Cross-dimensional interaction and texture segregation

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How do different dimensions (e.g., color and form) interact when the visual system locates boundaries in surfaces? Seven experiments are reported in which subjects located a target "singleton" element that was unique in a given dimension. Minimal interference occurred when another dimension, known to be irrelevant, was varied randomly, even if the specific identity of the target feature was unknown (Experiments 1-4). These results argue against the hypothesis of a single difference-detection process that operates on multidimensional representations. However, performance was also little affected by whether the subjects knew in advance which dimension contained the singleton (Experiment 5), so an attentional set to suppress the irrelevant dimension was not implicated. On the other hand, singletons in the (prespecified) irrelevant dimension did produce major interference when the target was unspecified (Experiments 6 and 7), which indicates that texture boundaries of similar types cannot be accessed completely independently for separable dimensions. Together, the results suggest that boundaries may be registered by detectors that respond to specific types and locations of boundaries specified by variation within a particular dimension; selection by boundary type is effective, but selection or suppression by dimension is relatively ineffective. Parallels with some recent neurophysiological findings are noted.

One of the major tasks confronting the visual system is the discrimination of different surfaces in the visual scene. An important source of information in this process is texture, that is, the repetition of similar elements on any particular surface. A number of studies have attempted to uncover what sort of differences between textural elements must be present in order for rapid and easy texture segregation to occur (Beck, 1982; Bergen & Julesz, 1983; Treisman & Gelade, 1980), and some consensus has been reached about the nature of such differences. It appears that segregation occurs whenever different regions differ in the density of a certain critical set of basic visual features, such as brightness, color, or line endings (terminators).

There is, however, much less agreement on the nature of the *processes* that segregate regions by texture and the way in which the output of these processes is made available to higher cognitive systems. Some recent data suggest that characterizations of these processes as operating in an all-or-none fashion are inaccurate (Enns, 1986). Initial attempts have recently been undertaken to formulate concrete models of the processes underlying segregation (e.g., Caelli, 1985); however, these models draw on empirical evidence only quite loosely.

In attempting to understand the processes responsible for texture segregation, one of the most fundamental questions would seem to be how differences and similarities in different dimensions are combined and accessed in the detection of object boundaries. Oddly, this issue has received little attention. Texture segregation clearly relies on the detection of differences between adjoining regions, so in some sense elements must be compared with neighboring elements. The boundaries between objects in a scene may be indicated by differences in one dimension, or, very often, by correlated differences in more than one dimension. Less often, there may be conflicts between groupings suggested in each dimension.

How is this multidimensional information processed as the human visual system detects surface boundaries? When elements differ along more than one dimension, one might ask whether the comparison operations are performed on a multidimensional representation of the elements, thus resulting in a single segregation of the field based on differences in all dimensions. More concretely, consider a display composed of a group of red Os adjacent to a group of blue Xs. The comparison operations can be said to be multidimensional if their inputs specify both the color and the form of each element, and if their output is a single representation of the visual field that records the presence of a textural border separating the two groups. Thus, the strength of this border would reflect the presence of difference along two dimensions¹ rather than just one dimension. An alternative conception would have it that comparisons are performed *separately* in each of the two dimensions, resulting in separate representations of the differences present in the display for each dimension of variation. Thus, in the case of the display

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described, there would be separate discontinuity "maps" for each dimension, one recording the border between the red and blue elements, and at least one other recording the border between the Xs and Os.

Treisman (1982) strongly advocated the latter view: that comparison operations are performed separately in each of the basic featural dimensions. This view is required by her conception of the limitations of so-called preattentive processes, of which texture segregation is seen as a prime example. According to Treisman, preattentive processes do not have access to information about the conjunction of separate features in particular locations; processes that require such information must rely on a serial attentional mechanism, which is the only mechanism that can yield reliably correct conjunctions of the features present in particular locations.

Treisman and Gelade (1980) presented some texture segregation experiments as evidence against the multidimensional comparison view. They asked whether texture segregation would readily occur when the difference could only be specified in terms of a conjunction of color and form. Thus, one region in the figure consisted of red Os and blue Vs, and the other region consisted of blue Os and red Vs. The results indicated a "complete failure of preattentive texture segregation with the conjunction displays" (p. 122).

Given that conjunctions of this kind do not seem to give rise to textural grouping, does it follow that textural grouping is not based on multidimensional comparisons of elements with their neighbors? Before accepting Treisman and Gelade's (1980) interpretation, it may be worth asking what assumptions *should* lead one to expect texture segregation to occur with such displays. Suppose that, contrary to Treisman and Gelade, texture segregation did operate on a multidimensional representation of each element. One plausible account is that texture segregation proceeds by detecting differences between adjoining elements (see Beck, 1982). It would be natural to propose, then, that a salient texture border would emerge between two regions if the average level of interneighbor difference between regions were high compared with the average level of interneighbor difference within a region. (Any model in the spirit of Caelli, 1985, would readily predict such effects, for example.) Consider then the displays of Treisman and Gelade, and assume for simplicity that color and form differences are both scaled at one unit and that multidimensional differences are computed with a city-block metric (i.e., a difference of two units for elements that differ in both form and color). In that case, the within-region differences are zero (half the time) and two (half the time), whereas the between-region differences are always exactly one. Given these fairly natural assumptions, there would be no reason to expect texture segregation to occur at the border between the two regions in Treisman and Gelade's conjunction condition.² In summary, the failure of conjunctions to induce texture segregation does not argue against the claim that the processes that generate texture segregation operate on multidimensional

representations, because a particularly simple model that does involve multidimensional element representations would also fail to generate such segregation.³

If this line of reasoning is correct, then we cannot conclude much about dimensional interaction in texture segregation simply by asking whether conjunctions mediate easy segregation, although these findings are certainly important.⁴ However, there is an obvious and seemingly rather direct experimental approach to dimensional interaction: to ask whether variation in one dimension *interferes* with segregation in another dimension. Such an approach would seem to allow strong tests of the multidimensional position, since variation in an irrelevant dimension would generate spurious difference cues and retard detection of a difference in any specified dimension. On the other hand, if differences in each dimension are computed separately and are selectively accessible, then variation in the other dimension should be harmless.

THE PRESENT APPROACH

The goal of the present paper is to characterize the multidimensional interactions that arise in a particularly simple form of boundary detection: the detection of a singleton element. We will ask when variation in an irrelevant dimension produces interference, and examine how such effects may depend on the subjects' knowledge of the identity of the singleton element and the nature of the variation in the irrelevant dimension. In addition, the effects of the subjects' knowledge of the relevant dimension will be examined to see whether a "set effect" for the specification of the relevant dimension may exist.

