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Is There Feature-Based Attentional Selection in Visual Search?

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A new paradigm combines *attentional cuing* and *rapid serial visual presentation* to disentangle the effects of perceptual filtering and location selection. Observers search successive, superimposed arrays, in which feature values are alternated for a target numeral among letters. Two dimensions, size (small, large) and color (red, green) are tested. Selective attention to feature values is jointly manipulated by instructions, presentation probabilities, and payoffs. In Experiment 1, the attended feature provides temporal, not spatial, information; observers show no attentional costs or benefits in response accuracy. In Experiment 2, the attended feature indicates a unique location; observers show consistent attentional costs and benefits. Selective attention to a particular size or color does not cause perceptual exclusion or admission of items containing that feature; it acts by guiding search processes to spatial locations that contain the to-be-attended feature.

It is obvious that one can easily find a red target in a field of green distractors, or a large target in an array of small distractors. Many studies have shown that detection times to the target (e.g., a red X) in a visual search task are faster when the target has a unique feature value (e.g., a red X among green Xs) than when the target does not (e.g., Bravo & Blake, 1990; Bravo & Nakayama, 1992; Cheal & Lyon, 1992; Duncan & Humphreys, 1989; D'Zmura, 1991; Egeth, Jonides, & Wall, 1972; Holliday & Braddick, 1991; Moraglia, Maloney, Fekete, & Al-Basi, 1989; Theeuwes, 1992; Treisman & Gelade, 1980; Treisman & Gomican, 1988; Treisman & Souther, 1985; Wolfe, Cave, & Franzel, 1989). The question we ask is, Do we attentionally select the target item on the basis of physical features (e.g., red, green, large, small)? That is, can we filter the visual input at an early stage of processing so that only red items are passed on higher stages, whereas green items are blocked by a perceptual filter (e.g., Broadbent, 1958)? Or, does the unique feature of the target attract our attention to its spatial location, and do we then select the item on the basis of spatial location?

There is overwhelming evidence in the author's own work and the literature for selection on the basis of location (e.g., Nissen, 1985; Posner, 1978; Shiffrin, 1988; Sperling & Dosher, 1986). In preliminary experiments in our laboratory, we were unable to find evidence for selection on the basis of features, and our search of the literature has yielded only a few studies in which selection on the basis of feature was not confounded by location. For example, responding to a stimulus of expected size is faster than responding to one of an unexpected size (Cave & Kosslyn, 1989; Larsen & Bundesen, 1978). Sperling and Melchner (1978) found more interference between concurrent searches for two targets of unequal size than for two targets of the same size, but, in their study, size was confounded with location. Indeed, there is indirect evidence that individuals do not select on the basis of physical features (e.g., Cave & Pashler, 1995; Tsal & Lavie, 1993). For example, Tsal and Lavie found that, after a search for a target on the basis of color (in which spatial location was irrelevant), observers nevertheless responded more quickly to a subsequent item when it was spatially adjacent to the target than when it was similarly colored. The present study is designed to disentangle the effects of spatial location and of physical features as determinants of stimulus selection in visual search.

Rapid Serial Visual Presentation (RSVP) Alternating-Feature Procedure

Experiment 1 is designed to determine whether physical features alone can be used to filter items that do not contain the to-be-attended feature value (e.g., red). To eliminate the possibility that the observer first selects a location on the basis of physical feature, and then processes the item in that location, Experiment 1 uses an RSVP search task in which successive arrays of characters are perfectly superimposed on each other. The successive arrays alternate in feature values in the cued dimension (e.g., red, green, red, green, . . .). However, all spatial locations have exactly the same feature sequence. Features are correlated with moments in time, not locations in space. On each trial, the observer is informed in advance about the target's probable

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feature value, and the observer then searches for the target (a digit) among the distractors (letters). The results of Experiment 1 show that there is no attentional selection on the basis of the physical features size and color. That is, when the attended feature fails to designate a location, then selective attention also fails.

It is important to recognize that rate is a critical parameter in these experiments in which features alternate in successive displays. When items are presented slowly, for example, one per second, then observers have no difficulty attending to one color or the other (Rock & Gutman, 1981). We can certainly imagine, when red and green digits are presented alternately superimposed on each other, that an observer could compute the sum of the red (or green) digits and ignore the other color. In this study, we are concerned with relative, fast presentation rates when there is insufficient time to alternate attention from frame to frame, so that all the frames have to be processed in more or less the same state of attention.

Therefore, Experiment 2 is a critical control experiment to demonstrate that, with the same observers, conditions, character sets, and presentation rates when an attended feature does indicate a spatial location, then selective attention can succeed. In Experiment 2, the stimuli are the same as Experiment 1, except that each array contains an odd item differing in feature value from the others. The target is always the odd item. The results of Experiment 2 indicate strong attentional selection, presumably because the to-be-attended feature now directs attention to a spatial location. Because selective attention requires the cue to designate a spatial location for it to succeed, we will conclude that selective attention is mediated by spatial location.

Direct Comparison of Physical With Attentional Filtering

An anonymous referee suggested that, if the observer were attending to red and there were only one red array in a long sequence of green arrays, an effect of selective attention might be observed. So it might. The problem with having just one array contain the to-be-attended feature is that this array might be entered into memory and the search would then be conducted in memory. An advantage of the RSVP alternating-feature procedure is that, after the first few arrays, the participant is in a steady state of search processing, so that our inferences really do pertain to steady-state search.

A further advantage of the RSVP alternating-feature procedure is that it enables a direct comparison of the effectiveness of filtering by selective attention with physical filtering of the stimuli. Suppose selective attention were perfect. Then, an observer attending to red would be able to completely ignore green arrays, just as if they had been physically eliminated. We can compare the observers' performance with selective attention to the case of real physical filtering, in which green arrays are physically eliminated (replaced with blanks). Indeed, with real filtering of green arrays, search performance (on the residual red arrays) is greatly improved. The percentage of improvement with selective attention compared with real physical filtering gives a measure of the relative efficiency of attentional selection. (Indeed, we will find attention selection efficiency to be zero.) The comparison of selective attention with actual physical filtering requires a greater variety of presentation conditions than is immediately evident. The full RSVP alternating-feature paradigm, with all its internal control conditions, is described in the Method section.

Experiment 1: Feature-Cued Search in Alternating-Feature Sequences

Experiment 1 investigates whether attentional selection can be based solely on physical features such as size and color. To disentangle effects of *feature selection* and *location selection,* we use a search paradigm that combines attentional cueing and RSVP (rapid serial visual presentation) (Figure 1). The effect of location selection is eliminated in Experiment 1 by correlating features with moments in time, not locations in space. Two dimensions, size and color, are studied separately. There is abundant evidence that attentional preparation for a particular color (Treisman & Gelade, 1980; Treisman & Gormican, 1988) or particular size (e.g., Cave & Kosslyn, 1989; Larsen & Bundesen, 1978) facilitates performance. The question addressed here is one of mechanism. Each dimension consists of two feature values: red and green for color; small and large for size. Selective attention to stimuli of different feature values was controlled jointly by instructions, presentation probabilities, and payoffs.

