According to a strong version of the spatial uncertainty hypothesis, the initial encoding of a display includes no location information, but this information can be recovered at later stages of processing. In contrast, according the Schneider and Shiffrin account, the initial encoding of a display preserved location information, but this information is discarded in more central representations on which report is based. The latter account predicts that stimulus presentation conditions should not influence the homogeneity effect and is thus invalidated by the DL–AL contrast.

General Discussion

It is not entirely surprising that the visual system has trouble processing collections of similar objects. Similar objects share many features, making them confusable. Multiple tokens are merely an extreme case along the similarity spectrum—they are identical on all relevant dimensions but spatial location. If the featural information used in identifying an object can become detached from location information, as a variety of experimental work suggests (e.g., Eriksen & Schultz, 1979; Estes et al., 1976; Mozer, 1983; Treisman & Gelade, 1980; Treisman & Schmidt, 1982; Wolford, 1975), featural information alone will be insufficient to distinguish one token from another. Thus, given the loss of location information, difficulty in detecting repetitions of an object seems certain.

The present experiments demonstrate such a homogeneity effect. The primary focus of the work, however, was to ask, At what stage of visual information processing is the effect manifested? Two qualitatively distinct homogeneity effects were discovered, one involving repetition of visual form and the other repetition of object identity. These effects appear to result from spatial uncertainty at two different stages of processing. The form homogeneity effect (Experiments 1 and 2) has the properties that (a) it occurs when repeated items in a display share a common visual form, and (b) it depends on the spatial proximity and adjacency of the items. Thus, one finds a form homogeneity effect for displays like *d d d d d* or *D D D D*, but not *d D d D d D d D d*. In contrast, the identity homogeneity effect (Experiments 3 and 4) (a) occurs when repeated items share a common identity, despite the lack of visual similarity, and (b) is not critically dependent on the adjacency of repeated items. Thus, one finds an identity homogeneity effect for the two *E*s in a display like *peb CER*.

A framework to account for these two effects can be found in MORSEL, a computational model of multiple object perception (Mozer, 1987, 1988). The primary component of MORSEL is a connectionist network that constructs a location-invariant representation of the identities of shapes on its "retina." For example, if two letters are presented in arbitrary locations on the retina, the network will encode which letters are there but not where they appear. The network consists of a hierarchy of feature detectors, starting at the lowest level with position-specific detectors for primitive visual features, and progressing

---

[2] Note that these intensity levels are internal parameters of the display terminal and should not be interpreted as bearing a direct relation to physical luminance. In particular, at intensity levels below 100, pixels were not of uniform brightness; some segments of letters seemed to vanish, even with long stimulus exposures. Thus, the intensity level manipulation was not merely a quantitative effect—low intensity levels did result in the degradation of stimulus quality. Another comment concerning the displays: In the data-limited condition, exposures were sufficiently long that the pattern mask played little or no role. Indeed, several pilot subjects were tested with no mask and the results were indistinguishable. However, the mask was retained to match attention-limited and data-limited conditions as closely as possible.

