Journal of Experimental Psychology:
Human Perception and Performance
1991, Vol. 17, No. 4, 924-941


0096-1523/91/$3.00

# Intra- and Interpattern Relations in Letter Recognition

Thomas Sanocki
University of South Florida

Strings of 4 unrelated letters were backward masked at varying durations to examine 3 major issues. (a) One issue concerned relational features. Letters with abnormal relations but normal elements were created by interchanging elements between large and small normal letters. Overall accuracy was higher for letters with normal relations, consistent with the idea that relational features are important in recognition. (b) Interpattern relations were examined by mixing large and small letters within strings. Relative to pure strings, accuracy was reduced, but only for small letters and only when in mixed strings. This effect can be attributed to attentional priority for larger forms over smaller forms, which also explains global precedence with hierarchical forms. (c) Forced-choice alternatives were manipulated in Experiments 2 and 3 to test feature integration theory. Relational information was found to be processed at least as early as feature presence or absence.

The present article concerns the process of recognizing letters, which are examples of highly familiar patterns. Of particular interest are several interrelated properties of patterns and groups of patterns that can be referred to as *spatial-size* relations. Such relations exist between elements of patterns or between patterns themselves. In this article, I assume that primitive, elemental features correspond to continuous collinear or curvilinear segments, or pieces of such segments, and that relational features involve relations between (combinations of values on) elemental feature dimensions. Intrapattern relations of interest here involve the relative locations and sizes of elements. Interpattern relations of interest here involve the relative size of neighboring patterns.

## Intrapattern Relations

Little is known about the processing of intrapattern relations such as relative location. For example, consider models in which features correspond to mutually exclusive, position-specific elements (e.g., McClelland & Rumelhart, 1981; Townsend & Ashby, 1982). In these models, location is resolved when a feature is detected because such information is assumed to be part of a feature's definition. This is more of an assumption than an explanation, however, and it has problems.[1] For example, evidence suggests that without focal attention, stimulus elements may be registered but not localized (Treisman & Gelade, 1980).

Other investigators have suggested that recognizing patterns or objects involves detecting relations between elements (e.g., Oden, 1979; Palmer, 1977). The relations could involve feature dimensions such as size, orientation, and relative location. Relations between elements can be represented together with more elemental features within a structural description (e.g., Palmer, 1977). A structural description is a hierarchy of structural units, each of which may include several elements and their interrelations. The encoding of relations between elements could provide information about the relative locations of elements (of course), and the encoding of multiple relations could provide information about the relative location of each element within a pattern.

Models that use structural descriptions gain explanatory power because the formalism is both powerful and flexible; however, these qualities also make the models difficult to test. Indeed, although many investigators agree that structural information is important in recognition (e.g., Massaro & Schmuller, 1975; Oden, 1979; Palmer, 1977; Pinker, 1984), there is very little direct evidence that relational information is used in pattern recognition (but see Oden, 1979).

Yet flexible representations could also become rather precise under certain conditions, and precision could enable certain types of empirical tests. The existence of letter fonts provides a reason for precision. Letters almost always appear together in the same font, having similar details and systematically related sizes. It would be adaptive for the visual system to become tuned for font-specific details because such tuning would increase the efficiency of recognition within the font. That such tuning occurs is supported by the finding that recognition is more efficient with target sets of $n$ letters of a single font than with $n$ letters of two or more fonts, for which font-specific tuning would not be possible (Sanocki, 1987, 1988).

Given that precise representations are used in letter recognition, it is possible to test certain types of structural descrip-

This research was supported in part by a University of South Florida Research and Creative Scholarship Award. I thank Gregg Oden for helpful comments on the research, and Carol Crumley, Robert Edelman, Ian Rosen, and Cecilia Puccini for their help in conducting the experiments.

Correspondence concerning this article should be addressed to Thomas Sanocki at the Department of Psychology, BEH 339, University of South Florida, Tampa, Florida 33620-8200. (Electronic mail: *Sanocki@figment.csee.usf.edu.*)

[1] The cited models have been designed to address problems other than spatial-size relations, and their simplified feature assumptions may have been adopted for convenience. The present comments are not meant to minimize the substantial contributions of these models but to point out that there may be a set of important issues hidden beneath assumptions of some important models.

tion models. The present experiments were motivated by the hypothesis that perhaps because of years of experience reading, perceivers have developed representations that include fairly precise information about relations that characterize common letters. Such representations might take different forms (see the General Discussion section), but the crucial characteristic of interest here is that they include fairly precise information about relations between elements of letters. Such representations have implications quite different from models that are based on simple elements only (or from structural description models that do not include precise relational information). In particular, if perceivers use precise relational information, then letters with relations unlike typical letters ought to be less perceptible than letters with typical relations because the "abnormal" letters would not match existing representations as well as normal letters would. This ought to occur even though abnormal letters have the same elements (but in somewhat different relations) as normal letters.

The relations of initial interest here were those involving the relative sizes of elements corresponding to ascenders, descenders, and bodies of (lowercase) letters, or to pieces of these units. The assumption that elements correspond to (or are contained within) ascenders, descenders, and bodies is consistent with the frequent observation that ascenders and descenders are particularly important for lowercase letters. In Bouma's (1971) analysis of letter confusions, the distinction between small letters and letters with ascenders and descenders was among the most important cues to letter identity, and such a distinction is consistent with a number of other feature sets that are based on local features (e.g., Keren & Baggen, 1981; McClelland & Rumelhart, 1981). Examples of the letters used in the present experiments are shown in Figure 1. Normal letters can be found in Rows 1 and 2. Abnormal intraletter size relations were created by switching the tops and bottoms (ascenders and descenders) of one size with the middles (bodies) of the other size. The abnormal letters are shown in Rows 3 and 4. Note that although these letters have abnormal interpart size relations, the elements themselves are the same as in the normal letters.

A potentially important consequence of interchanging the parts is the resultant change in the amounts of common and distinctive feature information. Common features are shared by many items in the stimulus set, whereas distinctive features

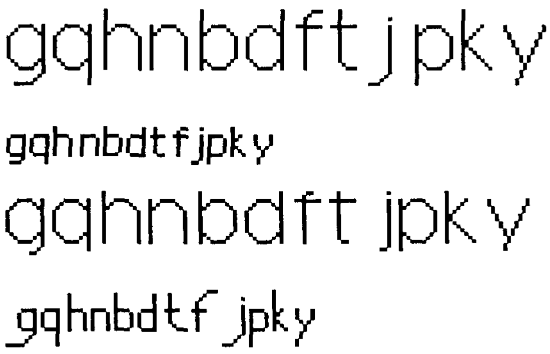


*Figure 1.* The two normal fonts and the two abnormal fonts (large-small and small-large), respectively. (These letters were used in Experiment 1.)

are specific to a limited number of the items and are more important for identification (e.g., see Keren & Baggen, 1981). In the present case, the bodies of the letters provide mainly common features, whereas the ascenders and descenders provide mainly distinctive features. Adding large ascenders and descenders to small bodies (Row 4) could increase the relative amount of distinctiveness and thereby increase perceptibility, whereas adding small ascenders and descenders to large bodies (Row 3) could reduce distinctiveness and decrease perceptibility. Models that emphasize precise relational information, however, predict that disrupting relational information ought to have effects in addition to those of altering distinctiveness. Therefore, overall, the prediction is that letters with abnormal relations ought to be less perceptible than letters with normal relations.

## Interpattern Relations

Also of interest here are interpattern relations between different patterns within the field of view. The main relation investigated here involves the relative sizes of neighboring patterns. Rudnicky and Kolers (1984) compared reading speeds for texts composed of same- and alternating-size letters and found a decrement for alternating size. Rudnicky and Kolers attributed the decrement to word-based pattern-analyzing processes. However, explanations in terms of more general mechanisms might be preferable, especially if size-mixing decrements can be obtained with strings of unrelated letters mixed in size.

An alternative account of size-mixing decrements follows from a literature on attending to forms at different size scales (e.g., Miller, 1981; Navon, 1977; Ward, 1982). In a typical experiment, a hierarchical form (e.g., a large *S* or *H* composed of smaller *S*s or *H*s) is presented for subjects to identify at either the larger or smaller scale. The most important result is that within certain boundary conditions, responses at the smaller scale suffer more from response inconsistency at the larger scale than responses at the larger scale suffer from inconsistency at the smaller scale (see Kimchi & Palmer, 1985; Kinchla & Wolfe, 1979; Martin, 1979; Pomerantz, 1983). Navon (1977, 1981) attributed this effect to processing dominance of global features (larger forms) over local features (smaller forms), which occurs because visual processing resources are allocated to global features before local features. There are problems with Navon's terminology and interpretation, however. Navon never established that the larger and smaller forms are in fact perceptual *features*; the actual features used in this situation are not known. Therefore the more conservative terminology of forms at different size scales is used here (see Kimchi & Palmer, 1985). Furthermore, Navon's interpretation in terms of feature processing now has much less support than alternative explanations in terms of attentional priority (e.g., Boer & Keuss, 1982; Miller, 1981; Paquet & Merikle, 1988; Ward, 1982). In these alternative explanations, larger forms are assumed to be a higher priority for attentional or decisional processing, perhaps because of a greater ecological importance or conspicuity of larger forms (see Miller, 1981; Ward, 1983). Early visual processing is not affected by size, however. Thus, large and small letters may activate letter codes at the same rate, but this information becomes available to attention or decision processes sooner for large forms than for small forms.

Decrements due to size mixing in Rudnicky and Kolers's (1984) reading experiments might occur because the availability of information about small letters in mixed strings is delayed. However, because reading time is a global measure of performance, differences between large and small letters within mixed strings would not have been detected in their experiments. In the present experiments, performance was measured for individual large and small letters in mixed-size and consistent-size strings. Given previous findings of an advantage for larger forms described earlier, a *size-dominance* effect is expected: The perceptibility of smaller letters ought to be reduced by the presence of larger letters. However, this ought to occur only for small letters in strings containing both large and small letters; with pure-size strings, performance for small letters ought to be closer to that for large letters.

## Time Course of Processing

To learn about the time course of the aforementioned effects, a backward masking task was used, and processing time was varied. Explanations of size-dominance effects in terms of resource allocation to large and small features predict differences early in the time course of processing (see Navon, 1981), whereas explanations in terms of attentional priority predict differences later in processing (see the following). An additional issue involving processing time concerns predictions about the processing of relations from feature integration theory (e.g., Treisman & Schmidt, 1982; Treisman & Souther, 1985). Treisman and Souther proposed that information about the presence or absence of elemental features is registered early in the time course of processing, whereas relations between elements are established in a later, attention-demanding process. In contrast, the present emphasis on detecting relations implies that relational information may be extracted directly from a familiar pattern, together with feature presence or absence. These ideas are examined in Experiments 2 and 3.

## Experiment 1

The main purpose of this experiment was to assess the effects of abnormality and size mixing on recognition. There were two groups of subjects. Each group received two *normal* blocks of trials, one with the large normal font and one with the small normal font. Each group also received two *abnormal* blocks. For the *abnormal-mixed* group, the sizes of the abnormal letters were mixed. For the *abnormal-pure* group, the abnormal letters were of consistent size within each abnormal block. Within each block for each group, the target set always consisted of six items. In addition, the aforementioned factors were crossed with two levels of processing time (stimulus onset asynchrony [SOA]) to provide some information about the time course of processing.