Task

On each trial, the observer was first presented with a visual cue indicating the strategy of attentional allocation for that trial (e.g., "attend only to large characters"). Then the observer viewed a rapid serial presentation of character arrays. Each array consisted of six characters, evenly spaced on the circumference of an imaginary circle. All of the characters except one were letter distractors. One array in the middle third of the sequence contained a digit, the target. The identity, location, and feature value of the target were chosen randomly and independently and were unknown to the observer (Figure 1). Every sequence contained exactly one target, and the task of the observer was to discover the identity, location, and feature value of the target.

Alternating-Feature Paradigm

We studied attentional filtering of information based directly on feature values (e.g., selectively attending to red items). We proposed to eliminate the possibility of a two-stage process in which the observer first selects a location on the basis of the feature value at that location and then selectively attends to that spatial location. Within each of the displays in Experiment 1, every character had the same feature value (e.g., red) in the cued dimension. Selective

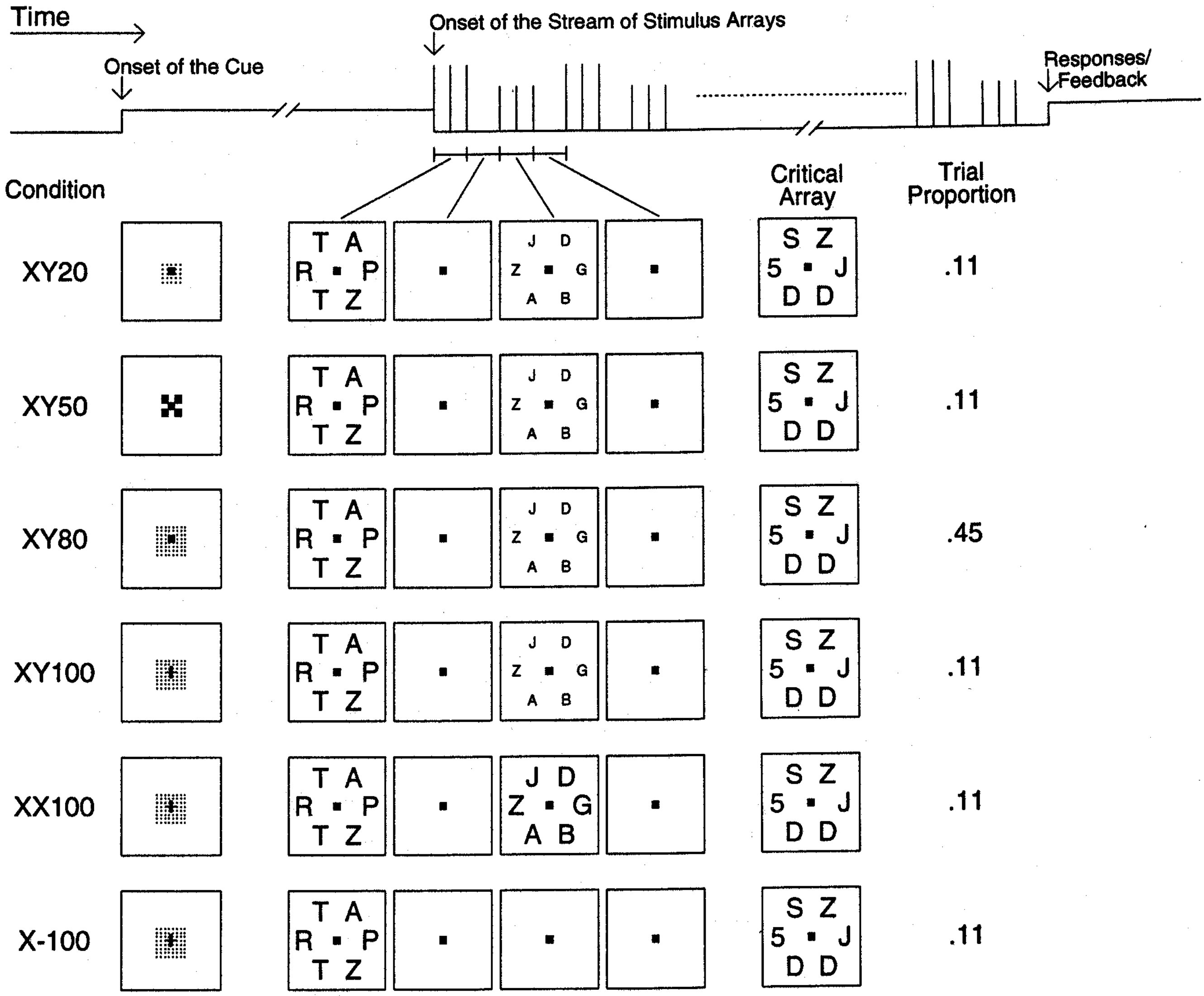

Figure 1. Procedure and representative conditions for Experiment 1. The cued dimension is size (X = large, Y = small). Within an array, all items are of the same size. A trial is initiated by a keypress (not shown) that produces a visual cue for 2 s (illustrated in leftmost column)—a symbol that indicates to the observer the possible feature values of the target and their probabilities. Then, a series of superimposed stimulus arrays is presented in rapid succession. Each array is exposed briefly (3 refreshes = 67 ms). Arrays are separated by blank screens with a fixation square (also 3 refreshes = 67 ms). The observer searches for an unknown digit (e.g., 5) among letters, typing responses (identity, location, feature value) at the end of the sequence. The central four columns indicate successive arrays prior to the critical array that is shown in the right-most column. Given large (X) targets, the six rows of arrays illustrate, from top to bottom, XY20, XY50, XY80, XY100, XX100, and X−100 conditions, where the numbers 20, 50, 80, and 100 indicate the probability of X targets in the condition. Given an X target, the column "Trial Proportion" indicates the conditional probability of each condition. The critical array is located between the 10th and 17th (or 5th and 9th for X−100) in a sequence. Ten (or 5 for X−100) arrays are presented after the critical array. Complete feedback is given after the responses.

attention to a feature value would not distinguish spatial locations.

Three kinds of sequences are used in the present study: Alternating-feature experimental sequences, same-feature control sequences, and half-blank sequences. In the main kind of experimental sequence, successive arrays alternate between the two feature values of the cued dimension. We designate this feature-alternating sequence (e.g., red-green-red-green-. . .) as XY, where X and Y refer to the feature values (Figure 1). The effect of selective attention was assessed by comparing identification accuracy on similar XY sequences under different attentional instructions.

Assessing the Efficiency of Attentional Filtering

In order to assess the effectiveness of selective attention relative to actual physical filtering (Figure 1), two kinds of control sequences were included. In the single-feature XX sequence, all arrays in a sequence have the same feature value in the cued dimension. If the observer were unable to discriminate X from Y feature values, performance in XX and XY arrays would be identical. Therefore, performance in the single-feature XX sequence describes one bound on performance. However, whereas a difference between XX and XY performance is sufficient to prove X-Y discriminability, the reverse is not true: Similar performance in XX and XY sequences can have many possible causes.

The half-blank sequence is created by replacing all characters of feature value Y in a XY sequence with blanks. Consider a trial in which the observer was told in advance to attend only to the large characters and to ignore small characters, and that the target would always be a large digit. Suppose the observer were able to attentionally filter out all the small characters. Then identification accuracy in the large/small alternating (XY) condition would be the same as that in a condition in which the small characters were physically replaced by blanks (i.e., the half-blank X− condition). In so far as attentional filtering approaches physical filtering, we can say that there is attentional selection on the basis of size. In so far as the observer does not distinguish between large and small characters, identification accuracy in the XY condition would be equal to that in a condition in which all characters are presented in large size (the XX condition). We expect identification accuracy in the XY condition to be bounded above by that in the X− condition, and bounded below by that in the XX condition.