Two previous lines of work have been reported that bear closely on this question, and their results are, from a very superficial standpoint, apparently conflicting. We begin by reviewing these studies, and by pointing out a conjecture that suggests itself in light of these studies—one that might provide a reconciliation of the apparent conflict. This conjecture then serves as the starting point for the experiments reported here; the first four experiments refute this conjecture.

The first relevant study was performed by Beck (1982), who reported several experiments that examined cross-dimensional interaction. Most important for present purposes is a supplementary experiment (p. 299) that examined response times for subjects to count the diagonal red or blue line segments in a display of about 40 segments. The items in the background were vertical segments that were either all red or a mixture of red and blue. The results showed that performance was unaffected by heterogeneity of the color of the items. In short, random variation in an irrelevant dimension was harmless.

The other relevant work is due to Callaghan, who reported two important studies that dealt with cross-dimensional interaction. These studies yielded findings that are superficially at odds with those of Beck (1982). In her first study, Callaghan (1984) required subjects to make a speeded response indicating which quadrant of a

large matrix differed from the remainder of the matrix in the elements composing it. On some trials, the elements in the target quadrant differed from the other quadrants in hue, and in other trials, the elements differed in brightness. When the quadrant differed in one dimension, the elements of the whole display could either be homogeneous in the other dimension, or they could vary randomly from item to item. The main finding was that random variation in hue interfered with segregation based on brightness, and vice versa, as assessed by response times. As Callaghan pointed out, such results are not entirely unexpected, given other findings concerning these particular dimensions. Hue and brightness are sometimes termed *integral dimensions* (Garner, 1974), because a variety of converging measures show that selective attention to one of these dimensions, given variation in the other, is difficult. For example, in speeded sorting tasks, orthogonal variation along one of these dimensions interferes with sorting based on the other dimension, whereas redundant variation facilitates performance. In a subsequent paper, Callaghan, Lasaga, and Garner (1986) used very similar methodology to examine visual texture segregation based on orientation and color. These dimensions are *not* integral; rather, they are separable, in the sense of Garner (1974), and thus are appropriate for asking the question with which we began. However, a similar pattern of results was observed: random variation along one dimension interfered with segregation along the other dimension.

The results of Beck (1982) and those of Callaghan et al. (1986) are superficially conflicting. Beck found that irrelevant color variation had no effect on subjects' performance in counting lines, whereas Callaghan et al. found interference in the detection of regions composed of elements differing in form. However, a conjecture about how the two results might be reconciled naturally suggests itself. Note that in the Beck task, the subject was searching for targets of *known* identity, which had to be counted. However, in both of the Callaghan experiments, the subject was looking for the region that was known only to *differ* from the remainder of the display: the specific identity of the elements composing the target quadrant was not known. One fairly natural account would predict that the specification of the particular form of the target would determine whether cross-dimensional interference appeared. Plausibly, an element that was both (1) known and (2) unique in its form could be detected in two different ways, only one of which would be impaired by variation in the other dimension. In the first way, the visual system presumably extracts local features that are present in different regions of the display, perhaps representing them in retinotopic maps composed of feature detectors. If the observer wishes to detect the presence of a particular known feature, he or she can simply "read off" the presence of activity in the relevant feature map (according to Treisman & Souther, 1985), or at least orient to the location of a token of the desired feature. This efficiency of this mechanism might not depend at

all on the uniqueness of the element with respect to the background. Furthermore, there is no reason to think that activity in one feature map would interfere with the detection of activity in another feature map. Hence, when the element's identity is known, detection would be unaffected by occurrences in the irrelevant dimension, as Beck's results indicate. The second way that a unique element (known or unknown) might be detected would rely on the detection of its difference from the background *per se*. In this mode, an observer would essentially be set to detect a boundary rather than a particular feature. If, counter to Treisman's (1982) view, texture boundaries were computed on multidimensional representations, then this second mode of detection would plainly fail to function as well if spurious differences were present in an irrelevant dimension. The consequence of this is that the detection of forms that are known only to *differ* from their surround would suffer major interference from the presence of variation in another dimension, since these targets could be detected only by the second detection strategy. This account could potentially explain why, in the Callaghan et al. work, color variation produced interference: the subject's lack of knowledge of the target elements' identity made the first strategy unavailable.

According to the conjecture just proposed, the critical difference between the two experiments is the fact that Beck's (1982) procedure allowed the subjects to know in advance the identity of the target. That is, the subject did not have to search for a difference, but could instead search for a specified feature. However, there are other factors that could account for the difference in the results. One possibly relevant difference is that in Callaghan's work (1984; Callaghan et al., 1986), the subjects did not even know the *dimension* in which the relevant segregation would occur. For example, one quadrant in her display might have differed from the rest of the display in either color or form. Even if the subjects *could* selectively attend to differences computed within any one dimension, this experimental design did not allow them to know in advance which dimension to attend to. Thus, the presence of any differences in the irrelevant dimension may have increased the expected time to determine which dimension was relevant. It could also account for the redundancy gain noted in certain of her conditions. Finally, the Callaghan task differed from the Beck task in that the subject had to detect an entire quadrant that was composed of different elements. As Callaghan (1984) pointed out, this added a factor to the experiment—that of within-quadrant similarity; in Beck's design, the differing items were singletons, and thus this factor played no role there.

We began our exploration of cross-dimensional interaction with a direct test of the conjecture just proposed: that random variation produces interference if the nature of a target singleton element is unknown (as in Callaghan et al., 1986), rather than known (as in Beck, 1982). To test this conjecture, the subjects search for a single element known to differ from its surround in a particular dimension; that is, the target is always a singleton in one

dimension. This dimension is known in advance to the subject. Two factors are manipulated: the presence of random variation in an irrelevant dimension, and the subjects' knowledge of the identity of the target element. If the conjecture described above is correct, then variation in an irrelevant dimension should be harmful when the target identity is not specified.

EXPERIMENT 1

In the first experiment, each display consisted of an array of 90 elements, one of which was different in form from the other 89 elements. The subjects' task was to determine which side of the display (right or left) contained this form singleton. Two factors were independently manipulated as blocked, within-subject variables. The first was whether the subject knew the form of the singleton in advance. In form-specified blocks, the fixation point that preceded each trial was a sample element of the differing form, whereas in form-unspecified blocks, the fixation point was an uninformative plus sign. The second factor was the presence or absence of irrelevant color heterogeneity in the display. In homogeneous-color blocks, the 90 elements were either all red or all green; the color was selected at random. In heterogeneous-color blocks, the color of each of the 90 elements was independently assigned to be either red or green, without constraint. The performance measure employed was accuracy, and the displays were masked with stimulus onset asynchronies (SOAs) of 50 and 100 msec. SOA was varied in mixed trials.