### *Method*

#### *Stimuli and Design*

The target sets were drawn from the normal and abnormal sans serif letters shown in Figure 1. The *small* (and normal) font was created first (Row 2). In that font, large letters (those with ascenders or descenders) were 0.65° of visual angle in height at the viewing distance used. The *large* (and normal) font was then created by magnifying the small font by a factor of 2 (Row 1). From these two fonts, two abnormal fonts were created: one by combining the middle regions of the large letters with the tops and bottoms of the small letters (the *large–small* font, Row 3) and the other in the opposite manner (the *small–large* font, Row 4). In this experiment, only six letters from the fonts (*b, d, f, g, h,* and *j*) were used.

The size relations in these fonts were guided by a normative study of fonts. Ten sans serif font families were selected from a collection of text fonts (Digital Typeface Library, 1985). A 20- or 21-point font was selected from each family and projected on a wall. Measurements were then made of the $x$ height, the height of ascenders above the $x$ height, and the distance of descenders below the baseline (bottom of $x$). The median ascender ratio (ascender height/$x$ height) was .38 ($M$ = .42, $SD$ = .127, range .30–.51), and the median descender ratio (descender height/$x$ height) was .40 ($M$ = .40, $SD$ = .072, range = .30–.51). For the normal fonts used here, these ratios were both .33; for the large–small font they were both .17; for the small–large font they were both .67. The norms were approximated as closely as possible given display limitations (e.g., ascenders on small letters were only 2 pixels in height).

There were two groups of subjects. For each group, there were two normal blocks, one with each of the normal fonts, and two abnormal blocks. For subjects in the abnormal-pure group, the abnormal large–small font and the small–large font were each used in one block. Therefore, each target string contained letters of only one size and was "pure." For subjects in the abnormal-mixed group, there were also two abnormal blocks, but each had three large–small letters and three small–large letters. Because each target string had four different letters chosen without replacement from the target set, it was mixed in size. Letters within target strings were always aligned along their baselines.

The order of the four blocks was counterbalanced in a Latin square design. Within each block, there was an equal number of trials at each of the two SOAs (78 and 108 ms) that were used.

#### *Procedure and Apparatus*

Subjects were tested individually in sessions lasting approximately 50 min. Each block consisted of 16 practice trials followed by 48 test trials. The first block for a subject (which varied with the order of the blocks) was preceded by an additional 16 practice trials in that condition. The experiment was controlled by an Apple IIGS microcomputer. Stimuli were displayed on an 11 in. (27.9 cm) Apple monitor, in white on black dot matrix letters. At the start of the experiment, the subjects were seated in front of the computer, with the backs of their heads resting comfortably against the wall of the sound-attenuated booth. The subjects were instructed to keep their heads against the wall so that viewing distance would remain constant, and covert checks by the experimenter indicated that every subject continued to follow this instruction.

For each trial, the computer randomly selected four target letters without replacement from the relevant target set. At the start of each trial, the mask appeared on the screen. A single noisy, patterned mask was used, constructed by repeated overlaying letter parts of various types and sizes. When the subject was ready, he or she pressed a "ready" key on the keyboard, and the mask was immediately replaced by the four target letters. Stimulus presentation was accomplished by switching between screens of the computer's memory and occurred within 17 ms. After the SOA elapsed, the target display was replaced by the mask. The mask was replaced 1 s later with four columns of two letters each. Each column contained the target from the corresponding position of the target string and a foil, randomly selected from the five remaining items in the target set. (Note that in the abnormal-mixed condition, this meant that the foil was often of a different size from the target.) Position within the column (top or bottom) was randomly determined. Each column was probed in turn, from left to right. The subject responded by pressing either an "upper" key (for the upper letter) or a "lower" key on the keypad. Following the last letter, the number correct and the number wrong for that trial were indicated by the computer in terms of high and low beeps. During the forced-choice probe, only question marks and *x*s were used; aside from these characters and the stimuli, no other characters appeared during the experiment.

### Subjects

Fifty-one students from introductory psychology courses at the University of South Florida participated. They received extra course credit for their participation. The data for 3 subjects were discarded because their overall level of accuracy was less than a minimal criterion (65%), leaving 24 subjects in each abnormality group.

## Results

Subjects' proportions correct were submitted to analyses of variance (ANOVAs), with variables of abnormality group (abnormal-pure vs. mixed), abnormality, SOA, and font size. For the font-size variable, the larger large-small font (large body, small ascenders and descenders) was treated as large, whereas the smaller small-large font was treated as small. For the abnormal-mixed group, each trial in the abnormal blocks involved both large and small target letters. The data were separated by target size and then analyzed in the same way as the data for the abnormal-pure group.

### Abnormality

Relative to the normal conditions, performance was lower overall in the abnormal conditions, $F(1, 46) = 12.85$, $p < .001$. This is consistent with the hypothesis that fairly precise relational information is important in letter recognition. The abnormality decrement was about the same magnitude for the two abnormality groups, $F(1, 46) < 1$. These data are shown in Table 1.

### Letter-Font Size

With regard to size effects, the main prediction was that the relative perceptibility of small items would be reduced when they are mixed with larger items in the abnormal-mixed condition. Evidence of such a size-dominance effect is provided by interactions involving font size. There was no main effect of font size, $F(1, 46) < 1$, but there was an interaction of font size and abnormality group, $F(1, 46) = 5.26$, $p < .05$, and a Font Size × Abnormality × Abnormality Group interaction, $F(1, 46) = 5.54$, $p < .05$. The three-way interaction is shown in Figure 2. The source of these interactions is at least in part a disadvantage for the small abnormal letters (small-large font) that occurs only when they are mixed with larger letters, that is, only for the abnormal-mixed group. Performance for those same letters in the pure blocks of the abnormal-pure group was higher than for the larger large-small font. This decrement for small letters in the mixed group is an example of size dominance for larger forms over smaller ones.

Table 1
*Mean Percentage of Correct Responses in Each Condition of Experiment 1*

| Condition | Abnormality group: Pure | Mixed |
|---|---|---|
| Normal | 79.8 | 82.3 |
| Abnormal | 77.5 | 79.8 |
| Difference | 2.3 | 2.5 |

These interactions also suggest that the abnormality effect depended on both font size and abnormality group. Within each abnormality group, performance for abnormal letters was compared with that for normal letters of the same size. In the abnormal-pure group, performance for large normal letters was higher than for the large-small abnormal letters, $F(1, 23) = 6.35$, $p < .05$, but performance for small normal letters was not different from that for the small-large abnormal letters ($F < 1$). In contrast, in the abnormal-mixed group, performance for large normal letters was not different from that for the large-small abnormal letters, $F(1, 23) = 1.01$, $p > .20$, but performance for small normal letters was higher than for the small-large abnormal letters, $F(1, 23) = 9.36$, $p < .01$.

### Additional Results

Processing time (SOA) had a main effect, $F(1, 46) = 15.84$, $p < .001$. Also of interest was a marginal Group × Abnormality × SOA interaction, $F(1, 46) = 3.13$, $.10 > p > .05$. This is shown in Figure 3. As can be seen, the rate of processing was similar for normal and abnormal letters when the abnormal letters were in pure strings ($F < 1$ for the Normality × SOA interaction in the pure group). The rates differed, however, when the abnormal letters were mixed in size, $F(1, 23) = 4.59$, $p < .05$, for the mixed group; the rate of processing was slowed by abnormality.

Identification accuracy varied with the position of items within strings, $F(3, 138) = 172.16$, $p < .001$. Accuracy was highest for the leftmost position and decreased with rightness, as was expected on the basis of previous research (e.g., Sanocki, 1988; Townsend, 1981). The effect can be attributed to the distribution of visual processing capacity across the stimulus string (Townsend, 1981). There was also a small Position × Size interaction, $F(3, 138) = 2.67$, $p < .05$. The relevant data are reported in Table 2. Further information regarding interactions with size and position effects are provided by the subsequent experiments.

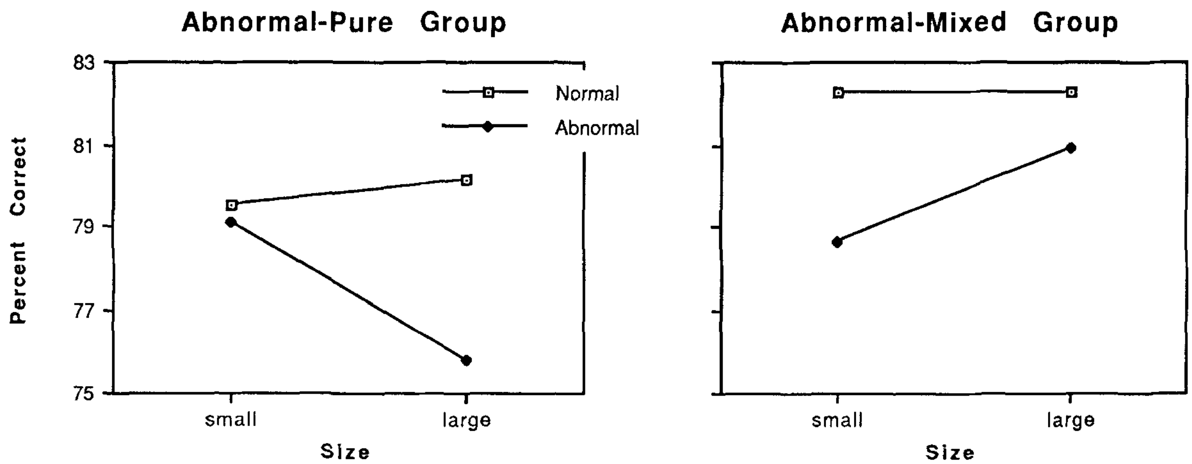


*Figure 2.* Percentage of correct responses as a function of letter-font size in the two mixing groups of Experiment 1.

## *Discussion*

There were two major findings in Experiment 1. First, the overall perceptibility of letters is reduced when they contain abnormal intrapattern relations. This effect can be attributed to the relations between elements rather than the elements themselves because the same elements were used in normal and abnormal conditions. This result is consistent with models in which precise relational information is represented and used, such as certain types of structural description models. However, the decrement for abnormal letters was restricted to certain conditions, and it is important to clarify the nature of these conditions. This is accomplished in the next experiment.

The second finding is a size-dominance effect; that is, there is an advantage for large abnormal letters over small abnormal letters only when the sizes were mixed within strings. When the sizes of the abnormal letters were not mixed (abnormal–pure group), the smaller ones are more perceptible. Because of this interaction, the size-dominance effect cannot be attributed to differences in baseline discriminability (cf. Pomerantz, 1983). The effect may be caused by the same process that causes the global dominance effect (e.g., Miller, 1981; Navon, 1977).

The advantage for small abnormal letters (small–large font) over large letters in the abnormal–pure group is probably related to the fact that the large ascenders and descenders of the small–large font are distinctive features within the set and therefore more important for recognition. However, the advantage is lost when the small–large font is mixed with the larger items of the large–small font in the abnormal–mixed group because of size dominance.