The maximum range of attentional filtering is estimated by the difference in identification accuracy between the XX and X− sequences. That is, let $P(\text{XX})$ be the probability of correct identification in the worst case, in which the observer does not distinguish between X and Y. Let $P(\text{X}-)$ be an estimate of the probability of correct identification in the ideal case, in which the observer perfectly filters the Y items. The actual amount of attentional filtering is the difference in identification accuracy between the XX and XY sequences, $P(\text{XY}) - P(\text{XX})$. We define the efficiency (eff) of actual attentional filtering (relative to perfect physical filtering) as the actual amount of attentional filtering divided by the maximum range of attentional filtering (see Sperling, Wurst, & Lu, 1992)

$$eff = \frac{P(\text{XY}) - P(\text{XX})}{P(\text{X}-) - P(\text{XX})}.$$

Control of Attention: Costs and Benefits

Suppose the observer were attending to small characters and a large target were presented. Is there a cost for misdirected attention? Suppose the observer were attending to small characters and a small target were presented. Is there a benefit for correctly directed attention? To evaluate the costs and benefits of selective attention, we included conditions in which the observer was instructed to distribute attention to both large and small characters in feature-alternating (XY) conditions (e.g., Posner, 1978). Given a large target, the observer might be instructed to pay 20% attention to large characters and 80% to small ones, 50% attention to large characters and 50% to small ones, 80% attention to large characters and 20% to small ones, or 100% attention to large characters and 0% to small ones (and be guaranteed that the target would be large). To further encourage the observer to behave according to the instructions, the presentation probabilities and payoffs were varied accordingly (see below). We define *cue validity* as 100% times the probability that the cue correctly indicates the feature of the target. If the observer were able to differentially weigh stimuli according to their physical features, his or her performance for the XY conditions would systematically vary with cue validity. That is, relative to the equal-attention condition (i.e., 50% cue validity), performance would be less accurate in the condition of low (e.g., 20%) cue validity, and more accurate in conditions of high (e.g., 80% and 100%) cue validity. The reduction in accuracy is a cost for misdirected attention; the increment in accuracy is a benefit for correctly directed attention.

Method

Observers

There were three observers: 2 New York University graduate students, S.S. and C.L., and one faculty member, B.M. S.S. was an author, C.L. was paid for his participation, and B.M. volunteered his services. All observers had corrected-to-normal vision. Each observer performed at least 2,000 practice trials before the experimental sessions.

Stimuli

Display apparatus. Stimuli were displayed on a computer-controlled color monitor with a 60-Hz, noninterlace refresh rate. All of the stimuli were presented against a uniform background of luminance 19 cd/m^2, and were viewed binocularly at a distance of 120 cm in a dimly lit room. A chin rest was used to fix the viewing distance.

Targets, distractors, fixation square, and visual cues. The target set consisted of 10 digits: 0, 1, 2, 3, 4, 5, 6, 7, 8, and 9. The distractor set consisted of 10 capital letters: A, B, D, G, J, P, R, S, T, and Z. A central fixation square remained on throughout a trial. The fixation square was 0.14 × 0.14 dva^2 (degrees of visual angle), and of luminance 150 cd/m^2. Various visual symbols (cues) were used to indicate different experimental conditions to the observers (see the *Design* section).

A single stimulus array was composed of the central fixation square and six characters. The six characters were equally spaced on an imaginary circle with a diameter of 1.58 degrees of visual angle (dva). One of the six locations was at one o'clock.

Size. Large- and small-size stimuli were used when the cued dimension was size (Figure 2). Stimuli appeared white on a gray

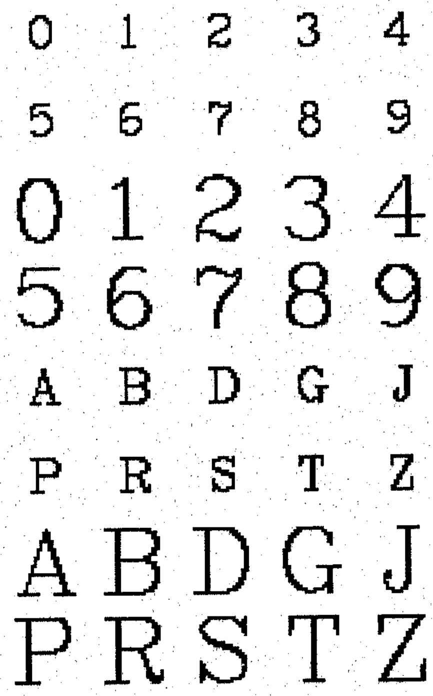

Figure 2. Small and large stimulus character sets. The width and height are 0.14° and 0.24° for the small 5, and 0.24° and 0.48° for the large 5. Red and green characters are of intermediate size (0.19° and 0.29°, not shown).

background. The luminance of the stimuli was about 150 cd/m^2 on a background of 19 cd/m^2. Character widths and heights were 0.24 and 0.48 dva for a large 5, and 0.14 and 0.24 dva for a small 5.

Color. Red and green stimuli were used when the cued dimension was color. The size of the stimuli was intermediate between the large and small sizes of the size condition. The width and height of the stimulus 5 were 0.19 and 0.29 dva. The luminance of the red and green stimuli was equated by flicker photometry and was about 45 cd/m^2.

Design

Target dimensions. For a given block of trials, the values of the target on three dimensions—identity, location, and size (or color)—were manipulated independently. The identity dimension consisted of 10 digits, the location dimension consisted of six spatial locations on an imaginary circle, the size dimension consisted of large and small feature values, and the color dimension consisted of red and green feature values. Size and color dimensions were conducted in separate blocks. In a block in which the size dimension was varied, the color dimension was constant (white), and in a block in which the color was varied, the size dimension was constant (intermediate between large and small).

Attentional instructions and cue validity. A visual cue indicated the attentional instruction, the type of stimulus sequence, and the payoffs that would be in effect for each trial. The instruction was "Pay *N*% of your attention to the feature value indicated by cue," in which *N*% was the probability of the target occurring with that feature value. Thereby, the cue indicated the probabilities with which the target would be presented in one feature value (e.g., large) with probability p and in the other feature value (e.g., small) with probability $1-p$. For a given feature value, the probability p was chosen randomly on each trial from among .2, .5, .8, and 1. The cue validity (20, 50, 80, or 100%) is defined as 100% times the probability that the cue correctly indicates the feature value of the target. See Figure 1 for illustrations using size as the cued dimension.

Experimental conditions (types of trials). Combinations of cue validities and presentation sequences yielded 12 experimental conditions, designated as XYN. In the notation XYN, the first element is the feature value of the target (X), the second element is the other feature value (Y), the third element (N) is a percentage, 100 times the probability of a target occurring with feature value of the first element (X). An advance cue to the participant always indicates X and N (and thereby Y). The 12 conditions are denoted as XY20, XY50, XY80, XY100, XX100, X−100, YX20, YX50, YX80, YX100, YY100, and Y−100.