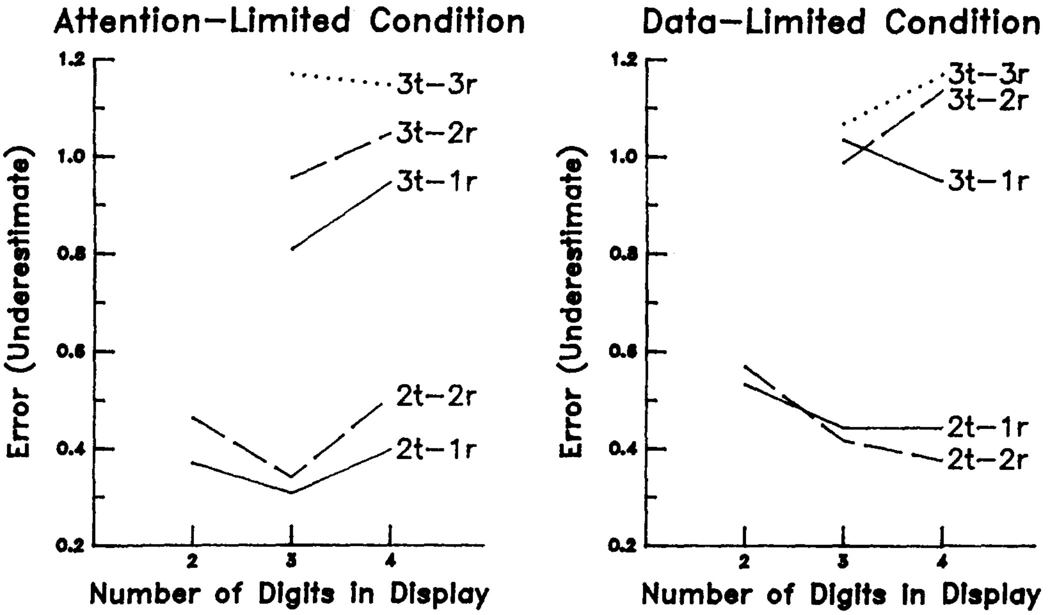

Figure 9. Mean error by display size and trial type in Experiment 5.

to a level composed of position-independent detectors for abstract object identities. Detectors at intervening levels register successively higher order features over increasingly larger regions of retinotopic space. The effect of this architecture is that both spatial uncertainty and featural complexity increase at higher levels of the system. Thus, there is local spatial uncertainty of visual form at low levels of global spatial uncertainty of identity information at the highest level.

The form homogeneity effect can be attributed to confusions at low levels of the system among visually identical stimuli in close proximity, and the identity homogeneity effect to confusions at the highest level among conceptually identical stimuli. Simulation experiments have been performed to verify that the qualitative behavior of the model is in accord with the present data (Mozer, 1988). In these simulations, the loss of location information at a given stage of processing leads to the inability to detect repeated instances of the perceptual units represented at that stage.

One must wonder how repetitions of an item can ever be perceived if the loss of location information is intrinsic to the processing system. There are several possibilities:

1. With form repetition, the loss of location information is only local; thus, in a display like *X X X X X*, the first and second *X*s might be confused as might the fourth and fifth, but the first two will not be confused with the last two.

2. The strength of activation of a "type" detector might be used to infer the number of tokens presented (Milner, 1974); however, if activation strength interacts with factors such as stimulus quality, as most models would presume, activation strength cannot be a terribly informative cue to numerosity.

3. Even if shape recognition processes do not encode absolute location information in their outputs, such information must be implicit in the activity of the system as a whole. We are currently exploring a computational mechanism whereby location information can be explicitly recovered once an identity is detected and deemed to be of interest (Pashler & Mozer, 1988). This mechanism operates backward through a connectionist network in a manner akin to the back-propagation learning algorithm (Rumelhart, Hinton, & Williams, 1986) and is sequential in nature.

4. Location information might be recovered via focal attention. Essentially, the notion is that by focusing on each display item in turn, the attentional system specifies the location of the object that is currently being processed. Consequently, this location information can be "bound" to the identity information produced by shape recognition processes, and one repetition can be distinguished from another. The close relation between focal attention and the ability to distinguish among repeated tokens are supported by the results of Experiment 5, in which a homogeneity effect was observed when performance was attention limited but not data limited.

Discovering the Functional Units of Perception

Experiments 3 and 4 showed that the context in which a target letter is embedded does not influence the identity homogeneity effect. These experiments contrasted contexts that were the same for each target with contexts that were different for each target, for example, for the target letter *E*, *BEC BEC* versus *BEC MES*. Experiment 4 further contrasted contexts that maintained the relative within-string position of the target with contexts that did not, for example *RE CE* versus *RE EC*. The results were unaffected by context type.