An additional finding is that abnormality slowed the rate of processing when sizes are mixed but not when sizes are consistent. However, because the full time course of processing was not examined in this experiment, the exact nature of

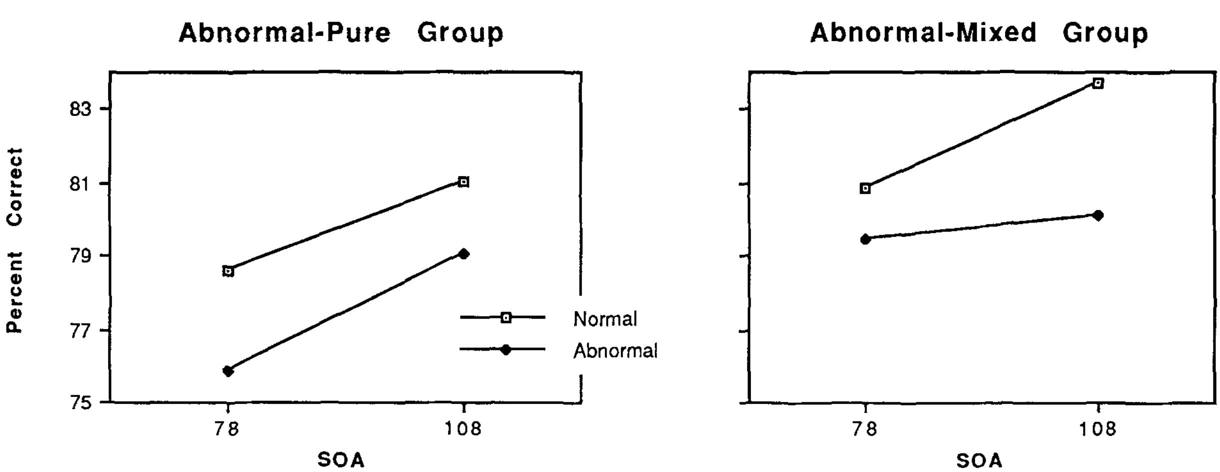


*Figure 3.* Percentage of correct responses as a function of processing time (SOA) in the two mixing groups of Experiment 1.

Table 2
*Percentage of Correct Responses for Each Letter Position and Size in Experiment 1*

| | Position | | | |
|---|---|---|---|---|
| Size | First | Second | Third | Fourth |
| Large | 93.2 | 87.1 | 72.0 | 66.7 |
| Small | 93.2 | 85.5 | 72.5 | 68.2 |

the time-course difference is not clear. The issue is examined further below.

## Experiment 2

Experiment 2 had several major purposes. First, it was designed to provide more information about abnormality and size-mixing effects and about their time course. To this end, five different SOAs were used, and size mixing was manipulated as a within-subject variable. The abnormal blocks now included two types of stimulus strings: pure-size strings of abnormal letters and mixed-size strings of abnormal letters. This provided a direct comparison of abnormal–pure and abnormal–mixed conditions and a strong test of the possibility that the time course of processing is affected by mixing size within strings.

The time course of size-dominance effects with mixed strings has implications with regard to the source of the effects. In particular, if visual processing resources are allocated to larger forms or features before smaller ones (Navon, 1977, 1981), then the advantage for larger items ought to be evident early in processing because only these items would initially receive a sufficient resource allocation. The small items may catch up later in processing, after accuracy has asymptoted for large items, because resources would be released for the small items (see Navon, 1981). In contrast, large forms could be a higher priority than small forms for postperceptual attentional or decisional processes (e.g., Miller, 1981; Ward, 1983). In the present case, later processes may encode letter identities into a mask-immune form such as a name code (e.g., Estes, 1978). If priority for later processing is the cause of size-dominance effects, then competition (and thus the decrement for smaller forms) ought to be greatest later in processing, when it is more likely that codes for both larger forms have been highly activated and are competing with the smaller forms for encoding.

An additional manipulation was introduced in Experiment 2 to provide further information about the microgenesis of the percept in the various conditions. The nature of the forced choices was manipulated to provide information about the availability of certain types of information at specific points in processing time. Two types of target–distractor pairs were embedded within each condition: featural pairs (e.g., *hn*), which differed by the presence or absence of an elemental feature (e.g., *ascender*), and relational pairs (e.g., *bd*), which had the same elements but in a different relationship (e.g., *side of ascender* and *body*). Consistent with the idea that relational features involve combined values on feature dimensions for two elemental features, correct discriminations between relational pairs required information about the (relative) location of two elements. For each type of pair, one member of the pair was used in the target string on a given trial and the other was used as its distractor. If there are differences in the availability of information about elemental features or about feature relations during processing, then there ought to be differences in the accuracy with which these types of discriminations are made.

This manipulation was motivated by feature integration theory (Treisman & Schmidt, 1982; Treisman & Souther, 1985). In this theory, it is assumed that the presence or absence of elemental features is first registered on separate feature maps. At this stage, however, the location of features is not resolved, and neighboring features have not been conjoined. Information about location and about relations between elemental features should not become available until after a subsequent, attention-based process termed *feature integration.* On the basis of this idea, one might expect that at some point early in processing there would be information available about the presence or absence of features but not about relations between features. At that time, there ought to be an advantage for featural pairs over relational pairs.[2,3]

The strong version of the relational feature hypothesis is that both elemental and relational features are extracted directly from the stimulus and serve as integral parts of every letter's representation. Therefore, no advantages for featural over relational discriminations are predicted for normal conditions. Effects of abnormality are more difficult to predict in the alternative models, but in general, abnormality ought to hurt both types of discriminations.

---

[2] Further assumptions about the forced-choice process are explicated here. The aforementioned predictions pertain to when subjects make a response from less-than-complete stimulus information. In one case, subjects may use partial information (e.g., information about features) in making forced choices. In this case, feature integration theory implies that subjects are more likely to have partial information about feature presence or absence than about relations between features. In a second case, subjects might use partial information before the forced-choice process. That is, they might use partial information during the stimulus display to arrive at an identification, even though it may be erroneous. Feature integration predicts that early in processing, information about each of the features ought to be available, but information about their relationship ought to be lacking. Therefore, the erroneous identifications will often be recombinations of the target letter's elements and ought to match the distractor of a relational pair more often than the distractor of a featural pair.

[3] One other issue concerns the relative ease of different discrimination types. Obviously, one type of discrimination could be made easier (e.g., by increasing physical differences), and this might influence the time course of processing. Note, however, that feature integration theory is based on a fundamental distinction on the basis of when information about feature presence or absence and relations is processed; specifically, at some point in time, information about presence or absence is available, but no information about relations is available. Therefore, as long as feature presence or absence is discriminable, different time courses will be predicted by feature integration theory.

## Method

### Stimuli and Design

The same fonts as in Experiment 1 were used, but they were increased to 12 letters each. The 12 letters are shown in Figure 1. There were two types of blocks: normal blocks with the small or large normal font and abnormal blocks in which all 24 abnormal letters were used as the target set. The abnormal blocks had two types of trials: pure strings of the small–large or large–small abnormal font and mixed-size strings with two letters from each abnormal font. Given the purposes of this experiment, and given the results of Experiment 1, it was appropriate to have more target items and more string types in the abnormal blocks than in the normal blocks; comparisons of performance for normal and abnormal letters with these factors equated were obtained in Experiment 1. In each session of the present experiment, a subject received the two normal blocks (one with each size) and two logically identical abnormal blocks. Order was counterbalanced across subjects and the two sessions.

Two pairs of letters were used for featural discriminations (*hn* and *gq*). As noted previously, the *h* and *n* differ by the presence or absence of an ascender. The *g* and *q* differ by the presence or absence of a horizontal element. The relational pairs (*bd* and *tf*) differ by the relative positions of the same elements.[4] Several steps were taken to verify that feature presence or absence was discriminable in the featural pairs. First, elements from the *hn* and *bd* pairs were presented to a separate group of subjects under the same conditions as the experiment. The presence–absence discrimination of the *hn* pair was tested in two ways: with a short line and no line (corresponding to the ascender) and with a long line and a short line (corresponding to the entire vertical stroke). The relational discrimination of the *bd* pair was also tested in a third condition with a long line that varied in horizontal position. Sizes and positions of the elements corresponded to the appropriate letter, presented between the second and third letter position. Stimuli were presented individually at the three intermediate SOAs. Discrimination was near perfect for all three of the discriminations. A second step was that in analyzing Experiment 2, a separate analysis was conducted for featural and relational pairs from the small–large font in the abnormal–pure condition. These letters had relatively large ascenders and descenders and thus larger features. For example, the ratio of the lengths of the vertical strokes of *n* and *h* was 6:10. Treisman and Gormican (1988) showed that popout effects indicative of a preattentive feature can be obtained with somewhat smaller differences (5:8 ratio; Experiment 1, easy condition). Finally, note that the horizontal element that distinguishes *g* from *q* ought to be discriminable in all cases because it differs from the other elements in orientation, which is a preattentive feature (e.g., see Treisman & Gormican, 1988).

On each trial in each condition, stimuli were selected randomly within the same constraints. One target item was chosen from a featural pair, one was chosen from a relational pair, and two were chosen without replacement from the remaining letters (i.e., from the unused featural pair and relational pair and the other four letters). For the forced choices, the foils for the one featural target and the one relational target were the other members of the pair; for the other two items, the foils were chosen from the remaining unused letters. No letters were repeated within trials (as targets or distractors), and the frequency of featural and relational items was equated. In the abnormal blocks, the foils were chosen to be the same size as their corresponding targets. Thus, font-size information would not aid the forced choices.

Within each block the five SOAs were used equally often and were randomly assigned to trials. The SOAs were 17, 51, 85, 119, and 153 ms. In the abnormal block, SOA was crossed with the four size types of trials: (a) all targets large, (b) all targets small, (c) featural and relational targets large and others small, and (d) featural and relational targets small and others large. Size types were randomly assigned to trials.

### Procedure, Apparatus, and Subjects

Subjects participated individually in two sessions lasting approximately 50 min each. A different order for the four blocks was used in each session. Each block consisted of 10 practice trials followed by 60 test trials; the first block of a session was preceded by an additional 20 trials of practice. In other regards, the apparatus and procedure were the same as in Experiment 1. Sixteen subjects from the same population as Experiment 1 participated for extra course credit.

## Results

Overall performance for individual subjects averaged between 64% and 79%. The 65% minimum performance criterion was not used in the present experiment because some short SOAs were used, resulting in lower overall accuracy levels.

### Abnormality and Mixing

The most general questions concern differences between the three main conditions (normal, abnormal–pure, and abnormal–mixed). Condition had a main effect, $F(2, 30) = 19.81$, $p < .001$, and interacted with SOA, $F(8, 120) = 2.68$, $p < .01$. These data are shown as the points in Figure 4.

To describe the effects more precisely, each subject's proportions of correct responses were fit to an exponential approach to asymptote (Wickelgren, 1977). Because of the .50 floor on performance, the function was $p = .50 + (a - .50)(1 - e^{-rt})$, where $a$ denotes the asymptote, $r$ denotes the rate, and $t$ denotes the amount of time since the delay (Wickelgren, 1977). Asymptote values were limited to the range .7 to 1.0, and rate values were limited to the range .01 to .09; the delay was set at 34 ms, which provided the best fit for each condition. Within these constraints, parameter values were selected to minimize the sum of the squared deviations. Functions for the group data are shown in Figure 4. The average root mean squared deviation for individual subjects was

---

[4] If features are very precise, then the *g* differs by having a diagonal segment and a horizontal tail; the *q* has a slightly longer vertical descender (see Figure 1). These are multiple presence or absence differences and do not qualify the manipulation. If features are very precise, however, then the large versions of *t* and *f* also differ by the direction of the diagonals that connect the horizontal and vertical segments (see Figure 1). This difference may involve the presence or absence of different diagonal features. Therefore, the relational nature of this pair is suspect, and the data will be examined by individual letter pair. A suspect pair was included in the experiment only because there are very few (if any) other relational discriminations in the lowercase alphabet (aside from *pq*, which was not included because of its similarity to *bd*).