Method

Subjects. Twenty-four undergraduates at the University of California, San Diego participated as subjects in the experiment in partial fulfillment of a course requirement.

Apparatus and Stimuli. The stimuli were presented on Princeton Graphics SR-12 monitors, which were controlled by IBM PC microcomputers equipped with Sigma Design Color-400 boards, that provided a display resolution of 640×400 pixels. Each display consisted of 90 colored elements arranged in five rows of 18 elements against a dark background. The overall dimensions of the display were 9.8 cm in width $\times$ 3 cm in height, with a typical viewing distance of 45 cm. The elements in the display measured about 0.3 cm in width $\times$ 0.4 cm in height, and they were separated from each other by about 0.2 cm horizontally and 0.3 cm vertically.

Each element was either an O or a / drawn from the standard IBM PC character set in 80-character mode. On any given trial, the identity of the target element was chosen randomly from this set of two characters. Its position in the display was also chosen randomly, with the single constraint that it should not appear in any of the four central columns; the purpose of this constraint was to remove any ambiguity in response selection, given accurate knowledge of the target's position in the display. In the homogeneous color blocks, the color of the entire display was randomly set to be either red or green. In the heterogeneous color blocks, the color of each element in the display, including the target, was independently and randomly assigned to be red or green. Thus, in no case was the color of the target predictable, and neither color nor form exhibited any dependencies from trial to trial. The colors were not assessed precisely, but they appeared highly discriminable (a judg-

ment that is confirmed by Experiments 3 and 5, reported below). The mask display consisted of 90 yellow pound signs (#), which occupied the same positions on the screen that the display elements had formerly occupied.

Design. The experiment was divided into eight blocks, each of which consisted of 66 trials. The two between-block factors each had two levels, which generated four block types: color heterogeneity (homogeneous vs. heterogeneous display color) crossed with target specification (specified vs. unspecified). The eight blocks of trials presented to each subject consisted of two blocks each of these four block types. Within each block of 66 trials, there were equal numbers of trials at each of the two SOAs (50 and 100 msec); the order of trials within each block was independently randomized for each subject. Thus, for each of the eight color $\times$ target specification $\times$ SOA cells, there were 33 observations in each of two blocks, for a total of 66 observations per cell per subject.

An equal number of subjects was assigned to each of four groups. The group assignment determined the order in which blocks of the four different block types were presented. For each subject, all four block types occurred once in the first half of the experiment and once again in the second half of the experiment. The sequence of blocks cycled twice through a particular permutation of the four block types; the four permutations that were employed represented a partial Latin square. The subjects were assigned to one of the four groups as a function of the order of their participation in the experiment.

Procedure. The subjects were given written instructions advising them that each display would contain a single item that differed from the remainder of the display in form, and that their task was to detect as accurately as possible whether the target element was on the right or the left side of the display. It was made clear to the subjects that accuracy, rather than speed, should be emphasized.

Prior to data collection, each subject worked through 96 practice trials in 12 miniblocks of 8 trials each. These practice miniblocks cycled through the four between-block conditions in the manner described in the experiment proper. However, the SOAs, which were constant throughout a given miniblock, began at 1 sec, and were reduced in the course of practice in a predetermined and gradual fashion.

Each trial began with the presentation of a fixation point. In target-unspecified blocks, this was the plus sign (+), whereas in target-specified blocks, it was a single example of the target element (O or /)—the form singleton in that trial. This fixation point appeared at the center of the display for 1,200 msec. It then disappeared, and, 50 msec later, the display appeared. The display was presented for a single refresh of the monitor, so the nominal duration of the display was 17 msec; the mask appeared after the specified SOA. The mask remained on the screen for 300 msec, at which time the screen was cleared. The subjects had unlimited time in which to make a response. They indicated that a target was on the left or right side of the display by pressing the B or N key, respectively, on the microcomputer keyboard. If the response was incorrect, a 600-Hz tone was immediately sounded for 750 msec to alert the subject to the error; if the response was correct, no tone sounded. The intertrial interval between correct responses and the appearance of the fixation point for the next trial was approximately 1 sec.

Results

Table 1 presents the subjects' average accuracy in the eight different conditions. An analysis of variance (ANOVA) was performed on the data. When the target was specified, performance showed a very small improvement (82.3% vs. 79.8%); this difference was significant [$F(1,23) = 6.4, p < .05$]. Performance was compara-

Table 1
Proportion Correct: Experiment 1

SOA	Condition	Color Variation	Proportion Correct
50	Unspecified	No	.747
		Yes	.756
	Specified	No	.750
		Yes	.787
100	Unspecified	No	.847
		Yes	.843
	Specified	No	.871
		Yes	.884

ble with and without color heterogeneity (81.7% and 80.4%, respectively); this difference, which actually favored the heterogeneous condition, was not significant [$F(1,23) = 1.7, p > .20$]. The interaction of color variation and target specification was nonsignificant [$F(1,23) = 1.2, p > .20$]. Unsurprisingly, performance was much better for the longer SOA (86.1% vs. 76.0%), and this effect was highly significant [$F(1,23) = 128.6, p < .001$]. The remaining interaction terms did not approach significance.

Discussion

The results of this experiment are fairly clear, and they strikingly disconfirm what seemed at the outset to be a reasonably common-sense conjecture: that observers can readily detect a form singleton only if there are not spurious differences present in irrelevant dimensions. Heterogeneity in the irrelevant dimension (color) had no significant effect in the present data, whether or not the target had been specified. An additional point of interest is the effect of knowing in advance the identity of the differing element. Target specification *did* have a significant but very modest effect here.

EXPERIMENT 2

To seek converging evidence for the finding of Experiment 1, a replication of that experiment was undertaken using reaction time (RT) rather than accuracy as the dependent measure. Typically, experimental variables in tasks of this nature produce comparable effects in the two kinds of experiments; however, such convergence cannot be assumed. Cases in which the convergence breaks down are of theoretical interest. Thus, Santee and Egeth (1982) found effects in letter perception that appeared in only one or the other of the two dependent measures. In the present experiment, one might expect color-heterogeneity effects in the RT case but not in the accuracy case if, for example, the color information could only be excluded for a very brief interval, or if this exclusion somehow depended on the presence of the mask. (Other possibilities will be discussed further below.)