Figure 1 illustrates the first six conditions. For example, XY20 represents a condition in which character arrays alternate between feature values X and Y, the cue indicates that the target will be presented in feature value X with probability 0.2 and in feature value Y with probability 0.8, and the target actually is presented with feature value X. There are several obvious constraints on the number of trials. For example, there have to be an equal number of XY50 and YX50 trials, and there have to be 4 times as many XY80 trials as XY20 trials. Within these constraints, the trial type was chosen randomly according to the following expected proportions (illustrated for X-target trials): XY20:XY50:XY80:XY100:XX100:X−100 were 11:11:45:11:11:11. With respect to the cued dimension, the probability of a trial with a target of one feature value was 0.5, and of the other feature value it was also 0.5.

Exposure duration and interstimulus interval (ISI). The exposure duration is the interval in which a character array is physically presented (refreshed at 60 Hz; see Figure 1). For size conditions, the exposure duration was 67 ms (i.e., image refreshed four times) for all 3 observers. For color conditions, the exposure durations were adjusted for each observer to approximately equalize their performance; the exposure durations were 67, 84, and 100 ms, respectively, for observers S.S., B.M., and C.L. The interstimulus interval (ISI) is the one between the offset of one character array and the onset of its succeeding character array. The ISI was equal to the exposure duration for the XY and XX sequences and was (by definition) 3 times as long as the exposure duration for the X− sequences. During the ISI, a blank screen with the central fixation square was presented.

Sequence length and times of occurrence of the target array. The length of a sequence is the number of character arrays presented in a trial. The target array is the character array that contains the digit (the target). Usually, in search experiments, the probability of target occurrence is distributed uniformly among the possible serial positions in which targets can occur. The problem with this procedure is that the aging distribution is not constant: The conditional probability of a target occurring at serial position $n+1$—given that it has not yet occurred—ultimately increases dramatically with n. To maintain a uniform incentive to search, the aging distribution should be constant.

Let $P(n)$ be the probability that the target is the nth character array in a sequence. The array number n of the target array was exponentially distributed between the 10th and 17th array for the XY and XX sequences; that is, $P(n) = 2 \times (1/3)^{n-9}$, $n \in [10, \ldots, 17]$. The memoryless property of exponential distributions ensures a constant expectation of the target as a function of time (i.e., independent of past history; see Sperling & Dosher, 1986, for review and references). Given that a target had not yet occurred at array n, $10 \leq n \leq 16$, the probability that the target would occur at array $n+1$ remains constant at one third throughout the critical sequence until its very last array. For the half-blank X sequences, targets occurred between the fifth and ninth array; that is $P(n) = 2 \times (1/3)^{n-4}$, $n \in$ in [5,. . ., 9]. After the critical array, there were 10 arrays for the XY and XX sequences and 5 arrays for the X− sequences. Hence, the sequence length was varied between 20 and 27 for the XY and XX sequences and between 10 and 14 for the X− sequences, with the target approximately in the middle of the sequences.

Payoff. A payoff matrix (Table 1) was implemented to fully define for the observers their optimal allocation of attention in accordance with each visual cue. For each trial, a score was defined for the participant according to the outcome of the trial, and the observer was told to achieve the maximum possible score. The score was posted after each trial. The score was proportional to cue validity (attentional incentive) and to the number of response alternatives (difficulty). One observer (C.L.) earned $6 per session, plus a bonus computed according to the payoff matrix.

Procedure

Stimulus presentation. The procedure and representative conditions of Experiment 1 are illustrated in Figure 1. The observer pressed a key to initiate a trial whenever he or she was ready. A visual cue was presented immediately for 2 s. A series of superimposed stimulus arrays was then presented in rapid succession.

Responses. To determine whether selective attention might have a differential effect on item, location, or feature information, observers were required, in succession, to make three keyboard responses to indicate the target's identity, the target's spatial location, and the target's feature in the cued dimension. The typed responses were displayed on the screen, and the observer was allowed to correct them before pressing the "enter" key.

Feedback. Feedback, displayed after the "enter" keypress, showed the actual identity, location, and feature value of the target, as well as the typed responses. Also displayed was the score for that trial and the cumulative score for the block of trials.

Experimental sessions. Observers ran seven experimental sessions for the size conditions and then seven sessions for the color conditions. Each session consisted of 20 warm-up trials and 200 experimental trials. The 12 types of experimental conditions were intermixed within a session.

Table 1
Payoff Matrix for Correct and Incorrect Responses

	Response[b]					
Validity (%)[a]	Identity (10)		Location (6)		Feature (2)	
100	+5.0	−0.0	+3.0	−0.0	+0.0	−1.0
80	+4.0	−0.0	+2.4	−0.0	+0.8	−0.8
50	+2.5	−0.0	+1.5	−0.0	+0.5	−0.5
20	+1.0	−0.0	+0.6	−0.0	+0.2	−0.2

Note. Payoff values for correct responses are indicated by +, and payoff values for incorrect responses are indicated by −. The number of alternatives for each response is indicated in the parentheses.
[a] Validity is the probability that the cue accurately indicates the feature of the target value ×100. [b] Three responses are scored. The net payoff is proportional to validity × the number of alternatives for each of the responses × payoff value.

Results and Discussion

Four Response Categories

All of the results were tabulated individually for each participant. For each cued dimension and for each feature value, data were summarized in four response categories: identity, location, feature, and identity-and-location. The identity, location, and feature categories consider the responses individually. The identity-and-location category requires both the identity and location responses to be correct. Data for triple joint accuracy of identity, location, and feature did not differ significantly from joint identity and location accuracy, and therefore are not presented here.

Because the cue provided significant information about the probable feature value of the target in the cued dimension, any systematic variation in response accuracy of the feature value of the target because of cue validity cannot be considered as an attentional effect without considerable additional justification. Our analyses and discussions will focus primarily on the identity, location, and identity-and-location categories. Identity and location are highly correlated in these data; therefore, whenever it is sufficient to consider only one response category, it will be identity-and-location, because of the low rate (1.67%) of chance guessing in this score.

Percentage of Correct Responses for Each Experimental Condition

The complete results are the percentage of correct responses of the four response categories for each condition of attentional instruction, each feature value, and each observer. Figure 3 shows results for the size dimension, and Figure 4 shows results for color. (We defer until later the discussion of feature–response accuracy.)

Results for the identity responses appear similar to those for the location responses and to those for the identity-and-location responses. These data suggest that, in these experimental conditions, when a target is detected, both its identity and location become available.

Zero efficiency of attentional filtering on the basis of physical features. For every response category, feature value, and observer, response accuracy in the half-blank (X−100) condition is higher than that of any of the other conditions. This superiority of the half-blank condition is verified by chi-square tests that compare the performance of the half-blank (X−100) condition with that of the feature-alternating (XY100) condition and the single-feature (XX100) condition, respectively (Table 2). As mentioned above, the efficiency of attentional filtering, relative to perfect physical filtering, can be indexed by the ratio of the actual amount of attentional filtering to the maximum range of attentional filtering (see Sperling et al., 1992). The maximum range of attentional filtering is defined by the difference in response accuracy between the XX100 (single-feature) and the X−100 (half-blank) conditions. The significant difference between the X−100 and the XX100