0.034.[5] Differences among the rate parameters in the three conditions were marginally reliable, $F(2, 30) = 3.12$, $p = .06$. Planned comparisons indicated that as predicted, the rate was slower in the abnormal–mixed condition (.039) than in the other two conditions, $F(1, 15) = 10.65$, $p < .01$. The rates in the normal (.052) and abnormal–pure (.054) conditions did not differ ($F < 1$). This indicates that some factor associated with mixing the sizes of adjacent abnormal letters slows the rate of recognition.

The asymptote parameters differed between conditions, $F(2, 30) = 6.56$, $p < .01$. Planned comparisons indicated that the asymptote was higher in the normal condition (.85) than in the other two conditions, $F(1, 15) = 15.43$, $p < .01$, but did not differ between the abnormal–pure (.82) and abnormal–mixed (.81) conditions ($F < 1$). Thus, abnormality reduces the asymptote to which performance is driven. The failure of the asymptotes to approach unity was due mainly to low asymptotes at rightward string positions, a finding that is consistent with previous research (e.g., Sanocki, 1988; Townsend, 1981). The asymptote levels are considered together with size-dominance effects in the following discussion.

Because more analytic analyses reduced the numbers of observations in each condition, further statistical analyses were limited to ANOVAs. In some cases, group means were fit as above for interpretive purposes.

## *Letter–Font Size*

The data for large and small letters qualify the asymptote effects reported above and are relevant to the issue of size-dominance effects. The main effect of size was marginally reliable, $F(1, 15) = 4.27$, $.10 > p > .05$. More important, size interacted with condition, $F(2, 30) = 24.40$, $p < .001$, and with SOA, $F(4, 60) = 2.61$, $p < .01$.

The data are shown in Figure 5 (points) together with functions fit to the group data. Asymptote and rate parameters are also given in the figure and are useful for comparing conditions. These data qualify the finding that asymptotes were lower in the abnormal–pure condition. The data for that condition are shown in the middle panel. As can be seen, there is a marked difference between large and small letters.

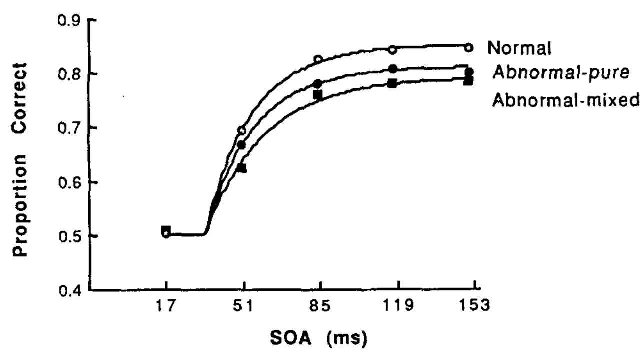


*Figure 4.* Proportion of correct responses as a function of processing time (SOA) for the three main conditions of Experiment 2. (Data are denoted by points, and best fitting functions are denoted by lines.)

Relative to normal letters (Figure 5, top panel), the asymptote is lower for large abnormal letters but not small ones. Therefore, the lower asymptote obtained above for the abnormal–pure condition is due entirely to effects on large letters (large–small font). Reasons for this are given in the *Discussion* section. In contrast to the abnormal–pure condition, asymptotes are low in relation to normal conditions for both large and small abnormal letters in the abnormal–mixed condition (Figure 5, bottom panel). In addition, rates are reduced in both cases. Thus, the asymptote and rate reductions in the abnormal–mixed condition hold for both large and small letters.

There is also evidence of a size-dominance effect. For pure strings in the abnormal–pure condition (Figure 5, middle panel), there is an advantage for small abnormal letters over large ones, $F(1, 15) = 26.76$, $p < .01$. In contrast, for mixed strings in the abnormal–mixed condition (Figure 5, bottom panel), performance is reduced for the small letters (relative to the abnormal–pure condition), and the advantage over large letters is eliminated, $F(1, 15) = 1.43$, $p > .20$. Thus, performance for smaller items is reduced by the presence of larger ones. As can be seen by examining rate and asymptote parameters, size dominance reduced both rate and asymptote parameters for small letters. This result could be consistent with explanations of the size-dominance effect in terms of resource allocation (which predict early effects such as rate effects) or attentional priority (which predict later effects such as asymptote effects). Less ambiguous evidence was obtained in the next experiment.

## *Featural and Relational Discriminations*

*Normal letters.* On each trial there was one featural discrimination, one relational discrimination, and two filler items. The present analyses concern only the two discriminations. The data for normal letters are shown in Figure 6. There was no effect of discrimination type, $F(1, 15) < 1$, and no interactions involving type approached significance. As can be seen, the functions for these two types of discriminations are similar; it appears that information necessary for a featural discrimination does not become available earlier than information necessary for a relational discrimination. This result is inconsistent with the prediction from feature integration theory but consistent with the idea that relational information is extracted directly from the stimulus.

*Discrimination type and abnormality.* Further analyses included the three main conditions. There was an overall advantage of relational over featural discriminations, $F(1, 15) = 18.97$, $p < .001$; however, type interacted with condition, $F(2, 30) = 3.43$, $p < .05$. This interaction is shown in Table 3. As noted above, for normal letters there was no difference due to discrimination type. The small advantage for relational

[5] Fits with delay varied and rate fixed were also successful and produced a pattern of effects similar to that reported above. Therefore, the present rate differences could also be viewed as differences in delay. Fits with both delay and rate varied were not appreciably better than fits with only one of these two parameters varied.

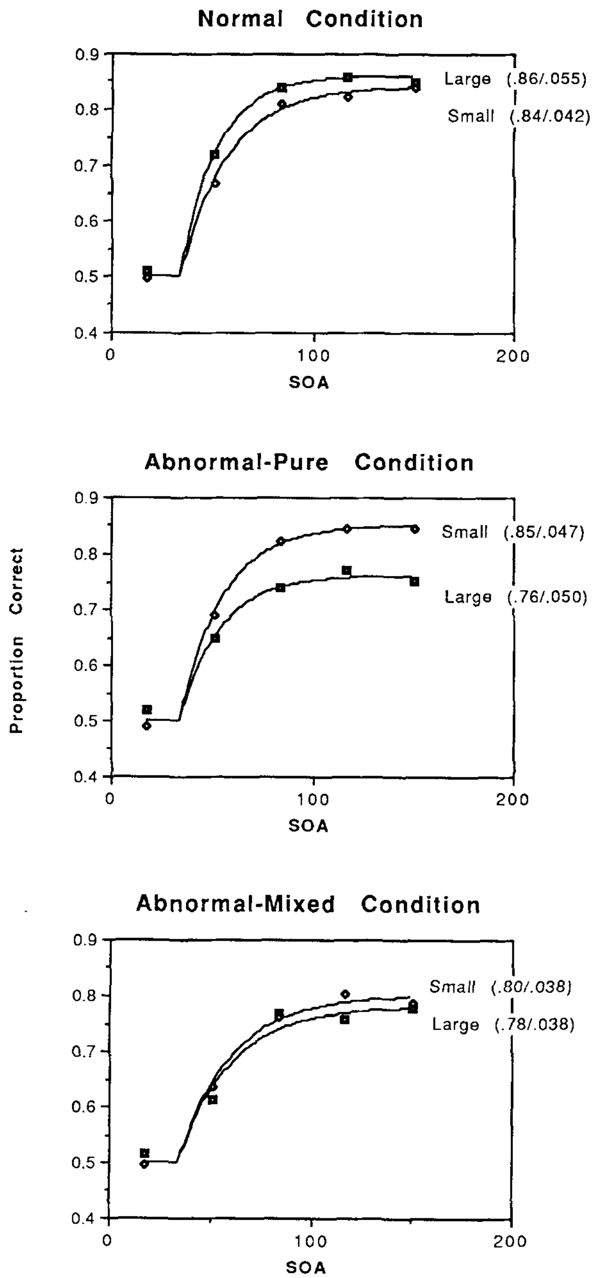


*Figure 5.* Proportion of correct responses as a function of processing time (SOA) for each size within the three main conditions of Experiment 2. (Shown are data [points], best fitting functions [lines], and asymptote and rate parameters, respectively.)

discriminations in the abnormal-pure conditions was not reliable, $F(1, 15) = 1.84$, $p > .10$, but the larger advantage in the abnormal-mixed condition was reliable, $F(1, 15) = 13.68$, $p < .01$. This implies that abnormality and mixing interfere more with the determination of feature presence or absence than with the determination of relations between features.

One further set of analyses was conducted on the data for the small-large font in the abnormal-pure condition, which had relatively large ascenders and descenders. In an analysis of all letter pairs, there was a marginal advantage for the relational pairs, $F(1, 15) = 4.33$, $.10 > p > .05$. In an analysis focusing on the *hn* and *bd* pairs, there was no difference between the featural and relational pairs, $F(1, 15) = 1.04$, $p > .20$. The lack of an advantage for featural discriminations in the latter case was of particular interest because there are data indicating that the line lengths discriminating between *h* and *n* in the small-large font are preattentively discriminable (Treisman & Gormican, 1988, Experiment 1).

## *Position and Size*

Position had a main effect, $F(3, 45) = 93.31$, $p < .001$, and it interacted with size and with condition: Size × Position interaction, $F(3, 45) = 3.24$, $p < .05$; Condition × Position interaction, $F(6, 90) = 2.28$, $p < .05$. The Size × Condition × Position interaction was marginal, $F(6, 90) = 1.92$, $.10 > p > .05$. The main effect of position is not of much interest (it may be determined by probe order), but the interactions with size are. The interactions can be seen in Figure 7. The middle panel shows position effects for small abnormal letters (and small normal letters for comparison). As can be seen, there is a reduction in performance for small items in mixed strings (abnormal-mixed condition), but at Positions 3 and 4 only. The difference between the abnormal-pure and abnormal-mixed conditions was not reliable at Positions 1 or 2 (*ps* $> .10$), but the difference was reliable at Position 3, $F(1, 15) = 12.18$, $p < .01$, and marginal at Position 4, $F(1, 15) = 4.54$, $p = .05$. This indicates that the size-dominance effect of large forms over small forms is restricted to the rightmost positions.

There was also a Position × SOA interaction, $F(12, 180) = 18.64$, $p < .001$. This interaction simply reflects the fact that there were no position effects when performance was near the floor, at the shortest SOA. Position effects at the four longest SOAs were virtually identical. These data are reported in Table 4. Position and SOA did not interact with size or condition (*ps* $< .10$).