The present experiment, therefore, involved stimulus presentations identical to those of Experiment 1 (except for the absence of a mask in the present experiment and

a longer exposure duration); the task was identical, except for the emphasis on speed here.

Method

Subjects. Sixteen undergraduates at the University of California, San Diego participated as subjects in the experiment in partial fulfillment of a course requirement.

Apparatus and Stimuli. The apparatus and stimuli were identical to those used in Experiment 1, except that no mask was presented, and each display remained on the screen for 150 msec and then disappeared.

Design. The experiment was divided into 12 blocks, each of which consisted of 50 trials. Thus, for each of the four color $\times$ target specification conditions, there were 50 observations in each of 3 blocks, for a total of 150 observations per cell per session.

The different block types were presented as in Experiment 1, except that the sequence of blocks cycled three times, rather than twice, through each permutation of the four block types.

Procedure. The subjects were given written instructions advising them that both speed and accuracy should be emphasized. Prior to data collection, each subject worked through 96 practice blocks in 8 miniblocks of 12 trials. These miniblocks cycled through the conditions in the same manner as the blocks in the experiment proper. The procedure essentially followed Experiment 1 with respect to stimulus events and feedback.

Results

Response times longer than 1,200 msec or shorter than 200 msec were discarded, which led to the loss of well under 1% of the trials. Table 2 presents the subjects' mean correct RTs and the proportion of errors in the four different conditions. An ANOVA was performed on the RT data. When the target was specified, performance was slightly better (423 msec vs. 429 msec); the effect was not significant [$F(1,15) = 3.5, p > .05$]. Similarly, there was a small trend toward superior performance without color heterogeneity (420 msec vs. 432 msec); this effect was also nonsignificant [$F(1,15) = 3.8, p > .05$]. Finally, the interaction of color variation and target specification was also nonsignificant [$F(1,15) = 0.3, p > .50$]. A similar analysis of the error data revealed no significant effects.

Discussion

The results of this experiment are broadly supportive of the findings of Experiment 1. Neither color heterogeneity nor target specification produced a significant effect here, despite the very large total number of observations per condition (2,400). The trends in the data may be real, but what is probably most important for present purposes is that the magnitude of any of these effects is

Table 2
RTs and Error Proportions: Experiment 2

Condition	Color Variation	Mean RTs*	Error Proportions
Unspecified	No	423	.034
	Yes	436	.037
Specified	No	418	.029
	Yes	428	.034

*In milliseconds.

very small—on the order of 10 msec. The expected interaction is also absent.

EXPERIMENT 3

The results of the two previous experiments indicate that irrelevant color variation had only negligible effects on the detection of an element that differed in form from its surround, whether or not the nature of that element was known in advance to the subject, and regardless of whether the experiment was data-limited or speeded. One possible concern is simply that the color variation might not have been very salient. The color variation was judged to be highly noticeable by the author; nonetheless, it would be useful to have some objective assurance. In addition, there is a more interesting possibility that merits investigation: that apparent "suppression" of the color heterogeneities might have been possible only because color information might have arrived later in time than the form information (Boynton, 1979). Thus, the subjects might have accomplished this color suppression simply by attending to the earliest available interitem difference information. One way to deal with both of these issues is simply to reverse the two dimensions; that is, to require subjects to detect a color inhomogeneity while ignoring a form inhomogeneity. If performance is comparable to the previous results, then these results cannot be attributed to lack of salience or to delays in the extraction of the chromatic information.

Method

Subjects. Sixteen undergraduates at the University of California, San Diego participated as subjects in the experiment in partial fulfillment of a course requirement.

Apparatus and Stimuli. The apparatus and stimuli were identical to those used in Experiment 2, except for the reversal of the role played by the dimensions of color and form.

Design. The design followed that of Experiment 2.

Procedure. The procedure followed that of Experiment 2, with a few exceptions. The fixation point was always a plus sign. When the target was specified, the plus sign was red or green, which indicated the color of the singleton in the display that followed.

Results

Response times longer than 1,200 msec or shorter than 200 msec were discarded. Table 3 presents the subjects' mean correct RTs and the proportions of errors in the four different conditions. An ANOVA was performed on the data. Specification of the target did not produce any sign of superiority (393 msec vs. 394 msec) [$F(1,15) = 0.16$, $p > .60$]. Performance was comparable with and without form variation (392 msec vs. 394 msec) [$F(1,15) = 0.8$, $p > .30$]. The interaction of form variation and target specification was also nonsignificant [$F(1,15) = 0.5$, $p > .50$]. A similar analysis of the error data revealed no significant effects.

Discussion

The results are very similar to those of Experiment 2. They indicate that target specification and irrelevant form

inhomogeneity have essentially no effect on speeded search for the location of a color inhomogeneity in these displays. The virtual harmlessness of random variation in an irrelevant dimension, observed in the two previous experiments, is therefore *not* due to a lack of saliency, or to slow registration, of the chromatic information contained in the present displays.

EXPERIMENT 4

In the two previous experiments, RTs to detect an inhomogeneity in one dimension were virtually unaffected by the presence of an inhomogeneity in another dimension, even when the target singleton feature was not specified in advance to the subjects. The generality of this conclusion, however, is limited by the fact that, in each case, the set of potential stimuli included only two different elements. As a consequence, the subjects knew in advance that the configuration of the display would consist of, for example, either a / among Os or an O among /s. Logically speaking, the subjects could therefore deduce the identity of the target element by sampling as few as two elements; for example, if the first two elements sampled were Os, then it could be inferred that the target must be a /. It seems unlikely that the subjects could have used a strategy based on this fact so rapidly, but it cannot be completely ruled out without adequate empirical evidence.

In the present experiment, therefore, the potential stimulus set included four elements: X, O, a period (.), and /. Naturally, any given display included only two distinct types of elements, but the subjects did not know the identity of either of these elements in advance (although, as before, they did know that the relevant dimension was form).

Method

Subjects. Sixteen undergraduates at the University of California, San Diego participated as subjects in the experiment in partial fulfillment of a course requirement.

Apparatus and Stimuli. The apparatus and stimuli were identical to those used in Experiment 2 except that, on each trial, distinct target and distractor elements were chosen at random from the set X, O, ., and /.

Design. The design followed that of Experiment 2.

Procedure. The procedure followed that of Experiment 2.