It seemed possible that embedding the target letters in unique contexts might serve to distinguish one token of a target from another, thereby attenuating or eliminating the homogeneity effect. Because this did not occur, the following conclusion can be drawn: To the extent that viewing time is limited, and thereby focal attention is prevented, letter strings are encoded in terms of the identities of individual letters, without regard to their neighbors or even their relative within-string position. In other words, the functional units of perception are abstract letter identities; there was no support for the existence of higher order perceptual units.

This finding is troublesome to any model that proposes an automatic influence of higher order units (e.g., McClelland & Rumelhart, 1981; Mozer, 1988) and even to accounts that do not assume that automatic analysis proceeds beyond the letter level (e.g., feature integration theory, Treisman & Gelade, 1980). It would seem that such accounts would minimally require that letters be tagged with their relative within-string letter position. Otherwise, it would be impossible to determine the relative ordering of letters in a word, and a host of confusions would ensue. (Treisman & Souther, 1986, seem amenable to this view in their treatment of letter migration errors in terms of feature integration theory.) Contrary to this argument and to converging evidence for letter encodings that are specific to the relative within-string position (Mason, 1975; McClelland, 1976; McClelland & Johnston, 1977; Shallice & McGill, 1978), Experiment 4 found no support for position-specific representations.

One way around the dilemma posed here is the possibility that subjects use different levels of representation in different tasks. Estes (1975) reached a similar conclusion in stating, "If the task orientation is strictly directed to the identification of letters rather than to the identification of words as units . . . [then] the identification of letters, as distinguished from letter sequences, may be independent of context" (pp. 18–19). Thus, although there may be perceptual units both for single letters and for higher order information, subjects may have selectively ignored the higher order information in Experiments 3 and 4 because it was not germane to the task. This could explain the context's inability to influence the homogeneity effect, even if higher order detectors did exist.

One sad consequence of such an explanation is that the homogeneity paradigm cannot be used to study the functional units of perception, simply because the functional units are task dependent. (A similar conclusion regarding task specificity was drawn by Francolini & Egeth, 1979, and can be reached by comparing the letter migration studies of Treisman & Souther, 1986, and McClelland & Mozer, 1986.) Perhaps if the task orientation encouraged subjects to identify strings as units—for example, report identities of all strings in the display containing a target letter—it might be possible to use the homogeneity paradigm to examine the issue of higher order units in perception.

Homogeneity Effects in Time and in Motor Control

Kanwisher (1987; Kanwisher & Potter, in press) has explored a phenomenon closely related to the homogeneity effect using rapid serial visual presentation of words. She found that subjects had difficulty detecting the second occurrence of a word in a sentence when the words were presented at a rate of about six or more per second. The difficulty occurred even when the two instances were nonconsecutive, when they differed in case, when they were spatially as well as temporally displaced, and when omission of the second instance upset the syntax or meaning of the sentence. Further, the phenomenon did not occur with auditory presentation. Several plausible accounts of the phenomenon were ruled out by Kanwisher, including forgetting and a refractory period for recognition of repeated instances. Kanwisher discusses the general issue of type recognition versus token individuation, proposing that a word must be tagged by, say, its position in a sequence or there will be no means of distinguishing one instance of the word from another. If temporal tagging processes do not have sufficient time to operate under rapid presentation conditions, repeated instances will pass undetected. This explanation is much like the one given for the homogeneity effect, except that the tagging is temporal in nature, not spatial.

Homogeneity effects have also been found in motor behavior. With skilled typists, two sorts of errors are particularly interesting: doubling errors, such as *bokk* for *book*, and alternation errors, such as *thses* for *these* (Rumelhart & Norman, 1982). The existence of these errors forced Rumelhart and Norman to consider a model of the typing process in which repeated letters of a word are not coded as distinct entities. The model has motor schema for each letter type, but not for each token of a letter in a word. This is the motor analogue to the representation suggested by the homogeneity effect in perception.