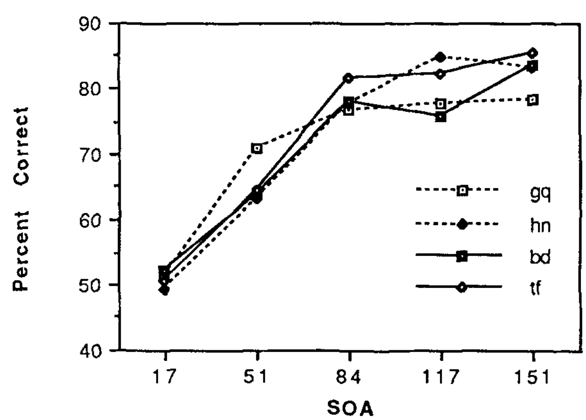


*Figure 6.* Percentage of correct responses as a function of processing time (SOA) for featural (dotted lines) and relational (solid lines) letter pairs in the normal condition of Experiment 2.

Table 3
*Percentage of Correct Responses for Featural and Relational Discriminations in Each Condition of Experiment 2*

| Type | Condition | | |
|---|---|---|---|
| | Normal | Abnormal–pure | Abnormal–mixed |
| Featural | 71.4 | 66.8 | 64.8 |
| Relational | 71.8 | 68.9 | 69.2 |

## *Discussion*

### *Abnormality*

In Experiment 2, the overall decrement obtained for abnormal letters in Experiment 1 was replicated and extended. The findings provide further support for the idea that precise relational information is important in letter recognition.

The data from the abnormal-pure string condition indicate that for pure string items, abnormality has an adverse effect on the large–small font but not the small–large font. (This result was also obtained in Experiment 1.) The decrement for the large–small font was a reduction in the asymptote to which performance is driven. One way to explain the decrement is to assume that there are detectors for relations between letter bodies and ascenders or descenders. A simple way to imagine one type of relation detector might be as a template for the upper or lower portion of a letter, including part of the body. Because the ascenders and descenders of the large–small font are relatively small, they would not activate such detectors as strongly as larger ones. In contrast, increasing ascender or descender size beyond that of normal fonts (small–large font) does not appear to aid perceptibility. It is possible that relation detectors have a limited "receptive field" (limited to the size of normal relations) and that extension of ascenders and descenders beyond the receptive field might not affect such detectors.

In the abnormal–mixed condition, performance was lower (relative to normal conditions) for both abnormal fonts. The decrement for the small–large font seems to be a size-dominance effect (see the following). For both fonts, both asymptote levels and rates were lowered. However, as noted (Footnote 5), the rate effect could also be interpreted as a difference in delay, which corresponds to when accuracy begins to rise above chance levels. A possible mechanism will be considered in the General Discussion section after additional relevant data are reported and interpreted.[6]

### *Size Dominance*

A size-dominance effect was obtained in Experiment 2 for mixed strings, although the present negative effect of larger forms on smaller forms consisted only of eliminating an advantage that occurred for small letters in pure strings. Size dominance reduced both the rate and asymptote of processing. This could be consistent with the idea that resources are allocated to large letters before small ones (Navon, 1977, 1981) or with the idea that large letters are a higher priority for postidentification processes (e.g., Miller, 1981).

The relative loss for small forms occurred only at Positions 3 and 4. These were also the positions in which performance asymptoted at levels considerably below 1, a result obtained in other experiments (Sanocki, 1988; Townsend, 1981). An interpretation of both of these findings follows from the idea that performance in this situation is limited by attentional capacity (e.g., Shibuya & Bundesen, 1988; Townsend, 1981). Perhaps because of left-to-right reading habits, subjects allocate more attention to leftward positions, and performance levels at rightward positions are thus limited by reduced capacity. Indeed, Townsend (1981) found that performance levels for rightward positions remained at about 75% throughout 100 ms of asymptotic processing time, a result that rules out interpretations in terms of encoding or scanning time. The size-dominance effect may be greater at rightward positions because of the capacity of limitations. Such a limitation could arise if capacity is allocated to large forms before small forms (Navon, 1977) or if large forms are a higher priority for postidentification processes that require attention (e.g., Miller, 1981), such as encoding items into a mask-immune form (see Estes, 1978).

An alternative interpretation of the Position × Size interaction ought to be considered because accuracy was always probed in a left-to-right order. Namely, the variation in the size-dominance effect could result from memory or response strategies determined by probe order. However, this interpretation runs into a problem. The size-dominance effect depends on a superficial property of the forms (size). It is usually assumed, however, that letters in a masking task are encoded into an abstract, mask-immune code for which size information is irrelevant. Therefore, size should not affect memory or response processes that use the mask-immune code; it should only affect identification or encoding processes that precede memory. Thus, effects involving size (e.g., size dominance) are more likely to occur at a stage preceding memory or response stages. Although changes in probe order may alter the relation between size dominance and position, this could happen because probe order affects the allocation of attention rather than because of a direct relation between size and memory or response processes.

### *Featural Versus Relational Information*

There was no evidence in the present experiments of an advantage of featural over relational discriminations. This is

[6] The finding of higher performance in the abnormal-pure condition than in the abnormal-mixed condition contrasts with Experiment 1 (in which, relative to the normal conditions, there were equal decrements for the two abnormal conditions). The difference between experiments probably stems from differences in the constraints on the forced choices. In Experiment 1, foils for the forced choices were randomly chosen from the six target items, so in the abnormal-mixed condition the choice was often between a large and small letter, and font-size information would be relevant. Font size was not relevant to forced choices in the other conditions of Experiment 1 or in the abnormal-mixed condition of Experiment 2 (in which the size of the target and foil was always equated in forced choices). Therefore, the use of font-size information in the abnormal-mixed condition of Experiment 1 may have reduced the abnormality decrement for that condition.

inconsistent with the idea from feature integration theory that feature presence or absence is registered before relations between features are formed (e.g., Treisman & Souther, 1985) but consistent with the idea that relational information is directly encoded. An additional finding was that the accuracy of featural discriminations was hurt more by abnormality and mixing than the accuracy of relational discriminations. This result was not predicted, but it suggests that there might be interesting differences in the mechanisms for encoding information about presence or absence and information about relations. These differences ought to be explored in future research.

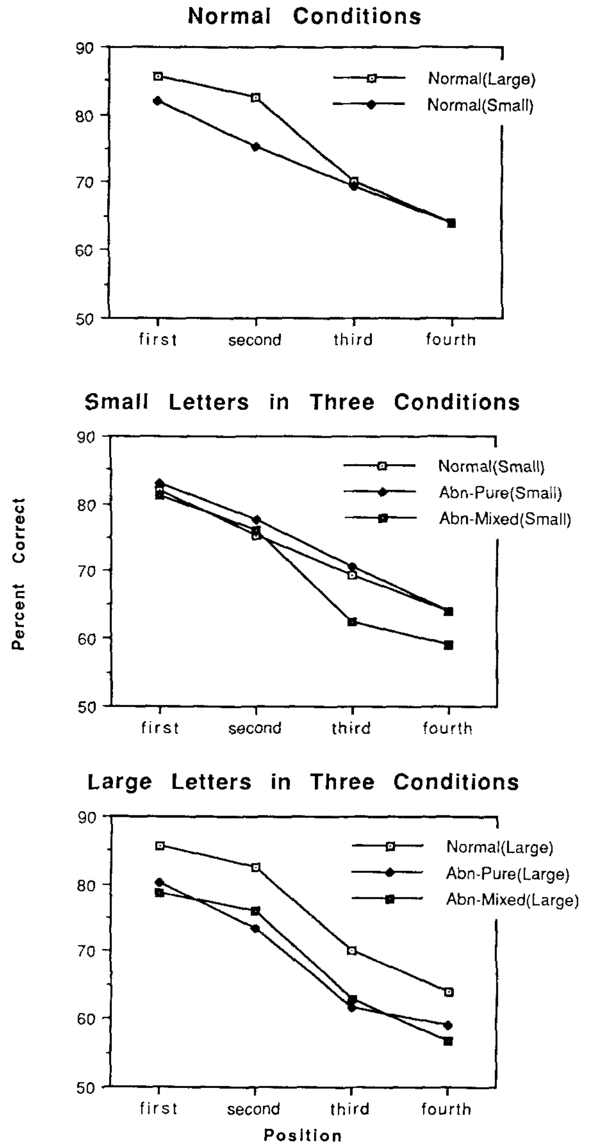


*Figure 7.* Percentage of correct responses as a function of string position in Experiment 2. (The top panel contains data for small and large letters within the normal condition, whereas the middle and bottom panels contain data for small and large letters, respectively, in each of the three main conditions.)

## Experiment 3

The previous experiments have provided strong evidence that abnormal letters are less perceptible than normal letters. The effect is observed as a reduction in asymptotic levels of performance for the large-small letters. Furthermore, in the abnormal-mixed condition, there were two effects of size mixing: The rate of processing was reduced (or processing was delayed), and smaller items in mixed strings suffered from the presence of larger items (the size-dominance effect). These two size-mixing effects occurred only with abnormal letters, however. Would these same effects also occur if normal letters were mixed in size?

In Experiment 3, there were normal blocks with large and small letters and a more heterogeneous (mixed) block, as in Experiment 2. However, in Experiment 3, all of the items in the heterogeneous block were normal letters. There again were two types of strings in the heterogeneous block (pure and mixed), but now the pure strings consisted of small or large normal letters (normal-pure condition), and the mixed strings consisted of two small and two large normal letters (normal-mixed condition). If size mixing per se caused the rate reduction and size-dominance effects in Experiment 2, then similar effects ought to be observed in Experiment 3. In contrast, if abnormality also contributes to these effects, then the effects ought to be reduced or eliminated in Experiment 3. In addition, the comparison of featural and relational discriminations was repeated in Experiment 3.

### *Method*

The method was the same as in Experiment 2, except that large and small normal letters replaced the large and small abnormal letters in the heterogeneous blocks. The three main conditions were *normal* (normal blocks), and *normal-pure* and *normal-mixed* (from the heterogeneous block). Eight new subjects from the same population as the previous experiments participated.

### *Results*

Overall performance for individual subjects averaged between 64% and 80%.

#### *Normal and Heterogeneous Conditions*

As in Experiment 2, the initial analyses concerned differences among the three main conditions (normal, normal-

Table 4
*Percentage of Correct Responses for Each Position at Each Stimulus Onset Asynchrony (SOA, in Milliseconds) in Experiment 2*

| | Position | | | |
|---|---|---|---|---|
| SOA | First | Second | Third | Fourth |
| 17 | 51.5 | 49.0 | 50.8 | 50.8 |
| 50 | 80.7 | 70.8 | 60.6 | 56.1 |
| 84 | 91.9 | 86.8 | 73.6 | 66.8 |
| 117 | 93.7 | 89.9 | 75.1 | 68.4 |
| 150 | 93.8 | 90.4 | 75.6 | 67.2 |

pure, and normal–mixed). In the overall ANOVA, the effect of condition was not reliable, $F(2, 14) = 2.40$, $p < .10$, and there was no interaction with SOA, $F(8, 56) < 1$. To describe the time-course functions more accurately, each subject's proportions of correct responses were fit to an exponential approach to asymptote, as in Experiment 2. Functions for the group data are shown in Figure 8, together with the data (points). The search space was limited to the same range of asymptote and rate parameters as before; the value for delay was set at 17 ms, which provided the best fit for each condition in the present data. The root mean squared deviation for individual subjects averaged .028.