Results

Reaction times shorter than 200 msec or longer than 1,200 msec were discarded. Table 4 presents the subjects' average performances in the four different conditions. An

Table 3
RTs and Error Proportions: Experiment 3

Condition	Form Variation	Mean RTs*	Error Proportions
Unspecified	No	394	.028
	Yes	394	.024
Specified	No	395	.024
	Yes	391	.030

*In milliseconds.

Table 4
RTs and Error Proportions: Experiment 4

Condition	Color Variation	Mean RTs*	Error Proportions
Unspecified	No	464	.073
	Yes	475	.084
Specified	No	460	.080
	Yes	474	.096

*In milliseconds.

ANOVA was performed on the data. The specification of the target produced little sign of superiority (467 msec vs. 470 msec); the effect was nonsignificant [$F(1,15) = 0.70$, $p > .40$]. The increase in RTs with color heterogeneity was not noticeably larger in magnitude than in the previous experiments (474 msec vs. 462 msec); however, this effect was reliable [$F(1,15) = 25.3$, $p < .001$]. The interaction of color variation and target specification was not significant [$F(1,15) = 0.2$, $p > .60$]. The errors were analyzed likewise. The effect of color variation was significant [$F(1,15) = 14.8$, $p < .005$], which reflected an increase in errors with the random color variation. The other error effects were not significant.

Discussion

The results are quite similar to those of Experiment 2, to which the design is most comparable. The absolute RTs were slower in the current experiment, which probably reflects the fact that some of the target-background discriminations were more difficult in the present experiment than in the earlier ones. However, this did not produce any sizable advantage for target specification. In the present experiment, the harmful effect of color heterogeneity is reliable, but its magnitude (12.0 msec) is very similar to that observed in Experiment 2 (11.4 msec), in which the effect did not reach significance. It would plainly be unwise, therefore, to draw any conclusions from this difference between the analyses of the two experiments. It is very likely, then, that there is a small harmful effect of color heterogeneity present in both situations. For present purposes, however, the most important consideration is the fact that this effect is very small in magnitude, and that it does not interact with target specification.

EXPERIMENT 5

The results of the first four experiments indicate that random variation in an irrelevant dimension produced little or no impairment of singleton localization in a known, relevant dimension, whether or not the specific identity of the singleton feature was known by the subject. One might reasonably attribute this finding to the fact that the dimension along which the singleton was to stand out as unique was always known to the subject, whether or not the particular identity was known. As noted in the introduction, this aspect of the experiment differed from

the procedure of Callaghan et al. (1986), who did observe some interference in a related, but not identical, task. One might suggest, then, that the absence of a deleterious effect of random variation was due to the adoption of an attentional strategy that somehow filtered out the irrelevant dimension. This strategy could have taken several forms. One possibility is that the observer could have attentionally gated out any input from the irrelevant dimension, thus preventing this input from feeding into a comparison process that might ordinarily operate on multidimensional representations. So, for example, in Experiment 1, this gating might have squelched the input of chromatic information into a global differencing process that found the locations of boundaries in the field.

If such a conception is correct, then advance cuing of the relevant dimension in a segregation task should produce a very large facilitation effect—a “set effect”—especially when the irrelevant dimension contains spurious random variation. Experiment 5 was therefore designed to determine whether such a set effect exists. In this experiment, the subjects were explicitly cued on some trials as to the dimension along which the singleton would appear. Whether or not the subject was cued, the display always contained the (target) singleton in the critical dimension and random variation in the other dimension.

Method

Subjects. Eleven undergraduates at the University of California, San Diego participated as subjects in the experiment in partial fulfillment of a course requirement.

Apparatus and Stimuli. The apparatus and stimuli were similar to those of Experiments 2 and 3, except that the relevant singleton could appear in either color or form. When the singleton was in the color dimension, it could be red or green, and when it was in the form dimension, it could be a / or an O. The elements in the display were always randomly and independently assigned values on the other (irrelevant) dimension, exactly as in the preceding experiments.

Design. The experiment was divided into 12 blocks, each consisting of 52 trials. All manipulations were between-trials and within-block. There were four different conditions equally represented among the trials in a block: cued versus uncued trials, and color versus form singleton trials. In the cued trials, the subjects were warned in advance as to whether the singleton would appear in color or in form. In the uncued trials, the subjects were not warned.

Procedure. The procedure differed from the previous experiments only in the identity of the fixation point, which either did or did not provide a cue as to the relevant dimension. The subjects were advised about the meaning of the cues; no particular suggestions were offered as to whether they would find them helpful. On cued trials, the fixation point was either a C (for color trial) or an F (for form trial); on uncued trials, it was always a plus sign. The fixation point remained present for 1,500 msec, and was replaced after 50 msec by the display, which remained present for 150 msec and then disappeared (not masked).

Results

Reaction times that were shorter than 200 msec or longer than 1,200 msec were discarded. Table 5 presents the subjects' mean RTs and their accuracy in the four different conditions. An ANOVA was performed on the

Table 5
RTs and Error Proportions: Experiment 5

Condition	Dimension Specified	Mean RTs*	Error Proportions
Color	No	393	.029
	Yes	380	.046
Form	No	435	.088
	Yes	430	.096

*In milliseconds.

RT data. The cuing of the dimension produced an advantage averaging 8.8 msec; the effect was significant [$F(1,10) = 7.9, p < .02$]. The subjects responded an average of 45.7 msec faster to color trials than to form trials [$F(1,10) = 11.1, p < .01$]. There was an interaction of cuing and dimension; specifically, there was a larger cuing effect for color (12.4 msec) than for form (5.2 msec) [$F(1,10) = 6.2, p < .05$].

The error rates were analyzed likewise. Accuracy was significantly better for color trials than for form trials [$F(1,10) = 17.2, p < .005$]. There was also a nonsignificant trend toward fewer errors in the uncued condition [$F(1,10) = 3.3, .05 < p < .10$]. The interaction of cuing and dimension was not significant.

Discussion

The results indicate that the cuing of the dimension of the singleton, against a background of random assignment in the irrelevant dimension, produces only a very minor advantage (averaging 8.8 msec). Furthermore, even this figure may overestimate the true advantage, since indications of a speed/accuracy tradeoff appear in the data in the form of a trend toward poorer accuracy on cued trials.⁵

EXPERIMENT 6

In Experiments 1–4, the detection of a single inhomogeneity in one dimension was affected by random variation in another dimension to only the most minor degree, even when the identity of the (unique) target element was not specified in advance to the subjects. Furthermore, there was no interaction between target specification and random variation in the irrelevant dimension. This result runs counter to the predictions of a conjecture that was proposed initially to account for the results of Beck (1982) and Callaghan et al. (1986). Experiment 5 showed that specification of the dimension by itself had only minimal effects. From this, it can be concluded that the absence of any major effect of random variation in the irrelevant dimension is *not* due to a suppression of the irrelevant dimension on the basis of knowledge of which dimension is relevant.