Relation to the Repeated-Letter Inferiority Effect

Another paradigm involving repeated target letters in a display has been explored by several investigators (Bjork & Murray, 1977; Egeth & Santee, 1981; Keren & Boer, 1985; Santee & Egeth, 1980). In the Bjork and Murray study, a 4 × 4 matrix was briefly presented containing either one or two letters with all remaining positions filled by a single, repeated background character (#). This display was followed by a mask, and simultaneously, an arrow pointing to one of the four columns. Subjects were required to make a forced-choice judgment as to what letter appeared in the cued column (only one letter could appear in a column). The choices were fixed throughout the experiment: *B* or *R*. The uncued column could also contain one of the targets *B* or *R*, or a nontarget letter, *P* or *K*. The finding in all these investigations was that accuracy of report was lower for a letter flanked by itself (*BB* displays) than for a letter flanked by the other target letter (*BR*) or by one of the nontarget letters (*BP* or *BK*).

This effect, the repeated-letter inferiority effect, or RLIE (Egeth & Santee, 1981), is strikingly similar to the homogeneity effect reported here. In both cases, performance is poorer for two repetitions of the same target letter than for two distinct target letters. An account of the RLIE in terms of types and tokens is easy to provide: If exposures are brief, often subjects will be unable to focus attention on each display item in turn. When this occurs, identity information will often be correctly detected but location information will not. Thus, for *BB* displays, subjects will have the impression that only a single letter was present and will be uncertain as to its location. If on only a small proportion of these trials subjects are willing to guess the alternative target (*R*), the RLIE will be obtained. (A detailed argument is presented in the Appendix.)

Santee and Egeth (1980, Experiment 3) suggested a similar hypothesis to explain the RLIE, which they attempted to test with an experiment in which subjects were shown displays like those of Bjork and Murray (1977), but instead of a poststimulus cue to guide report, subjects were simply required to indicate by a "yes" or "no" response whether at leaset one target letter was present in the display (see also Santee & Egeth, 1982, Experiments 2 and 3). Accuracy was lower on *BB*-type displays than on *BR*-type displays, leading Santee and Egeth to rule out the spatial uncertainty hypothesis. They were perhaps too hasty in their judgment. An alternative explanation of this experiment can be formulated in terms of types and tokens: To the extent that subjects can access only type information, one would expect *BR* displays to be easier than *BB* displays because two distinct letter types are present in *BR* displays but only one in *BB* displays. (Estes, 1982, presents a similar argument.) Thus, this experiment is hardly conclusive, and in fact might be taken as further support for the spatial uncertainty hypothesis.

Just as the homogeneity effect reported in the present set of experiments depends on both form and identity repetition, so does the RLIE. Egeth and Santee (1981) compared *BB*-type displays with *BR*-type displays when the two letters were printed in different cases (similar to the present Experiments 3 and 4). The repetition of conceptual identity exerted a detrimental effect on target identification, although not as great as that exerted by the repetition of physical form. Another finding concerning the RLIE is also in accord with the spatial uncertainty hypothesis: Positional uncertainty of the target is a necessary condition for obtaining the RLIE (Eriksen & Eriksen, 1979; Keren & Boer, 1985).

Santee and Egeth (1982) obtained an RLIE when performance was limited by pattern masking but not by brief-exposure, nonmasked presentation. This intriguing property of the RLIE was not systematically explored in the current work, although in pilot experiments, I was unable to obtain a reliable identity homogeneity effect without pattern masking. Repeated letters will be more difficult to process under conditions of pattern masking if pattern masking specifically disrupts the ability to recover location information from the display. The connectionist model of Pashler and Mozer (1988) has precisely this property: An iconic trace is necessary to recover location information given stimulus identity. This trace is obliterated by pattern masking, but degrades gradually under no-mask or energy-masked conditions. Thus, the effects of masking may be reconciled with the spatial uncertainty hypothesis.

In summary, both the homogeneity effect and the RLIE seem interpretable in terms of a model in which spatial uncertainty renders the visual system unable to distinguish among tokens without the use of serial processing. The extent to which such spatial uncertainty complicates perception in naturalistic settings is questionable, although it does point to yet another limit on the ability to process visual information in parallel.

References

Bjork, E. L., & Murray, J. T. (1977). On the nature of input channels in visual processing. *Psychological Review, 84,* 472–484.