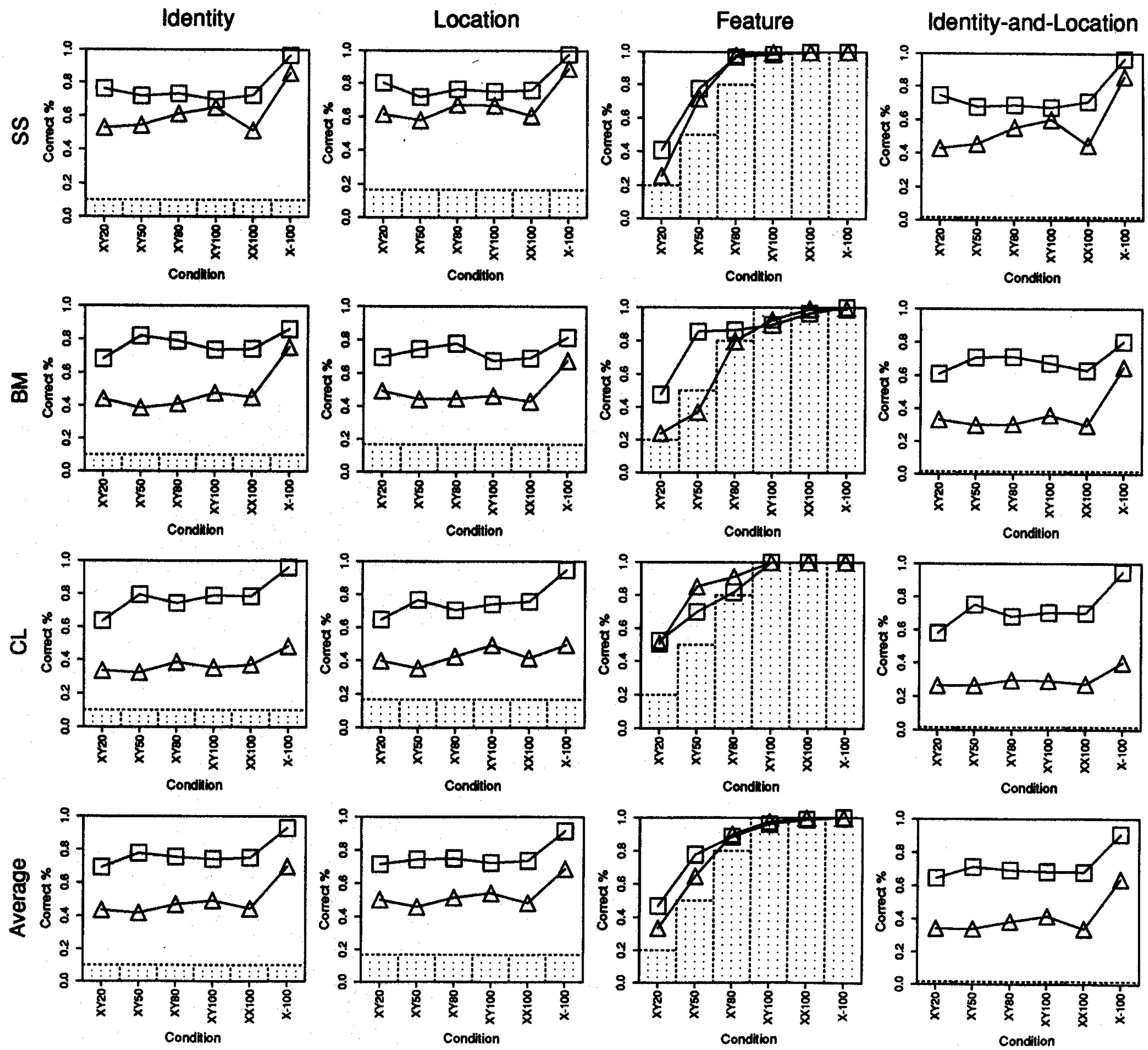

Figure 3. Percentage of correct responses versus experimental conditions for the size dimension in Experiment 1. The ordinate indicates the percentage of correct responses; the abscissa indicates the experimental conditions: XY20 indicates both XY20 and YX20, XY50 indicates both XY50 and YX50, and similarly for XY80, XY100, XX100, X−100. In the notation XYN, the first element, X, indicates the feature value of the target; the second element, Y, indicates the other feature value; and the third element, N, is the expected percentage of first-element targets. Target feature value *large* is indicated by squares, and target feature *small* is indicated by triangles. The dotted-line histogram below curves represents the expected probability of correct responses by pure chance guessing. Each row represents a different observer, and each column represents a different response category.

conditions indicates that there is a nonzero range within which attentional filtering could operate.

The efficiency of attentional filtering is defined by the difference in response accuracy between the XX100 and the XY100 (feature-alternating) conditions divided by the range, $[P(\text{XY100}) - P(\text{XX100})]/[P(\text{X}-100) - P(\text{XX100})]$. Although response accuracy in the single-feature (XX100) condition is noticeably lower than XY100 in some of the panels, the difference in the average is very small and is not statistically significant (Table 2). The efficiency of attentional filtering is zero because the numerator is zero. In other words, there was no statistically sig-