Where do these results leave us in our exploration of cross-dimensional interaction? The absence of an effect of random variation speaks directly against the possibility that difference detection is performed by a process that compares multidimensional representations of individual

elements, deriving a single measure of similarity or difference and settling on boundaries accordingly. As such, the results support Treisman's (1982) hypothesis that the computation of textural boundaries proceeds separately for different dimensions. The absence of any sizable effect from random variation does not, however, demonstrate that boundaries, having been extracted separately for each dimension, can always be independently accessed without any kind of interference.

The fact that prespecification of the relevant dimension produces at most a negligible advantage in singleton detection (Experiment 5) raises a counterintuitive possibility: that even when the relevant dimension *is* specified in advance, the effective exclusion of irrelevant variation in the irrelevant dimension is not based on the dimension along which it occurs, but rather on something about the spatial organization of the relevant and irrelevant discontinuities. Perhaps singleton detection is mediated by detectors that respond only when there is a unique element present in a given dimension and when there is a high level of homogeneity to the background elements in that same dimension. Such units might even be specifically responsive to particular features in one region, and to the absence of those features in adjoining regions (a possibility discussed further in the General Discussion). Such discontinuity detectors would probably not be activated to any major degree by random variation in any particular feature (depending, of course, on the precise circuitry involved). If this account is correct, and boundary detectors are indeed specific to the outline form of the discontinuity itself, then we might expect that major interference *could* be generated by variation in the irrelevant dimension that activates detectors for similar kinds of boundary configurations.

To summarize the argument at this point: The fact that irrelevant-dimension variations do not produce much interference might be due to effective suppression of the irrelevant dimension, but the lack of a set effect by dimension argues against this; we are left with the possibility that effective selection is based on the outline form of the boundary itself. Therefore, for all we know thus far, the visual system might be capable of effective selection by spatial organization of discontinuities, but not by dimension of discontinuity. If this is actually the case, we can predict major interference from variation in a dimension that is known to be irrelevant, if that variation is similar in its outline to the target form (i.e., a singleton). Experiment 6 tested this prediction.

In the following experiment, as in Experiment 1, the subjects' accuracy in the detection of singleton forms was studied. The major difference, however, was that when irrelevant variation in the color dimension was present, it took the form of color singletons instead of the random assignment of colors to all the forms. More concretely, in the distractor condition two single items were presented in a color that was different from that of the background; they were always in the same two fixed positions, placed symmetrically about the vertical midline. The manipula-

Table 6
Proportion Correct: Experiment 6

Condition	Color Variation	Proportion Correct
Unspecified	No	.773
	Yes	.678
Specified	No	.800
	Yes	.779

tion of target-identity specification, which was included in the first four experiments, was included here as well to determine whether interference, if present, could be bypassed by the specification of the target identity, as conjectured in the introduction.

Method

Subjects. Twelve undergraduates at the University of California, San Diego participated as subjects in the experiment in partial fulfillment of a course requirement.

Apparatus and Stimuli. The apparatus and stimuli were identical to those used in Experiment 1, except for the nature of the color variation. On variable-color trials, the entire background was either red or green except for two elements, which were of the opposite color from the background. These elements were placed in two positions on the middle row of the display (Positions 2 and 17 in the row of 18 items).

Design. The design followed that of Experiment 1 exactly, except that only a single SOA was used—50 msec. As in that experiment, the experimental variables were blocked.

Procedure. The procedure followed that of Experiment 1.

Results

Table 6 presents the subjects' average accuracy in the four different conditions. An ANOVA was performed on these data. The effect of color inhomogeneity averaged 5.7%, and the effect was significant [$F(1,11) = 8.8$, $p < .02$]. The effect of target specification averaged 6.4%, and was also significant [$F(1,11) = 9.6$, $p < .01$]. Finally, the two variables interacted; the color effect was larger when the target was unspecified (9.4%) than when it was specified (2.2%) [$F(1,11) = 7.3$, $p < .02$].

Discussion

The interaction that was originally conjectured to result from the introduction of *any* heterogeneities in the irrelevant dimension finally appears in this experiment, in which unique heterogeneities in color (i.e., color singletons) are introduced, rather than the random variation in the irrelevant dimension employed in the first four experiments. These heterogeneities have a major effect (9.4%) when the target is unspecified. The two key results to be explained, therefore, are (1) why singletons should be so much more harmful than random variation, and (2) why foreknowledge of the target identity mitigates these harmful effects. The conjecture described in the introduction provides a plausible answer to (2): an alternative strategy is invoked (at least on some trials, or to some degree on all trials) that involves consulting units that detect the presence of the feature target apart from its unique-

ness or difference from its neighboring elements. We address question (1) further in the next experiment, and return to it at length in the General Discussion.

EXPERIMENT 7

In Experiment 6, accuracy at detecting singletons in form was substantially impaired when singleton inhomogeneities in color were introduced. Furthermore, this impairment was large when the target was unspecified.

Why do singletons in the irrelevant dimension provide so much more impairment than random variation in the irrelevant dimension? Broadly speaking, at least two different aspects of the singleton could be critical. First, it might be simply because singletons in color generate more salient textural boundaries than random variations. Random variation in the color dimension may not provide a suitable input for the detection of any boundaries whatever in the color domain, but any salient boundaries might suffice to produce major interference. Alternatively, it might be that the singletons produce large interference effects precisely because their spatial scale and/or outline form is of the same kind as the target; that is, they are both specifically singletons. Thus, one account predicts that any salient boundary detected in the irrelevant dimension would produce interference; another predicts that only boundaries of the same type as those being sought would produce interference.

We can therefore test these two accounts by determining whether the detection of singletons in form is impaired by nonsingleton textural patterns in the color domain that would seem to generate compelling grouping organizations of the display. For this purpose, a range of textural organizations in the color dimension were presented in Experiment 7. Three of these were nonsingletons: horizontal stripes, vertical stripes, and a checkerboard pattern. Three other conditions involved singletons: four singletons in random positions, four singletons in fixed positions, and two singletons in random positions in the display. This experiment used RTs as the primary dependent measure, thereby allowing the robustness of the interference observed in Experiment 6 to be assessed.

Method

Subjects. Twenty-one undergraduates at the University of California, San Diego, participated as subjects in the experiment in partial fulfillment of a course requirement.