Collins, J. F., & Eriksen, C. W. (1967). The perception of multiple simultaneously presented forms as a function of foveal spacing. *Perception & Psychophysics, 2,* 369–373.

Egeth, H. E., & Santee, J. L. (1981). Conceptual and perceptual components of interletter inhibition. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 506–517.

Eriksen, C. W., & Eriksen, B. A. (1979). Target redundancy in visual search: Do repetitions of the target within the display impair processing? *Perception & Psychophysics, 25,* 249–263.

Eriksen, C. W., & Schultz D. W. (1979). Information processing in visual search: A continuous flow conception and experimental results. *Perception & Psychophysics, 25,* 249–263.

Estes, W. K. (1972). Interactons of signal and background variables in visual processing. *Perception & Psychophysics,12,* 278–286.

Estes, W. K. (1975). Memory, perception, and decision in letter identification. In R. L. Solso (Ed.), *Information processing and cognition: The Loyola symposium* (pp. 3-31). Hillsdale, NJ: Erlbaum.

Estes, W. K. (1982). Similarity-related channel interactions in visual processing. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 353–380.

Estes, W. K., Allmeyer, D. H., & Reder, S. M. (1976). Serial position functions for letter identification at brief and extended exposure durations. *Perception & Psychophysics, 19,* 1–15.

Francolini, C. M., & Egeth, H. E. (1979). Perceptual selectivity is task dependent: The pop-out effect poops out. *Perception & Psychophysics, 25,* 99–110.

Frick, R. W. (1987). The homogeneity effect in counting. *Perception & Psychophysics, 41,* 8–16.

Kanwisher, N. G. (1987). Repetition blindness: Type recognition without token individuation. *Cognition, 27,* 117–143.

Kanwisher, N. G., & Potter, M. C. (in press). Repetition blindness: The effects of stimulus modality and spatial displacement. *Memory & Cognition.*

Kaufman, E. L., Lord, M. W., Reese, T. W., & Volkmann, J. (1949). The discrimination of visual number. *American Journal of Psychology, 62,* 498–525.

Keren, G., & Boer, L. C. (1985). Necessary conditions for repeated-letter inferiority: The role of positional uncertainty. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 601–612). Hillsdale, NJ: Erlbaum.

Krumhansl, C. L., & Thomas, A. C. (1977). Effect of level of confusability on reporting letters from briefly presented visual displays. *Perception & Psychophysics, 21,* 269–279.

Kucera, H., & Francis, W. N. (1967). *Computational analysis of present-day American English.* Providence, RI: Brown University Press.

Mandler, G., & Shebo, B. J. (1982). Subitizing: An analysis of its component processes. *Journal of Experimental Psychology: General, 111,* 1–22.

Mason, M. (1975). Reading ability and letter search time: Effects of orthographic structure defined by single letter positional frequency. *Journal of Experimental Psychology: General, 104,* 146–166.

McClelland, J. L. (1976). Preliminary letter identification in the perception of words and nonwords. *Journal of Experimental Psychology: Human Perception and Performance, 2,* 80–91.

McClelland, J. L. (1985). Putting knowledge in its place: A scheme for programming parallel processing structures on the fly. *Cognitive Science, 9,* 113–146.

McClelland, J. L., & Johnston, J. C. (1977). The role of familiar units in perception of words and nonwords. *Perception & Psychophysics, 22*, 249-261.

McClelland, J. L., & Mozer, M. C. (1986). Perceptual interactions in two-word displays: Familiarity and similarity effects. *Journal of Experimental Psychology: Human Perception and Performance, 12*, 18-35.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: Part I. An account of basic findings. *Psychological Review, 88*, 375-407.

Mewhort, D. J. K., & Campbell, A. J. (1978). Processing spatial information and the selective-masking effect. *Perception & Psychophysics, 24*, 93-101.

Milner, P. M. (1974). A model for visual shape recognition. *Psychological Review, 81*, 521-535.