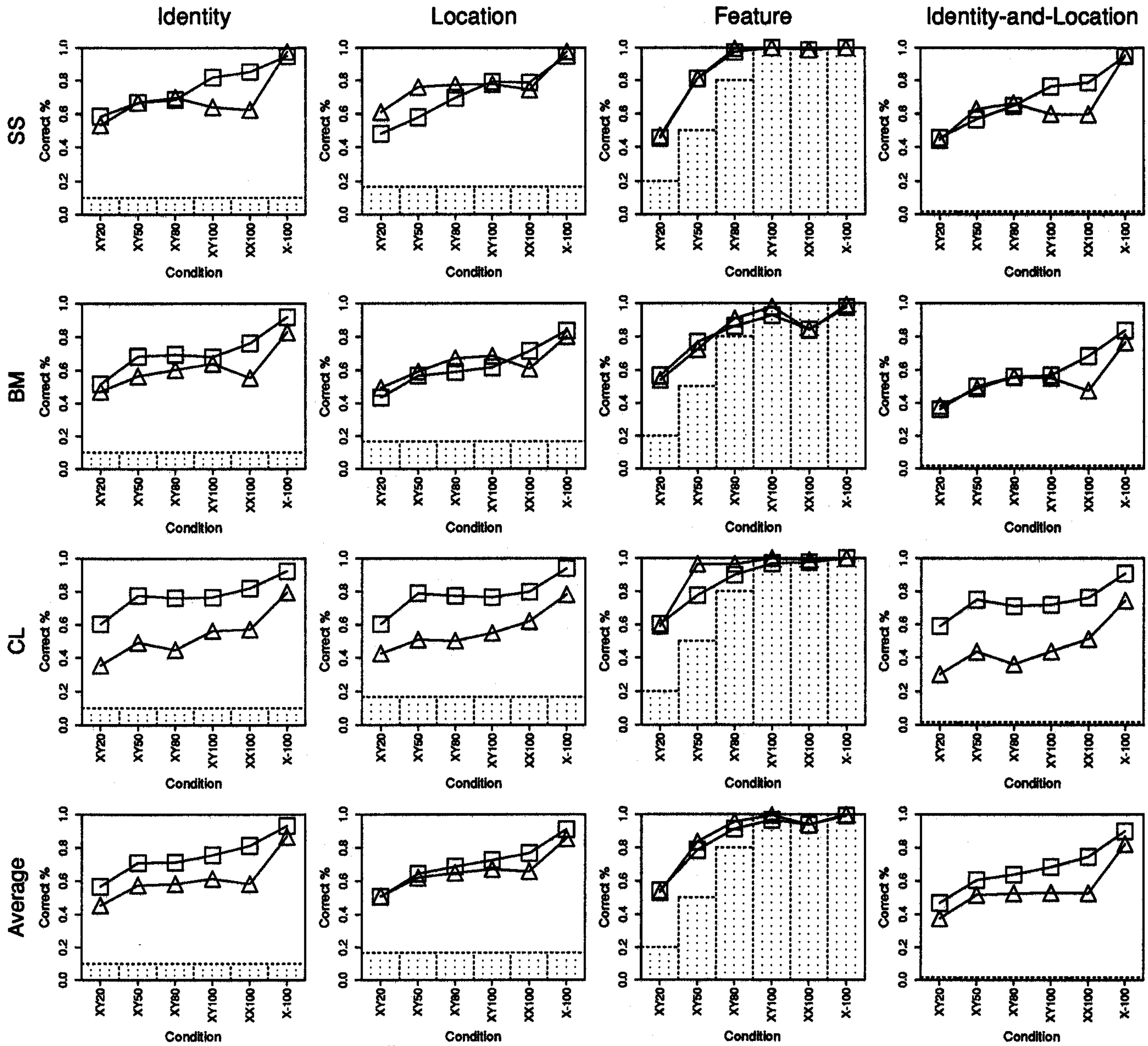

Figure 4. Percentage of correct responses versus experimental conditions for the color dimension in Experiment 1. Target feature value "green" is indicated by squares, and target feature value "red" is indicated by triangles. The ordinate indicates the percentage of correct responses; the abscissa indicates the experimental conditions: XY20 indicates both XY20 and YX20, XY50 indicates both XY50 and YX50, and similarly for XY80, XY100, XX100, X−100. In the notation XYN, the first element, X, indicates the feature value of the target; the second element, Y, indicates the other feature value; and the third element, N, is the expected percentage of first-element targets. [redacted] The dotted-line histogram below curves represents the expected probability of correct responses by pure chance guessing. Each row represents a different observer, and each column represents a different response category.

nificant attentional filtering on the basis of color or size for any observer or in the mean.

No effect of attentional instruction. The conclusions about attentional filtering were made by comparing performance in an attentional task with 100% attention (XY100) to the XX100 (single-feature) and the X−100 (half-blank) controls. On the other hand, the effect of attentional instruction is assessed by whether performance varies as the va-

Table 2
Chi-Square Values for Effects of Attentional Filtering in Experiment 1

Feature/Response category	XY100 versus XX100[a]			XY100 versus X−100[b]			XX100 versus X−100[c]		
	S.S.	B.M.	C.L.	S.S.	B.M.	C.L.	S.S.	B.M.	C.L.
				Size					
Small									
Identity (I)	2.57	0.11	0.05	7.40*	11.61**	2.49	18.88***	15.79***	1.93
Location (L)	0.54	0.18	0.83	9.12*	6.63*	0.00	14.55***	10.23**	0.99
I&L	3.13	0.67	0.07	10.67**	12.16**	1.87	25.47***	20.89***	2.82
Large									
Identity	0.11	0.00	0.00	22.62***	4.24	10.43**	18.54***	3.77	10.49***
Location	0.01	0.06	0.05	19.35***	4.62	12.74**	17.57***	3.38	10.91**
I&L	0.20	0.38	0.00	25.68***	3.83	16.16***	20.36***	6.15*	15.98***
				Color					
Red									
Identity	2.63	0.46	0.05	4.24	4.97	12.48**	11.61**	2.37	10.30**
Location	5.17	0.02	0.47	5.97	3.13	9.27**	18.59***	3.57	5.33
I&L	2.17	0.42	0.00	3.70	5.68	11.68**	9.94**	2.97	11.26**
Green									
Identity	0.07	0.41	2.15	13.22***	9.30**	1.85	15.35***	12.99**	7.65*
Location	1.16	0.60	1.47	6.60*	3.93	0.32	12.91**	7.31*	3.06
I&L	0.90	0.15	3.00	10.95**	7.25*	0.74	17.96***	9.01*	6.46*

Note. S.S., B.M., and C.L. indicate observers.
[a] When XY100 is greater than XX100, it indicates the presence of attentional filtering. [b] When X−100 is greater than XY100, it indicates that attentional filtering is not perfect. [c] When X−100 is greater than XX100, the difference indicates the maximum range of possible attentional filtering.
* $p < .05$, $\chi^2_{(.95,2)} = 5.99$. ** $p < .01$, $\chi^2_{(.99,2)} = 9.21$. *** $p < .001$, $\chi^2_{(.999,2)} = 13.82$.

lidity of the attentional cue is varied from 20% to 100% in the conditions XY20, XY50, XY80, and XY100. Although there is a suggestion of a slight trend in the average data for performance to improve with increasing amount of attention and in occasional instances when observers performed less well in conditions of 20% cue validity (i.e., XY20), these are very small effects. None of the effects of attentional instructions even approaches statistical significance in chi-square tests. In other words, compared with the equal-attention condition XY50, there is no significant cost for attending to characters of wrong feature, nor any significant benefit for attending to characters of correct feature.

Secondary results—stimulus asymmetry. For all participants, responses were more accurate for large targets than they were for small targets. Green targets tended to be detected better than red ones, but the superiority of green over red varied among observers. These observations were confirmed by matched *t* tests. It should be noted that all the stimuli were perfectly visible in isolated single presentations; detectability differences became apparent only under conditions of rapid serial visual presentation.

Attention Operating Characteristics (AOCs)

The effects of attentional conditions are best illustrated by means of attention operating characteristics (AOCs). Figures 5 and 6 regraph the data for Figures 2 and 3 as AOCs. Typical AOCs (lines of slope −1) were observed only in the feature response category for both size and color conditions, and we have already indicated that this category primarily represents information contained in the attentional cue, not in the stimulus itself. For results of the identity, location, and identity-and-location response categories, the points X, O, and Y, representing the three attentional allocations (20/80, 50/50, 80/20), are clustered at the independence point. The independence point is so called because it represents the performance that would be achieved by an observer who was able to perform the two-component attentional tasks independently, that is, the two-feature alternating conditions with 100% attention devoted to feature X (i.e., the XY100 condition) and the two-feature alternate conditions with 100% attention devoted to feature Y (YX100). When points cluster at the independence point, it means that two concurrent searches (for each kind of target, X, Y) are just as efficient as a single search for one kind of target. Obviously, there is no cost for misdirected attention and no benefit for correctly directed attention.

Summary

In Experiment 1 we studied the possibility of attentional selection solely on the basis of physical features using a search paradigm that combines attentional cueing and RSVP. To test the observer's ability to perform feature-based stimulus selection, we excluded a possible two-stage process—using physical feature to direct attention to a spatial location and then selecting the item in that location—by correlating features only with moments in time, but not with locations in space. Two dimensions, size (small vs. large) and color (red vs. green), were studied separately.