Apparatus and Stimuli. The apparatus and stimuli were similar to those used in Experiment 2, with several exceptions. The display was exposed for 150 msec. Seven conditions were compared, involving different variations in the color domain: (1) homogeneous color background (color randomly selected); (2) horizontal stripes of alternating color throughout the display; (3) vertical stripes of alternating color throughout the display; (4) a checkerboard pattern of red and green imposed on the entire display; (5) four color singletons, located in fixed positions symmetric about the vertical midline—the 3rd and 16th positions on Rows 2 and 4 of the display; (6) four color singletons, in four different randomly selected locations; and (7) two color singletons, in two different randomly selected locations.

Design. There were 14 blocks of 50 trials, with 2 blocks in each of the seven conditions. The order of blocks was counterbalanced as in Experiment 1.

Procedure. The procedure followed that of Experiment 2.

Results

Reaction times that were shorter than 200 msec or longer than 1,200 msec were discarded. Table 7 presents the subjects' average performance in the seven different conditions. The conditions differed significantly, as assessed by an overall ANOVA [$F(6,120) = 26.4$, $p < .001$]. A clear pattern is evident: the three singleton conditions (5–7) are elevated compared with either the control condition (1) or the three nonsingleton conditions (2–4). The mean RTs were 478 msec, 431 msec, and 427 msec for these three groups, respectively. When the different conditions within these groups were pooled, an overall difference between the three emerged [$F(2,40) = 42.3$, $p < .001$]. By planned comparison, the difference between the control and the nonsingleton conditions (2–4) was nonsignificant [$F(1,20) = 1.4$, $p > .25$], whereas the difference between the control and the singleton conditions (5–7) was highly significant [$F(1,20) = 44.4$, $p < .001$].

Discussion

The results show very clearly that it is singletons in the irrelevant dimension, rather than just the presence of any compelling textural organization in that dimension, that produces interference in the speeded detection of form singletons. The general implications of these results are discussed in the General Discussion. At this point, it seems appropriate to comment again on the two studies that motivated the conjecture that began this series of studies: the findings of Beck (1982) and of Callaghan et al. (1986). Beck observed no interference from random color variation on the counting of specified target forms. The present results support and generalize the Beck result quite clearly: random color variation is harmless, even if the target form is not specified (Experiments 1–4). Callaghan et al., on the other hand, did observe some interference from random variation on the detection of a quadrant that differed from the background in one (unspecified) dimension. As Callaghan et al. pointed out, the detection of a quadrant was a somewhat more complex situation than the detection of a singleton because of the within-quadrant varia-

tion factor. Thus, the results of the experiments reported here cannot provide a complete account for the Callaghan et al. results. They do, however, suggest certain possibilities. In view of the results of Experiment 7, it is possible that random variation in an irrelevant dimension produces the spurious activation of borders that mimic a disparate quadrant to a greater degree than they mimic the presence of singletons. To verify this conjecture, it would be useful to systematically investigate the detection of disparate quadrants (i.e., the Callaghan et al. task) with the sorts of nonrandom variations introduced in Experiment 7, and others as well. A particularly interesting manipulation, analogous to Experiments 6 and 7, would be the presence of quadrants or borders in a dimension that was specified to the subject as irrelevant. The results of Experiments 6 and 7 suggest that even with prespecification of the relevant dimension (which was not present in the Callaghan et al. study), borders and quadrants might provide particularly strong interference.

GENERAL DISCUSSION

The seven experiments reported here were designed to explore whether and when variation in an irrelevant dimension would affect the detection of singularities in a given dimension. The goal of these studies was to begin to characterize how the information from different dimensions interacts in the underlying boundary detection processes, and what forms of selective attention are available to control or modify these interactions. As described in the introduction, previous investigations of this topic had produced intriguing but inconclusive results. This investigation was restricted at the outset to the simplest possible case of a boundary detection: the location of a singleton element that was unique in a given dimension. The present series of experiments included some important variables that had not been previously investigated, such as the nature of possible competing organizations in an irrelevant dimension, the subjects' knowledge of the identity of a target element, and their knowledge of the relevant dimension.

We began with a conjecture that seemed to be suggested by earlier results: perhaps the detection of a singleton element whose identity was unspecified—that is, an element that could only be found based on its uniqueness in a given dimension—would suffer substantial interference if random variation were introduced in another dimension. On the other hand, it was expected that random variation would not impair detection when the singleton's identity was known. This conjecture seemed to provide a promising explanation of the superficially conflicting results of Beck (1982) and of Callaghan et al. (1986).

The results did not support this expectation, however. Instead, random variation in an irrelevant dimension was found to be virtually harmless, and the minimal interference that was produced did not interact with target specification. With one possible caveat (discussed shortly), this

Table 7
RTs and Proportion Correct: Experiment 7

Color Variation	Mean RTs*	Errors (%)
Homogeneous	427	3.8
Horizontal	431	4.3
Vertical	432	5.6
Checkerboard	430	4.2
Singletons (4) (fixed)	480	6.6
Singletons (4) (random)	471	5.9
Singletons (2) (random)	482	8.7

*In milliseconds.

suggests that the detection of singletons was not being accomplished by a multidimensional comparison process, in the sense described in the introduction. If the comparison process were multidimensional, the spurious differences and similarities in the irrelevant dimension would have obviously slowed any computational process that worked to settle on the appropriate boundaries (e.g., Caelli, 1985).

As just noted, there is a possible exception to this line of reasoning, a possibility whereby a multidimensional comparison might be consistent with the results just noted. This exception would apply if the input from the irrelevant dimension could simply be suppressed before being input into the comparison process. Experiment 5, therefore, considered the possibility that the irrelevant dimension could be suppressed by some form of attentional gating on the basis of the subject's foreknowledge of which dimension was relevant. The results of this experiment showed, however, that specification of the relevant dimension had minimal or nonexistent effects on RTs to locate a singleton in that dimension. This was despite the fact that random variation was always present in the irrelevant dimension! Plainly, suppression of information from the irrelevant dimension would operate much more effectively if the relevant dimension were known in advance. Indeed, it is difficult to see how such suppression could preclude interference from random variation if it were not preset on the basis of foreknowledge of the relevant dimension. Given the finding that any such "set effect" is minimal or nonexistent under these conditions, we conclude that suppression cannot play a major role.