There was no main effect of condition on the rate parameters, $F(2, 14) < 1$. Planned comparisons were conducted as in Experiment 2. There were no reliable differences in rate between the normal–mixed condition (.028) and the other two conditions or between the normal (.031) and normal–pure (.0029) conditions ($F$s $< 1$). For asymptote parameters, the main effect of condition was marginal, $F(2, 14) = 3.28$, $.10 > p > .05$. Planned comparisons indicated that there was no difference between the normal (.88) and the normal–pure and normal–mixed conditions, $F(1, 7) < 1$, but there was a difference between the normal–pure (.88) and normal–mixed (.85) conditions, $F(1, 7) = 7.88$, $p < .05$.

These results contrast with those of Experiment 2. First, there were no reliable rate differences in the present experiment, in contrast to the effect in the abnormal–mixed condition of Experiment 2. This indicates that simply mixing size does not create rate differences; pattern abnormality and mixing are both necessary. The second contrast is that a reliably lower asymptote was obtained for the normal–mixed condition. In Experiment 2, lower asymptote values were obtained, but only in conditions with abnormal letters. This latter effect is clarified below.

## Font–Letter Size

There was an overall advantage for large letters, $F(1, 7) = 18.90$, $p < .01$, but size interacted with condition, $F(2, 14) = 13.48$, $p < .001$, and with SOA, $F(4, 28) = 4.33$, $p < .01$. The data are shown in Figure 9 (points) together with functions fit to the group data and with rate and asymptote values. These data qualify the finding above that asymptotes were lower in the normal–mixed condition. As can be seen in Figure 9, in the normal–mixed condition (bottom panel) the asymptote was reduced only for the small normal letters; the asymptote for large normal letters was unaffected. This indicates that the lower asymptote reported above stems from negative size-dominance effects on small letters.

There was a strong size-dominance effect in the present data. The results for large and small letters were quite similar in the normal and normal–pure conditions (top and middle panels of Figure 9). In particular, there was no effect of size in the normal–pure condition, $F(1, 7) = 3.00$, $p > .10$. However, in the normal–mixed condition (bottom panel), performance is markedly reduced for the small letters but not for the large ones, and the difference between large and small letters is reliable, $F(1, 7) = 40.72$, $p < .01$. This is a particularly striking example of the size-dominance effect. Furthermore,

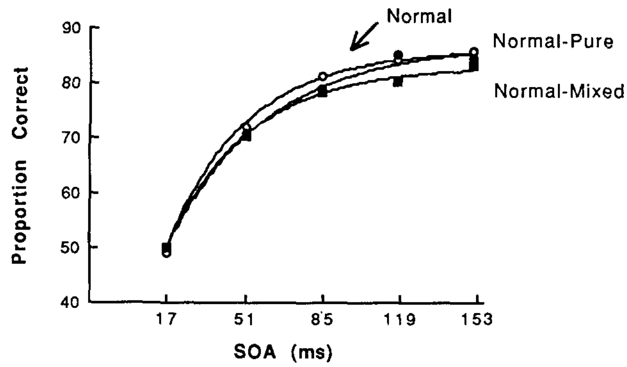


*Figure 8.* Proportion of correct responses as a function of processing time (SOA) for the three main conditions of Experiment 3. (Data are denoted by points, and best fitting functions are denoted by lines.)

note that the decrement for small letters occurs mainly at the longer SOAs. The asymptote was reduced in the mixed condition, but the rate was not. This is inconsistent with the idea that the size-dominance effect is due to resources being allocated to large items before small ones (Navon, 1981) but consistent with explanations in terms of attentional priority for larger items (e.g., Miller, 1981). Smaller items may be a lower priority for an attentional process that encodes them into mask-immune forms. The lower rate for small letters in mixed strings of Experiment 2 can be attributed to particularities of that condition (see the General Discussion section).

## Featural and Relational Discriminations

*Normal condition.* The data for featural and relational discriminations in the normal condition are shown in Figure 10. As can be seen, there is an advantage for relational discriminations. There was a main effect of type, $F(1, 7) = 6.07$, $p < .05$, and a marginal interaction of type and SOA, $F(4, 28) = 2.53$, $.10 > p > .05$. Each relational pair was at least as perceptible as each featural pair. Thus, these results, like the results of Experiment 2, provide no support for the idea from feature integration theory that information necessary for a featural discrimination becomes available earlier than information necessary for a relational discrimination.

*All three main conditions.* When all three conditions are included in the analysis, there is again an overall advantage of relational discriminations over featural discriminations, $F(1, 7) = 14.11$, $p < .001$, and the Discrimination Type × SOA interaction is reliable, $F(4, 28) = 6.05$, $p < .01$. These effects had the same form as in Figure 10. The Discrimination Type × Condition interaction obtained in Experiment 2 was not obtained in the present experiment. The relevant data are reported in Table 5. This indicates that abnormality was a necessary factor in the previous interaction.

## Position and Size

Position had a main effect, $F(3, 21) = 29.15$, $p < .001$, and interacted with size and condition: Size × Position interaction, $F(3, 21) = 4.27$, $p < .05$; Condition × Position interaction,

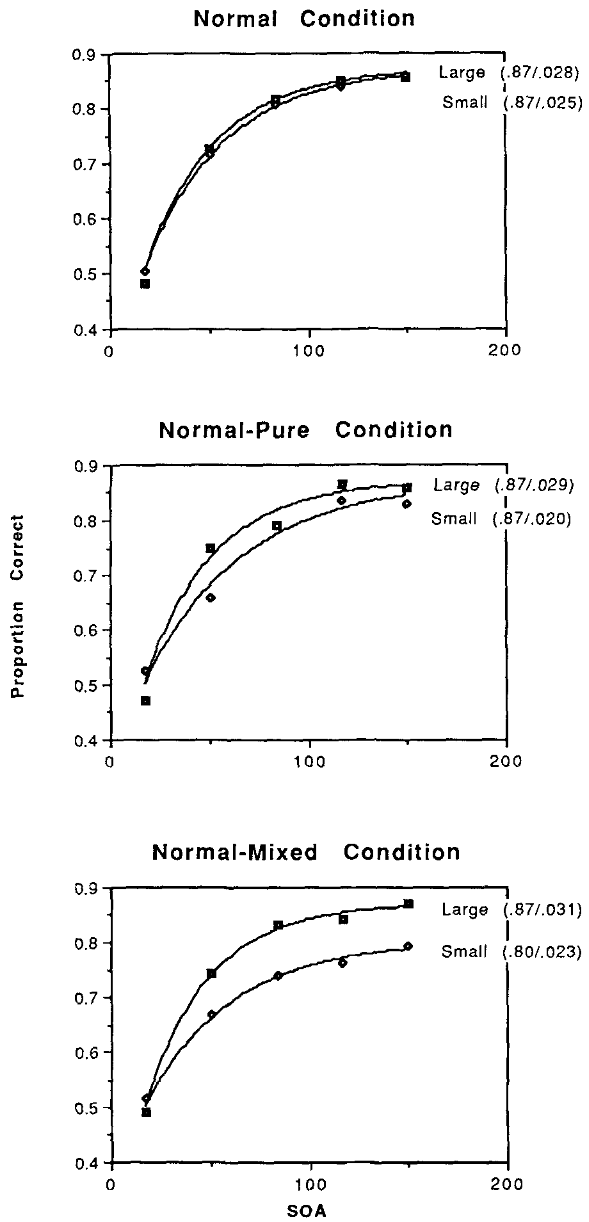


*Figure 9.* Proportion of correct responses as a function of processing time (SOA) for each size within the three main conditions of Experiment 3. (Shown are data [points], best fitting functions [lines], and asymptote and rate parameters, respectively.)

$F(6, 42) = 2.14$, $.10 > p > .05$. The interaction of these variables can be seen in Figure 11. These interactions are consistent with the pattern of results obtained in Experiment 2. The middle panel shows position effects for small letters in pure and mixed strings and, for comparison, for small letters in the normal block. There was a reduction in performance for small items in mixed strings, but at Positions 3 and 4 only. For these letters, there were no differences between the normal-pure and normal-mixed conditions at Positions 1 and 2 ($ps > .10$). The difference at Position 3 was reliable, $F(1, 7) = 11.98$, $p < .05$, but the difference at Position 4 was

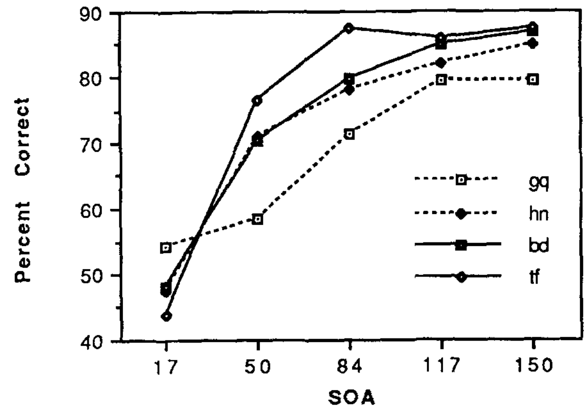


*Figure 10.* Percentage of correct responses as a function of processing time (SOA) for featural (dotted lines) and relational (solid lines) letter pairs in the normal condition of Experiment 3.

not, $F(1, 7) = 2.40$, $p > .10$. This replicates the finding in Experiment 2 that the size-dominance effect of large forms over small forms is restricted to the rightmost positions (and Position 3 in particular). The effect is independent of abnormality because it occurred for normal letters.

There was also a Position × SOA interaction, $F(12, 84) = 11.31$, $p < .001$; it had the same form as in Experiment 2 (Table 4). Interactions involving position and SOA and size or condition did not approach reliability ($ps > .20$).

## General Discussion

### *Major Findings*

#### *Intrapattern Relations*

The main finding concerning intrapattern relations was that overall, letters containing normal interelement size relations were more perceptible than letters having abnormal relations. This finding supports the claim that fairly precise relational information is used in letter recognition. Relational information may be processed by detectors that have become specialized for relations that characterize common letters. As noted below, such detectors are consistent with several additional constraints provided by the results. The first constraint is that the decrement for abnormal relations was asymmetrical, occurring for the large–small font, which had abnormally small ascenders and descenders, but not for the small–large font, which had abnormally large ascenders and descenders.