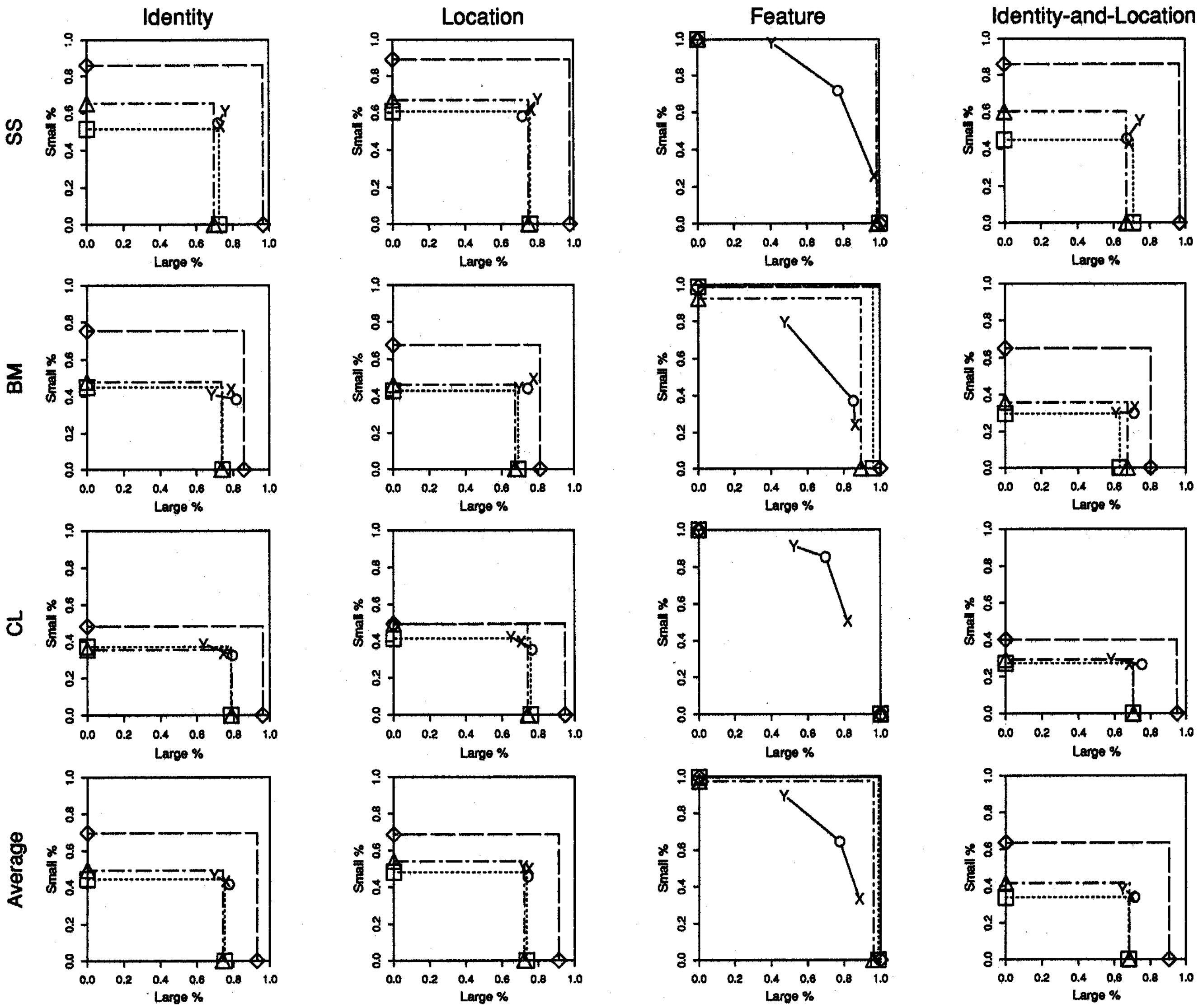

Figure 5. Attention operating characteristics for the size dimension in Experiment 1. Each row represents data from a different observer; each column represents a different response category. The *x* axis is the percentage of correct responses for large targets. The *y* axis is for small targets. X indicates the joint performance for the XY80 and YX20 (attend to X); O indicates XY50 and YX50, Y indicates XY20 and YX80 (attend to Y), where X = large and Y = small. Triangles indicate performance for the XY100 and YX100 conditions; squares for XX100 and YY100; diamonds for X−100 and Y−100. Three borders are indicated: The outermost border (long-dash lines), defined by X−100 and Y−100, represents the upper limit of expected performance. The innermost border (dotted lines), defined by XX100 and YY100, represents the lower limit of expected performance. The intersection of the middle-dash lines, defined by XY100 and YX100 is the independence point—the performance that would be achieved in divided attention tasks if there were no costs for dividing attention.

The results showed no benefits for attending to particular items on the basis of their physical features and no costs for attending to a feature different from that of the target.

Experiment 2: Searching Feature-Defined Locations

Experiment 1 showed that there was no attentional selection on the basis of physical features. The purpose of Experiment 2 is to demonstrate that precisely the same physical features (red vs. green color and large vs. small size) support excellent attentional selection when these features direct attention to a spatial location. The notion is that, even though Experiment 1 showed that there is no direct selection of items with a particular feature value (e.g., red), the feature can guide attention to the spatial location of an