Mozer, M. C. (1983). Letter migration in word perception. *Journal of Experimental Psychology: Human Perception and Performance, 9*, 531-546.

Mozer, M. C. (1987). Early parallel processing in reading: A connectionist approach. In M. Coltheart (Ed.), *Attention and performance XII: The psychology of reading* (pp. 83-104). Hillsdale, NJ; Erlbaum.

Mozer, M. C. (1988). *The perception of multiple objects: A parallel, distributed processing approach* (ICS Technical Report 8803). La Jolla: University of California, San Diego, Institute for Cognitive Science.

Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognitive Psychology, 7*, 44-64.

Pashler, H., & Badgio, P. C. (1985). Visual attention and stimulus identification. *Journal of Experimental Psychology: Human Perception and Performance, 11*, 105-121.

Pashler, H., & Badgio, P. C. (1987). Attentional issues in the identification of alphanumeric characters. In M. Coltheart (Ed.), *Attention and performance XII: The psychology of reading* (pp. 63-82). Hillsdale, NJ: Erlbaum.

Pashler, H., & Mozer, M. C. (1988). *Recovering the "where" from the "what": A connectionist account of spatial localization and perceptual masking.* Manuscript in preparation.

Rudnicky, A. I., & Kolers, P. A. (1984). Size and case of types as stimuli in reading. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 231-249.

Rumelhart, D. E., Hinton, G. E., & Williams, R. J. (1986). Learning internal representations by error propagation. In D. E. Rumelhart & J. L. McClelland (Eds.), *Parallel distributed processing: Explorations in the microstructure of cognition. Vol. I: Foundations* (pp. 318-362). Cambridge, MA: MIT Press/Bradford Books.

Rumelhart, D. E., & McClelland, J. L. (1982). An interactive activation model of context effects in letter perception: Part II. The contextual enhancement effect and some tests and extensions of the model. *Psychological Review, 89*, 60-84.

Rumelhart, D. E., & Norman, D. A. (1982). Simulating a skilled typist: A study of skilled cognitive-motor performance. *Cognitive Science, 6*, 1-36.

Santee, J. L., & Egeth, H. E. (1980). Interference in letter identification: A test of feature-specific inhibition. *Perception & Psychophysics, 27*, 321-330.

Santee, J. L., & Egeth, H. E. (1982). Independence versus interference in the perceptual processing of letters. *Perception & Psychophysics, 31*, 101-116.

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search and attention. *Psychological Review, 84*, 1-66.

Shallice, T., & McGill, J. (1978). The origins of mixed errors. In J. Requin (Ed.), *Attention and performance VII* (pp. 193-208). Hillsdale, NJ: Erlbaum.

Townsend, J. T., Taylor, S. G., & Brown, D. R. (1971). Lateral masking for letters with unlimited viewing time. *Perception & Psychophysics, 10*, 375-378.

Treisman, A., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology, 12*, 97-136.

Treisman, A., & Schmidt, H. (1982). Illusory conjunctions in the perception of objects. *Cognitive Psychology, 14*, 107-141.

Treisman, A., & Souther, J. (1986). Illusory words: The roles of attention and of top-down constraints in conjoining letters to form words. *Journal of Experimental Psychology: Human Perception & Performance, 12*, 3-17.

Wolford, G. (1975). Perturbation model for letter identification. *Psychological Review, 82*, 184-199.

Wolford, G., & Hollingsworth, S. (1974). Lateral masking in visual information processing. *Perception & Psychophysics, 16*, 315-320.

Appendix

A Spatial Uncertainty Account of the Repeated-Letter Inferiority Effect

On any trial, the subject may or may not attend to the target and/or distractor. Denote the probability of attending to neither a_0, the probability of attending to exactly one or the other a_1, and the probability of sequentially attending to each a_2. If attention is focused on a letter, assume that its identity is correctly detected and tagged with its location. If attention is not focused on a letter, assume that its identity is correctly detected with probability d but is not bound to a location; however, if its identity is not correctly detected, no information about it is obtained. On the basis of these assumptions, each letter will be in one of three perceptual states: Its identity and location are detected (*IL*), its identity alone is detected (*I*), or nothing is detected (*N*). The three perceptual states of the target crossed with three perceptual states of the distractor yield nine possible perceptual states, as enumerated in Table A1.