Table 5
*Percentage of Correct Responses for Featural and Relational Discriminations in Each Condition of Experiment 3*

| Type | Normal | Normal-Pure | Normal-Mixed |
|---|---|---|---|
| | Condition | | |
| Featural | 70.6 | 68.5 | 67.8 |
| Relational | 75.1 | 74.1 | 72.0 |

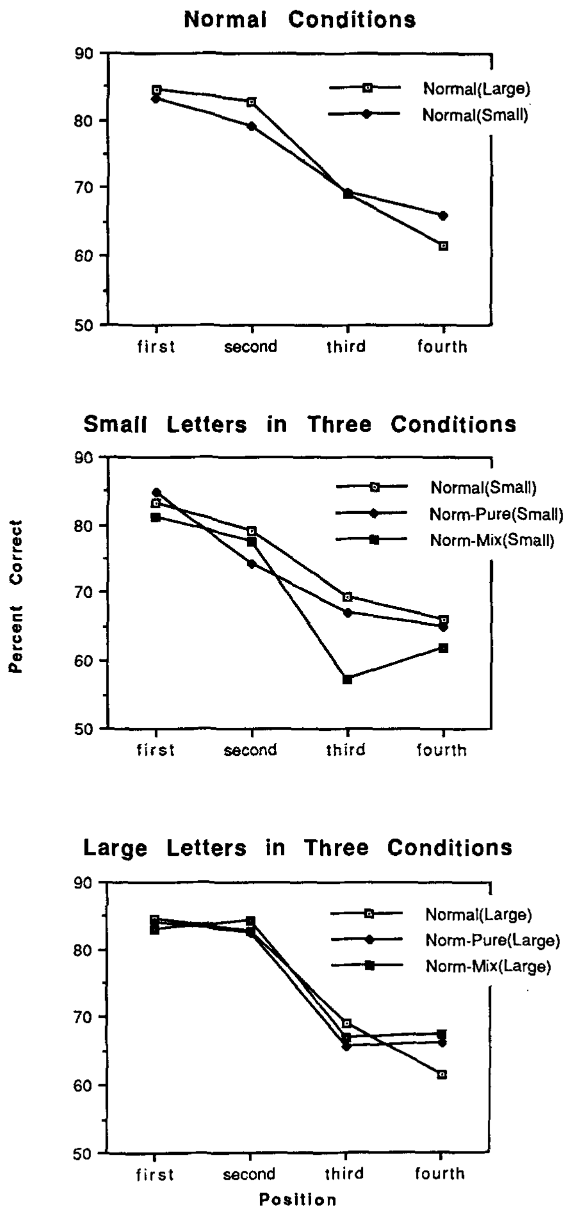


*Figure 11.* Percentage of correct responses as a function of string position in Experiment 3. (The top panel contains data for small and large letters within the normal condition, whereas the middle and bottom panels contain data for small and large letters, respectively, in each of the three main conditions.)

Second, the time-course functions in Experiment 2 indicated that the decrement for the large–small font was a reduction in the asymptote to which performance was driven. This effect can be attributed to lower activation levels of letter codes caused by increased featural mismatches for abnormal letters.

## *Interpattern Relations*

The main finding concerning interpattern relations was a size-dominance effect: The perceptibility of small letters was reduced by the presence of large letters. This effect can be explained in terms of the hypothesis that larger forms are a higher priority for postrecognition attentional or decision processes than smaller forms are (e.g., Boer & Keuss, 1982; Miller, 1981). In the present situation, larger forms may be a higher priority for a limited-capacity process that converts visual letter codes into abstract mask-immune codes. The size-dominance effect cannot be attributed to differences in baseline discriminability (cf. Pomerantz, 1983) because the effect consists of an interaction of size and condition (in pure string conditions, performance for small letters was equal to or greater than that for large letters). The results also seem inconsistent with an explanation in terms of resources being allocated to larger forms before smaller ones (e.g., Navon, 1981) because time-course functions in Experiment 3 indicated that size mixing causes lower asymptotes for small letters rather than effects early in processing. Size mixing did cause a slower rate of (or delay in) processing for abnormal letters in Experiment 2, but this result appears limited to mixed abnormal letters because it did not replicate with mixed normal letters in Experiment 3. A further result was that the size-mixing effect was restricted to rightward letter positions, and Position 3 in particular. If position effects are attentional, then the relation between size dominance and position is consistent with the attentional priority interpretation. Explanations are considered in more detail later in this section.

## *Featural Versus Relational Information*

Experiments 2 and 3 also provided information about the time course of featural discriminations, which require information about the presence or absence of elements, and relational discriminations, which require information about relations between elements. In the experiments, there was no evidence that information about elements was available earlier than information about their relationships. In fact, there were advantages for relational information in the abnormal-mixed condition of Experiment 2 and with normal letters in Experiment 3. These results are inconsistent with the idea from feature integration theory that information about elements is registered before their relations are registered (e.g., Treisman & Schmidt, 1982; Treisman & Souther, 1985) but consistent with the idea that relational information is extracted directly from the stimulus. The results may be handled within feature integration theory by adding the assumption that certain relational features are registered on their own feature maps. In fact, Treisman and Paterson (1984) provided evidence that certain relational features (which they refer to as "emergent" features) play a role in the recognition of familiar patterns. However, the addition of feature maps for relational features may compromise the nature of the theory because the number of feature maps would increase, and they would become more complex in nature. For example, relational features might be encoded as holistic configurations or shapes, but such entities would be more complex than simple lines, orientations, or colors, which define the more prototypical feature map (see Treisman & Gormican, 1988; Treisman & Schmidt, 1982; Treisman & Souther, 1985). The addition of feature maps also complicates the feature integration process, which must combine information from the separate maps.

## *Why Use Redundant Information?*

The hypothesis that subjects use fairly detailed, partially redundant relational information is consistent with the more general claim that humans use multiple sources of information in recognition (e.g., Oden, Rueckl, & Sanocki, 1991; Sanocki, 1988). By using additional information, the recognition process gains efficiency because redundant information can be pooled, and missing or inaccurate information can be compensated for. In the case of letter recognition, subjects appear able to use fairly detailed visual information about the current font to increase perceptual efficiency (Sanocki, 1988). This view contrasts with an assumption underlying much of the work on pattern recognition, which is that only a minimal set of features is used. Minimal feature-set models can explain the present results only if it is assumed that the minimal feature set contains relational features corresponding to the relations manipulated here. Although such an assumption could be made, the need to sharpen and enlarge the minimal feature set seems to reduce the appeal of the idea.

## *Sensitivity to Font Typicality*

An important implication of the present results is that the letter-recognition process seems to be fairly sensitive to the "typicality" of the letters, that is, the similarity between stimulus letters and letters encountered in the subject's prior history. This suggests an important qualification of the assertion, standard in many textbooks, that letters are recognized across a wide variety of fonts. Although this may be the case, it appears that letters of atypical fonts will not be recognized as efficiently as letters of typical fonts. A further implication of this finding is that the processes underlying the recognition of typical and atypical letters may be different and that careful exploration of such differences could be a fruitful approach to learning about the recognition process. Further exploration of the scope of typicality effects is needed.

Typicality effects also qualify the assertion that additional, partially redundant information is used to increase the efficiency of recognition. When additional information does not fit existing processing structures (e.g., small–large font), it may not be useful.

## *Differing Loci for Intra- and Interpattern Effects?*

The configurations of effects are consistent with the idea that intrapattern relations affected early processes involved in identifying individual letters, whereas interpattern relations affected later processes such as the encoding of identities into mask-immune forms. Intrapattern abnormality had very consistent effects, affecting the abnormal large–small letters in all conditions and at all letter positions. These effects were independent of other effects, such as position, which may be related to later, more attention-demanding processes. The interpattern size-dominance effects occurred for normal and abnormal letters but were more context dependent: They occurred only for small letters, only when they were mixed with large letters, and only at rightward positions, in which processing may be limited by attention. The apparent links between abnormality effects and identification processes on one hand, and between size-dominance effects and more attention-demanding postidentification processes on the other hand, would be consistent with a distinction between early, overlearned obligatory processes and later, more attention-demanding strategic processes (e.g., Logan, 1980; Posner, 1978; Shiffrin & Schneider, 1977).

## *Extracting Relational Information*

There are at least several different ways in which the relational information implicated here might be encoded. In one model outlined previously, the present results arise at the level of feature detectors. The set of feature detectors associated with a letter might include detectors for distinctive relations, for example, relations between letter bodies and ascenders or descenders. Thus, *b* might be distinguished in part by the feature *ascender above and on left side of body.* As noted earlier, a simple way to imagine such a detector might be as a template for the upper portion of the letter (or as a receptive field with off regions on each side of the on template). Abnormal letters with small ascenders or descenders (large–small font) would not activate such detectors as highly as normal letters because part of the ascender or descender would be missing. In an activation model such as McClelland and Rumelhart's (1981) that was augmented with the appropriate feature detectors, this could result in lower overall activation levels for letters that contain such features and cause lower asymptotes. In contrast, abnormally large ascenders and descenders would extend beyond the range of such detectors (e.g., beyond their receptive fields). The out-of-range portions should not affect the detectors, whereas the within-range portions should provide normal activation of the detector. This explains why performance for the small–large font was similar to performance for normal fonts.

Alternatively, the results could be explained in terms of specialized letter units that encode relational information implicitly. For example, in a second model, it is assumed that units for letters are size specific in that each letter unit receives inputs from feature units of a limited size range. Information about interpart size relations is represented implicitly by the size-specific units, and relational features are not necessary; the features could be simple, mutually exclusive but size-specific segments (e.g., McClelland & Rumelhart, 1981). In this model, an abnormal letter would activate both large and small feature units, which in turn activate letter units at different size scales. If the letter units are independent of each other, then the activity from an abnormal letter would be divided among at least two different-size letter units. In this model, the asymmetrical effects in pure string conditions can be explained if we assume that large ascenders and descenders activate distinctive features at both size scales. This assumption seems reasonable because most types of small distinctive features would be contained within the large distinctive features of the larger fonts. Thus, letters of the small–large font would activate small features for their bodies and for ascenders and descenders as well as large features for ascenders and descenders. Because a complete set of small features is activated, a small letter unit could become as highly activated as in normal conditions. In contrast, letters of the large–small font would activate large features for their bodies but small features for the ascenders and descenders. Neither large nor small letter units would receive as much activation as they receive in normal conditions, resulting in lower asymptotic levels.

This model seems capable of handling the present abnormality effects by using simple segment features and an implicit scheme for encoding relations. The model is generally consistent with the claim that fairly detailed information is used in recognition in that feature–letter connections are size specific. Note, however, that this model does not provide a solution for the problem of localizing and interrelating mutually exclusive features that was noted in the introduction. One way to solve such a problem might be to assume that relational features are detected and serve as additional inputs to the size-specific letter units.

One other alternative is that relational information is encoded implicitly in holistic template representations. Normal letters may be more perceptible than abnormal ones because they match existing templates better; however, the asymmetry in pure string conditions provides a problem for template models. Existing templates should not match either the large–small font or the small–large font. Therefore, decrements ought to occur in both cases, and the asymmetry obtained is inconsistent with the template model. In addition, evidence from similar situations is inconsistent with the idea of templates. In particular, the advantage for target sets of $n$ letters of one font over sets of $n$ letters of two fonts (e.g., Sanocki, 1988) presents difficulty for template models because the number of templates required in the two conditions is equal, and therefore there is no reason for the advantage in single-font conditions. Those results seem to require an explanation in terms of underlying similarities between components of same-font letters (e.g., Sanocki, 1987, 1989).

## *Explaining Size Dominance*

The size-dominance effects obtained have been generally consistent with the attentional priority explanation outlined in the introduction, although an alternative explanation also ought to be considered. In addition, two further aspects of the results present problems for a simple attentional priority explanation.

*Lateral masking.* A possible alternative explanation stems from the phenomenon of lateral masking (e.g., Estes, 1978; Wolford & Hollingsworth, 1974). In the present situation, *lateral masking* is assumed to refer to the reduction in the availability of featural information about a form because of the presence of other neighboring forms and the imperfect spatial resolution of the sensory system. Interior letters, which have two neighbors, are affected more than exterior letters, which have one neighbor, and larger forms have stronger negative effects on smaller forms because larger forms contain more information and therefore greater potential for interference. Size-dominance effects could be attributed to the stronger masking effects of large letters. However, a major problem for this explanation stems from the finding that size-dominance effects occurred mainly at Position 3 and to some extent at Position 4, but not at Position 2. Masking is expected to be strongest at Positions 2 and 3 and weakest at Positions 1 and 4.