The results of Experiments 6 and 7 showed that variation in the irrelevant dimension could, however, have harmful effects. When the variation took the form of singletons in the irrelevant dimension, a large interference effect appeared. Furthermore, this interference effect interacted substantially with target specification in the direction initially predicted: there was a much larger interference effect in the target-unspecified condition. These final experiments delineated several additional properties of the singleton interference effect:

1. The interference appears both in accuracy with masked displays and in response latencies with unlimited exposures.

2. The effect does not depend on trial-to-trial variation in the position of the singleton distractors: a sizable interference effect appears even when the singletons are presented in the same fixed positions on every trial, symmetrically placed about the vertical midline.

3. The effect does not depend simply on the fact that singletons (or their backgrounds) evoke a clear textural grouping within the display, because other regular patterns, such as checkerboards and stripes, are not effective.

What are the implications of these results? They support the conclusion drawn from Experiment 5: subjects do not have the ability to simply squelch out all information from an irrelevant dimension, even when it is specified in advance. Certain forms of variation in the irrele-

vant dimension have large effects, despite the subjects' best efforts to ignore this variation.

What is the source of these interference effects, and why are the effects so much larger than those of random variation in the irrelevant dimension? Callaghan et al. (1986) suggested that response competition probably explained the interference effect that they reported. Result 1, however, suggests that the interference observed here is probably not a response competition effect. Ordinarily, one expects accuracy in masked displays to be limited only by the perceptual component of the task, and not by the response selection component. Presumably, when the task is data limited and speed is not a factor, subjects generally allow enough time for the response selection stage to proceed with essentially asymptotic accuracy. This widely accepted assumption is supported by the findings of Santee and Egeth (1982), who studied the effect of response-incompatible flankers in a letter classification task and found that the response-competition interference appeared in RTs (in the speeded version), but not in accuracy (in a data-limited version).

CONCLUSIONS

The present results point toward a rather nonobvious conception of how input from separable dimensions interacts in the process of detecting and accessing object boundary information. The following account is certainly tentative, but seems to represent the most straightforward conclusions one might draw from the present series of experiments, together with previous results.

1. The detection of boundaries in the display is accomplished by detectors that are specific to the dimension defining the boundary *and* the spatial scale or outline of the boundary being detected. Thus, one might envision arrays of detectors that detect chromatic boundaries (or even more specifically, perhaps red/green boundaries) at a certain spatial scale. (These detectors may also be specific to different positions in the visual field; at the very least, their outputs indicate the spatial position of the detected boundary.) This conclusion entails the correctness of Treisman's (1982) hypothesis that boundary detection is not based on representations that conjoin different features present in particular locations.

2. The output of boundary detectors for a given scale and/or outline form is automatically pooled across the different dimensions of the underlying boundaries, and it is this pooled output that is centrally accessible.

3. The observer can voluntarily attend to these pooled representations, but cannot effectively either (1) suppress the outputs of specified irrelevant dimensions, or (2) attend to only those outputs representing comparisons within a particular specified dimension.

These three points attempt to sketch an overview of the way in which different dimensions contribute to boundary detection, and the limits on how subjects can selectively attend to the outputs of the detection process. The account is admittedly sketchy, but on the other hand, more

concrete models (e.g., Caelli, 1985) would appear to be prematurely specifying concrete details on interaction among features in advance of the relevant data. It is interesting to note some recent neurophysiological evidence that seems broadly consistent with Claim 1 above. Desimone, Schein, Moran, and Ungerleider (1985) described a number of single-cell recording studies of area V4 in monkey prestriate cortex. Typical cells in this area have large excitatory receptive fields with various combinations of orientation, chromatic, and other specificities. In addition, however, the cells often have large suppressive surrounds with the same sensitivities (i.e., if a bar oriented at 45° provides maximum excitation within the excitatory center, it will also provide maximum inhibition if it is presented in the suppressive surround). Desimone et al. suggested that such units may be performing operations involved in boundary detection. Indeed, activity in a large population of such units could potentially provide a distributed representation of the location of boundaries in the field, partially specific to the feature inducing the boundary and the shape and position of the boundary.

In short, the present (admittedly quite speculative) suggestion is that both the behavioral evidence presented here and the physiological evidence cited by Desimone et al. converge to some degree. They converge to favor the idea that visual boundary detection may not be accomplished by a process that extracts the location of discontinuities across the field in an iterative fashion, correlating different dimensions and features (as in Caelli, 1985). Rather, it might be accomplished rather more directly by a large population of units, each of which is "looking for" feature-specific boundaries in specific locations at specific spatial scales on the basis of within-dimension difference computations.

Clearly, these suggestions are very preliminary, and further investigation is required to arrive at a complete functional characterization of how input from different dimensions cooperates or interferes in the process of establishing object boundaries. The present paradigm, which involves the localization of singularities in the field, represents only one of a number of tasks that might profitably be studied; converging evidence will be useful in the further characterization of multidimensional interactions in human visual boundary detection.

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NOTES

- Obviously, the X and the O may differ in many form-related features; this is overlooked for the sake of simplicity in this discussion.
- This conclusion would, strictly speaking, depend on specific assumptions about how the interitem differences are used to arrive at a segregation (Beck's, 1982, "decision units"). For present purposes, it is sufficient to note that under many obvious decision models, these particular differences would not yield segregation. Furthermore, note that the results might well turn out the same if the differences were computed with a Euclidean, rather than a city-block, metric.
- It should be noted that this account makes the correct predictions for the other conditions of the experiment described. In particular, the "disjunction" condition consisting of red Os and green Os in one region and red Vs and green Vs in the other region should be easier than the conjunction condition just described. This is because the intraregion differences would be 0 and 1, while the interregion differences would be 1 and 2. The interested reader can also verify that this account correctly predicts intermediate performance for the conjunction condition of Experiment VI of Treisman and Gelade (1980).
- It is worth noting that Treisman (1982) has provided a separate argument for the idea that boundaries are computed separately within each dimension, on the basis of a finding that conjunction targets can be "camouflaged" by placing them at the boundaries of feature groups in both dimensions; the argument is interesting but raises issues too complex to be properly discussed or evaluated here.
- It would seem natural to dismiss this rather peculiar trend, but the same pattern appeared (and was significant) in another experiment, which was like Experiment 5 except that cuing was manipulated by blocking versus mixing of trials, rather than with explicit cues in mixed trials. That experiment also showed another mildly peculiar feature present in the results of Experiment 5, namely, that the cuing effect was larger for the easier dimension (color); one might naturally have expected the opposite. No explanation for these oddities will be offered here; we can, however, safely conclude that cuing does not produce the large advantage that would have been expected on many accounts of the underlying processes.

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