Presumably, if the target identity and location are detected, the target will be reported correctly. However, in some perceptual states, the identity of one of the letters in the display is detected, but the available location information is insufficient to determine whether this identity belongs to the target letter. In these states, assume that the subject will report this identity with probability g (for guess) and will select the alternative response with probability $1 - g$. (One expects g to be less than 1 because the subject cannot tell if this is in fact the target identity or if the true target identity passed undetected, in which case it may or may not be the correct target identity. Thus, a guess is in order.) Table A1 lists the probability of correctly reporting the target identity on *BR* and *BB* trials for each perceptual state.

There will be an advantage for *BR* trials over *BB* trials when

$$P(\text{correct} \mid BR) > P(\text{correct} \mid BB).$$

Because

$P(\text{correct} \mid BR) =$

$$\sum_i P(\text{correct} \mid BR \ \& \ \text{perceptual state } i)\text{P}(\text{perceptual state } i),$$

and similarly for $P(\text{correct} \mid BB)$, Table A1 can be used to rewrite the above inequality as

$$a_0d(1-d)(1-g) + .5a_1(1-d)(1-g) + .5a_0d^2 + .5a_1d >$$
$$a_0d(1-d)g + .5a_1(1-d)g + a_0d^2g + .5a_1dg.$$

(The perceptual states in which *BR* and *BB* do not differ have been canceled out.) This reduces to

$$g < .5 + \frac{.25a_1d}{2a_0d(1-d) + a_1(1-d) + a_0(1-d)^2 + .5a_1d}.$$

If exposure durations are relatively long and stimulus quality is good, one would expect a_0 to approach zero (because subjects have sufficient time to attend to at least one letter) and d to approach 1. At these limits of a_0 and d, the above equation reduces to $g < 1$. It was argued previously that g should always be less than 1; hence, a repeated-letter inferiority effect (RLIE) should be obtained.

Three comments regarding this analysis are in order. First, the analysis ignores the possibility of a fourth perceptual state in which letter identities are incorrectly registered. I have worked out a model that allows a letter to be incorrectly perceived as the alternative target or as a distractor. This model is complex and its predictions are not as direct. If, however, d is relatively large, as one might expect if stimulus quality is good, the complex model reduces to the simple one presented above. Second, one prediction the model makes is that the RLIE might well disappear for presentation conditions that yield very low accuracy rates. This is because under some values of a_0, a_1, and d (e.g., when a_1 is zero), g must be less than .5 in order to obtain a RLIE, and this is by no means guaranteed. Third, this model makes no assumption as to whether the spatial uncertainty occurs at a low or high level. Thus, it permits a RLIE for both repeated forms and repeated identities.

Table A1
Probability of Correctly Reporting the Target Identity on BR and BB Trials

Perceptual state of target	Perceptual state of distractor	*P* (perceptual state)	*P* (correct/ perceptual state)	
			BR	*BB*
N	N	$a_0(1-d)^2$	.5	.5
N	I	$a_0d(1-d)$	$1-g$	g
N	IL	$.5a_1(1-d)$	$1-g$	g
I	N	$a_0d(1-d)$	g	g
I	I	a_0d^2	.5	g
I	IL	$.5a_1d$	1	g
IL	N	$.5a_1(1-d)$	1	1
IL	I	$.5a_1d$	1	1
IL	IL	a_2	1	1

Note. N = nothing is detected, I = identity alone is detected, IL = identity and location are detected, a_0 = probability of attending to neither the target nor the distractor, a_1 = probability of attending to exactly one or the other, a_2 = probability of sequentially attending to each, g = probability of guessing a correctly perceived letter identity when the available location information is insufficient to determine whether this identity belongs to the target letter.

Received January 14, 1988
Revision received August 2, 1988
Accepted August 3, 1988 ■