Additional evidence against certain masking explanations stems from examination of size-mixing effects for small abnormal letters with ascenders and descenders. Masking could be expected to have more adverse effects on letters whose distinctive features (i.e., ascenders or descenders) were in regions that could be obscured by neighboring letters. Because letters were aligned along their baselines, the ascenders of the small abnormal letters (small-large font) were quite low in relation to the other font; that is, they barely extended above the bodies of the larger letters. Thus, a large letter could obscure the ascender of a small letter. In contrast, the descenders of small abnormal letters extended below the descenders of the larger letters. Therefore, descenders of the small letters were not obscured by large letters; if anything, they ought to be more salient because they protruded. If masking caused the mixing decrement for smaller letters, then the negative effects ought to be stronger for small abnormal letters with ascenders than for small abnormal letters with descenders.

In Experiment 1, the most relevant and direct comparison concerns performance for letters in the normal and the abnormal-mixed conditions of the abnormal-mixed group. These data are shown in Table 6. As can be seen, the decrement in the abnormal-mixed condition was slightly smaller for small letters with descenders than for small letters with ascenders. The difference is very small, however, and could account for only a fraction of the size-dominance effect. In Experiment 2, the most relevant and direct comparison is between performance for certain pairs of small abnormal letters in the abnormal-pure and abnormal-mixed conditions. In Table 6, data from a featural pair with descenders and a pair with an ascender are shown. In addition, data from a relational pair with ascenders are shown. As can be seen, the pair of letters with descenders suffered more than the other pairs in the mixed condition relative to the pure condition. This is contrary to the prediction by the lateral masking explanation.

*Attentional priority.* The major effects are consistent with an explanation in terms of attentional priority for large forms over smaller forms (e.g., Boer & Keuss, 1982; Miller, 1981). The idea is that larger forms are a higher priority for postrecognition attentional or decisional processes, and it is used in the following model. Feature information is assumed to activate letter units at the four letter positions in parallel. The mask is assumed to terminate processing, and consequently there are two main processes that must be completed for a letter to be recognized. First, enough featural information must be extracted to activate the appropriate letter unit; second, the letter must be encoded into an abstract mask-immune name code (Estes, 1978). This encoding process requires attentional resources, and there are not enough resources for all four items (see Shibuya & Bundesen, 1988; Townsend, 1981). Resources may be required to create an

Table 6
*Sizes of Decrements (in %) for Small Letters With Ascenders and Descenders in Experiments 1 and 2*

| | Letters | | | | |
|---|---|---|---|---|---|
| Experiment/Condition | gj | bdfh | gq | hn | bd |
| Experiment 1 | | | | | |
| Normal | 82.8 | 81.9 | — | — | — |
| Abnormal–mixed | 79.7 | 78.4 | — | — | — |
| Decrement | 3.1 | 3.5 | — | — | — |
| Experiment 2 | | | | | |
| Abnormal–pure string | — | — | 66.5 | 72.4 | 70.0 |
| Abnormal–mixed string | — | — | 61.2 | 69.4 | 72.9 |
| Decrement | — | — | 5.3 | 3.0 | −2.9 |

*Note.* A dash indicates that these letters were not used in the experiment.

object file for each letter than includes information about identity and location (e.g., Kahneman & Treisman, 1984). Perhaps because of reading habits, subjects allocated sufficient resources to leftward letter positions, and performance is limited only by the availability of featural information, asymptoting at close to 100% (Sanocki, 1988; Townsend, 1981; present data). In contrast, there are not enough resources for rightward items, and performance asymptotes at levels below 75% (e.g., Sanocki, 1988; Townsend, 1981; present data).

In this model, size-dominance effects arise at rightward letter positions, in which there are not enough resources to ensure encoding of activated letter units. Larger forms may warrant higher priority for resources because they are more ecologically significant (Navon, 1977), more conspicuous (Ward, 1982), or because they are larger and attention is allocated across space (therefore, items that take up more space receive more resources). In any case, the effect ought to be stronger later in processing, when performance depends more on encoding resources than on the availability of featural information. Such an expectation is consistent with the finding that size dominance resulted in lower asymptotes in Experiments 2 and 3.

However, further aspects of the results seem to require a somewhat more complicated explanation. First, note that if larger items have priority over smaller ones, then there ought to be an advantage for large items among small items relative to large items among other large items because small items would provide less competition for resources. There was no evidence of such an advantage. Therefore, it may be necessary to add a further assumption to the attentional priority model. One potentially reasonable assumption is that different-size letters require different processing channels and that switching between size channels requires additional time. Thus, the positive effects for large letters in mixed strings (i.e., those having less resource competition) would be offset by negative effects of having to switch channels. In studies of the perception of hierarchical forms, Miller (1981) and Paquet and Merikle (1988) obtained evidence consistent with the idea that large and small forms occupy different processing channels (although size differences were much greater in those studies).

The idea of priority and channel switching also provides a partial explanation of one last puzzling result. That result is the reduction in rate of (or delay in) processing for both sizes in the abnormal–mixed condition of Experiment 2. It is not clear how this result would follow from a simple attentional priority explanation; however, such a result can be at least partially explained in terms of the channel-priority model. Because of the priority for large channels, the encoding of items in small channels will sometimes be delayed until after encoding of items in large channels. On the trials in which encoding the small channels was delayed, the delay will be greatest when the large forms are recognized relatively slowly. This was the case in Experiment 2 because the larger, large–small font was the least perceptible font (relative to same-size normal letters, the rate and asymptotes were reduced in the pure string condition). Thus, there will be negative effects on the small–large letters even at short SOAs because their encoding will be delayed by the presence of less perceptible large–small letters in higher priority channels. Difficulties from switching channels could also contribute to the slower rates for larger letters in abnormal–mixed conditions.

However, channel priority probably depends on a weighted combination of several factors. When positions have sufficient resources allocated to them (i.e., leftward positions), items in those positions seem to have a high priority. The priority for leftward positions may be modified to some extent by instructions (Wolford & Hollingsworth, 1974), and size-dominance effects may vary accordingly. Salience probably affects priority. Salience could favor items at the ends of strings and explain the fact that size dominance was greater in Position 3 than 4, even though the amount of resources allocated to those positions, as indexed by performance, was about equal. Other physical qualities such as brightness might also be relevant. The property of being a target rather than a distractor is relevant (e.g., Shibuya & Bundesen, 1988). In addition, if attention switching takes time, then consistency with adjacent channels might be an additional factor. Further research is needed on the channel-priority explanation as well as on the relations among the present phenomena and global dominance and size-mixing effects in reading.

## References

Boer, L. C., & Keuss, P. J. G. (1982). Global precedence as a postperceptual effect: An analysis of speed-accuracy tradeoff functions. *Perception & Psychophysics, 31,* 358–366.

Bouma, H. (1971). Visual recognition of isolated lower-case letters. *Vision Research, 11,* 459–474.

Digital Typeface Library. (1985). *Digital typeface library.* New York: Author.

Estes, W. K. (1978). Perceptual processing in letter recognition and reading. In E. C. Carterette & M. P. Friedman (Eds.), *Perceptual processing* (pp. 163–220). New York: Academic Press.

Kahneman, D., & Treisman, A. (1984). Changing views of attention and automaticity. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of attention* (pp. 29–61). New York: Academic Press.

Keren, G., & Baggen, S. (1981). Recognition models of alphanumeric characters. *Perception & Psychophysics, 29,* 234–246.

Kimchi, R., & Palmer, S. (1985). Separability and integrality of global and local levels of hierarchical patterns. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 673–688.

Kinchla, R. A., & Wolfe, J. M. (1979). The order of visual processing: "Top-down," "bottom-up" or "middle-out." *Perception & Psychophysics, 25,* 225–231.

Logan, G. D. (1980). Attention and automaticity in Stroop and priming tasks: Theory and data. *Cognitive Psychology, 12,* 523–553.

Martin, M. (1979). Local and global processing: The role of sparsity. *Memory & Cognition, 7,* 476–484.

Massaro, D. W., & Schmuller, J. (1975). Visual features, preperceptual storage and processing time in reading. In D. W. Massaro (Ed.), *Understanding language* (pp. 207–239). New York: Academic Press.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive model of context effects in letter perception: 1. An account of basic findings. *Psychological Review, 80,* 375–407.

Miller, J. (1981). Global precedence in attention and decision. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 1161–1174.

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

Navon, D. (1981). The forest revisited: More on global precedence. *Psychological Research, 43,* 1–32.

Oden, G. C. (1979). A fuzzy logical model of letter identification. *Journal of Experimental Psychology: Human Perception and Performance, 5,* 336–352.

Oden, G. C., Rueckl, J. G., & Sanocki, T. (1991). Making sentences make sense, or words to that effect. In G. B. Simpson (Ed.), *Understanding word and sentence* (pp. 286–303). Amsterdam: North-Holland.

Palmer, S. E. (1977). Hierarchical structure in perceptual representation. *Cognitive Psychology, 9,* 441–474.

Paquet, L., & Merikle, P. M. (1988). Global precedence in attended and nonattended objects. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 89–100.

Pinker, S. (1984). Visual cognition: An introduction. *Cognition, 18,* 1–63.

Pomerantz, J. R. (1983). Global and local precedence: Selective attention in form and motion perception. *Journal of Experimental Psychology: General, 112,* 516–540.

Posner, M. I. (1978). *Chronometric explorations of mind.* Hillsdale, NJ: Erlbaum.

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

Sanocki, T. (1987). Visual knowledge underlying letter perception: Font-specific, schematic tuning. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 267–278.

Sanocki, T. (1988). Font regularity constraints on the process of letter recognition. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 472–480.

Sanocki, T. (1989, November). *Computational model of font-change and font-consistency effects in letter recognition.* Poster presented at the meeting of the Psychonomic Society.

Shibuya, H., & Bundesen, C. (1988). Visual selection from multielement displays: Measuring and modeling effects of exposure duration. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 591–600.

Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and general theory. *Psychological Review, 84,* 127–190.

Townsend, J. T. (1981). Some characteristics of visual whole report behavior. *Acta Psychologica, 47,* 149–173.

Townsend, J. T., & Ashby, F. G. (1982). Experimental test of contemporary mathematical models of visual letter recognition. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 834–864.

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

Treisman, A., & Gormican, S. (1988). Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review, 95,* 16–48.

Treisman, A., & Paterson, R. (1984). Emergent features, attention, and object perception. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 12–31.

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

Treisman, A., & Souther, J. (1985). Search asymmetry: A diagnostic for preattentive processing of separable features. *Journal of Experimental Psychology: General, 114,* 285–310.

Ward, L. M. (1982). Determinants of attention to local and global features of visual forms. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 562–581.

Ward, L. M. (1983). On processing dominance: comment on Pomerantz (1983). *Journal of Experimental Psychology: General, 112,* 541–546.

Wickelgren, W. (1977). Speed-accuracy tradeoff and information processing dynamics. *Acta Psychologica, 41,* 67–85.

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

Received March 5, 1990
Revision received January 3, 1991
Accepted January 25, 1991 ■