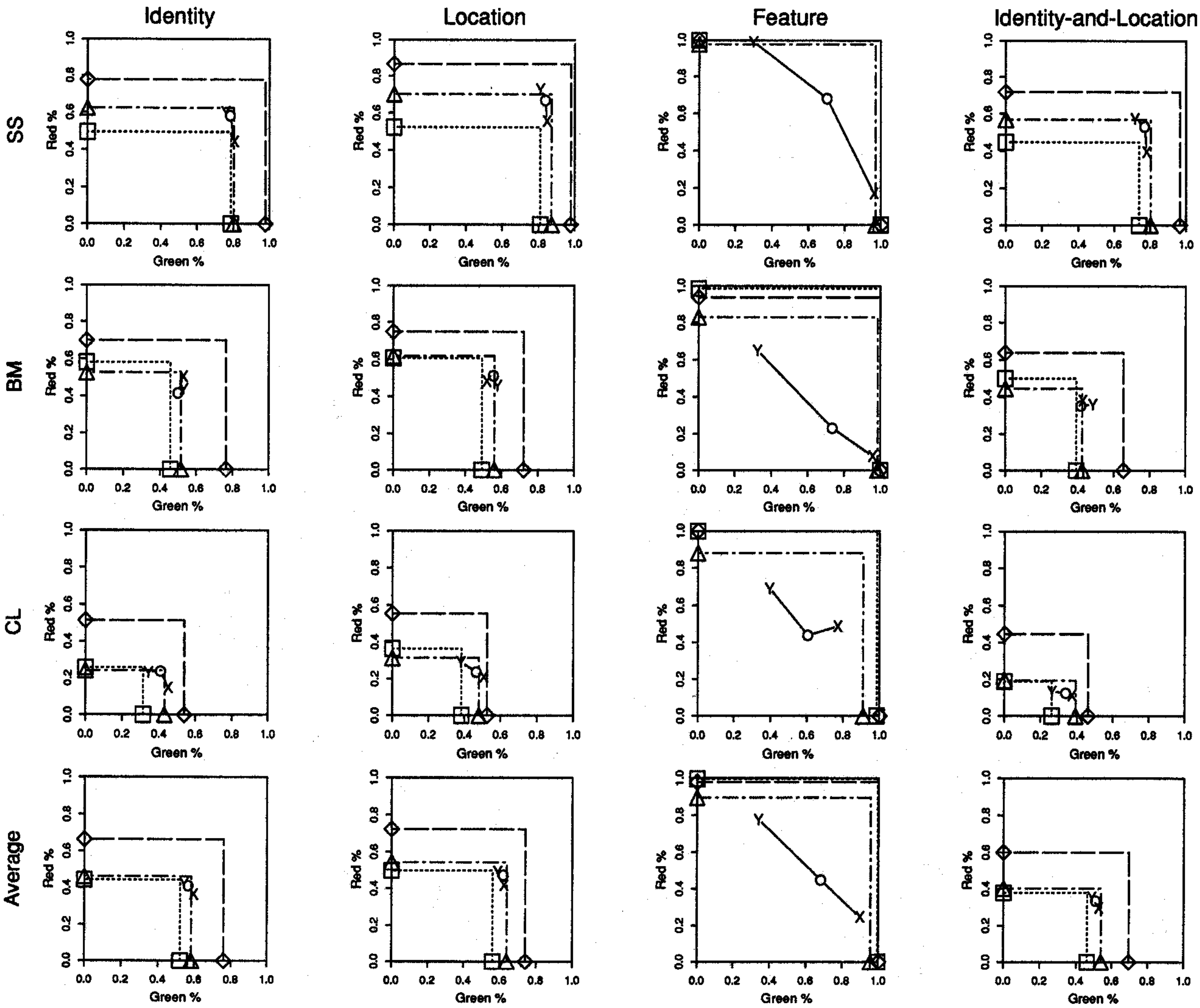

Figure 6. Attention operating characteristics for the color dimension in Experiment 1. The *x* axis is the percentage of correct responses for green targets, and the *y* axis is for red targets. Each row represents data from a different observer; each column represents a different response category. The *x* axis is the percentage of correct responses for large targets. The *y* axis is for small targets. X indicates the joint performance for the XY80 and YX20 (attend to X); O indicates *XY*50 and *YX*50, Y indicates XY20 and YX80 (attend to Y), where X = large and Y = small. Triangles indicate performance for the XY100 and YX100 conditions; squares for XX100 and YY100; diamonds for X−100 and Y−100. Three borders are indicated: The outermost border (long-dash lines), defined by X−100 and Y−100, represents the upper limit of expected performance. The innermost border (dotted lines), defined by XX100 and YY100, represents the lower limit of expected performance. The intersection of the middle-dash lines, defined by XY100 and YX100 is the independence point—the performance that would be achieved in divided attention tasks if there were no costs for dividing attention.

item with that feature value. Attentional selection is then made on the basis of spatial location.

Odd Item Stimuli

The stimulus presentation and task were the same as Experiment 1, except that only five of the six characters in the array had the same feature value and the sixth had a different value. The target item was always the odd item. In other words, the feature value of the odd item simultaneously served as a cue to the target's spatial location.

Strategic Options

In the experimental (feature-alternating) conditions of Experiment 1, attentionally filtering out the items of not-to-be-attended feature value would always eliminate one half of the arrays to be processed and, thereby, make the task much easier. In Experiment 2, the situation is quite different. Filtering out items with the not-to-be-attended feature might make the task harder. In successive arrays, it would leave 5, 1, 5, 1, 5, 1 ... items with the to-be-attended feature. A better strategy than perceptual filtering might be to first find the odd item, which would yield only one item to be searched in each array. The feature value could be used in combination with the odd-item search (directing attention to only odd items that have the requisite feature value), or the feature value might be used subsequently in the detection-decision process. In contrast to Experiment 1, the plausible strategic options involve either directing attention to a spatial location, or decision bias, or both, but not early perceptual filtering.

Method

The 3 observers, equipment, stimuli, stimulus dimensions, trial types, cues, procedure, exposure durations, ISIs, three responses, payoffs, and feedback are the same as in Experiment 1 (Figure 7). All arrays presented in Experiment 2 contain items with two feature values (red and green or large and small). The feature-alternating (XY), single-feature (XX), and half-blank (X) sequences are defined with reference to the odd items in a sequence (Figure 7). In the XY conditions of Experiment 2, the odd-item feature value alternates from array to array. In the XX and YY conditions, the feature value of the odd item remains the same throughout the sequence. The spatial location of each odd item was randomly chosen from among the three locations that were not identical or adjacent to the location of the odd item in the preceding array.

For each cued dimension, each observer completed seven experimental sessions. Each session consisted of 20 warm-up trials and 200 experimental trials. The 12 experimental conditions were intermixed within a session.

Results and Discussion

As in Experiment 1, all results are tabulated individually for each observer; data are summarized in four response categories: identity, location, feature, and identity-and-location; analyses and discussion will focus primarily on the identity, location, and identity-and-location categories. The results are the percentage correct of the four response categories for each condition of attentional instruction, each feature value, and each observer. As in Experiment 1, data for triple joint accuracy of identity, location, and feature did not differ significantly from joint identity-and-location accuracy and, therefore, are not further tabulated here. Figure 8 shows results for the size dimension, and Figure 9 shows results for color.

Again, results for the identity responses appear similar to those for the location and to the identity-and-location responses. Responses are more accurate for large targets than for small targets and are more accurate for green targets than red targets, as verified by matched *t* tests.

Efficiency of Attentional Filtering

As in Experiment 1, we approximate the maximum range of attentional filtering by $P(\text{X}-100) - P(\text{XX}100)$. As in Experiment 1, response accuracy in the half-blank condition (X−100) is higher than that of any of the other conditions (Table 3). However, the numerator for the index of attentional filtering, eff = $[P(\text{XY}100) - P(\text{XX}100)]/[P(\text{X}-100) - P(\text{XX}100)]$ is either zero or negative, whereas the denominator is positive. Hence, the efficiency of attentional filtering, as computed for Experiment 1, is negative or zero for the data of Experiment 2.

We expected the XX100 condition would be harder than the XY100 condition because, if the observer was able to direct attention only to the to-be-attended odd features, the XY100 condition would present the participants with 1, 0, 1, 0, ... items to process in successive arrays, whereas the XX100 condition would present the participants with 1, 1, 1, 1, ... items to process in successive arrays. In fact, there is a trend for XX100 to exceed XY100 in the size conditions and a statistically significant advantage of XX100 over XY100 in the color conditions. For example, 2 of the 3 observers in the detect-green conditions performed highly significantly better with GG100 than with GR100 (their green detections were better when all arrays had the same odd-green feature than when attending green in an alternating red-green odd feature). These data make the numerator in the search efficiency statistic zero or negative, indicating zero attentional selection, as in Experiment 1. The significance of XX100 superiority over XX100 will be considered below.

Effect of Attentional Instruction

The data show a significant trend for performance to improve with increasing amount of attention. The systematic performance variation because of cue validity is verified by a chi-square test across XY20, XY50, XY80, and XY100 conditions for each Observer × Feature Value × Response Category (Table 4). Unlike the null results of Experiment 1, 2 of the 3 observers showed highly significant attentional effects in both size and color dimensions, and the 3rd observer showed a strong trend in the same direction. In the odd-feature search, cue validity matters.

Costs and Benefits

Cost–benefit analyses using chi-square tests were performed to reveal the nature of the significant and marginally significant effects of attentional conditions (Table 5). Relative to the equal-attention condition (XY50), a cost is the reduction in response accuracy in the low cue validity condition (XY20), and a benefit is the increment in accuracy in the high cue validity conditions (XY80 and XY100). In the size dimension, there were moderate costs and benefits, but few reached statistical significance. In the color dimension, there were highly significant costs and benefits for 2 of the 3 observers. These are considered below in relation to AOCs.

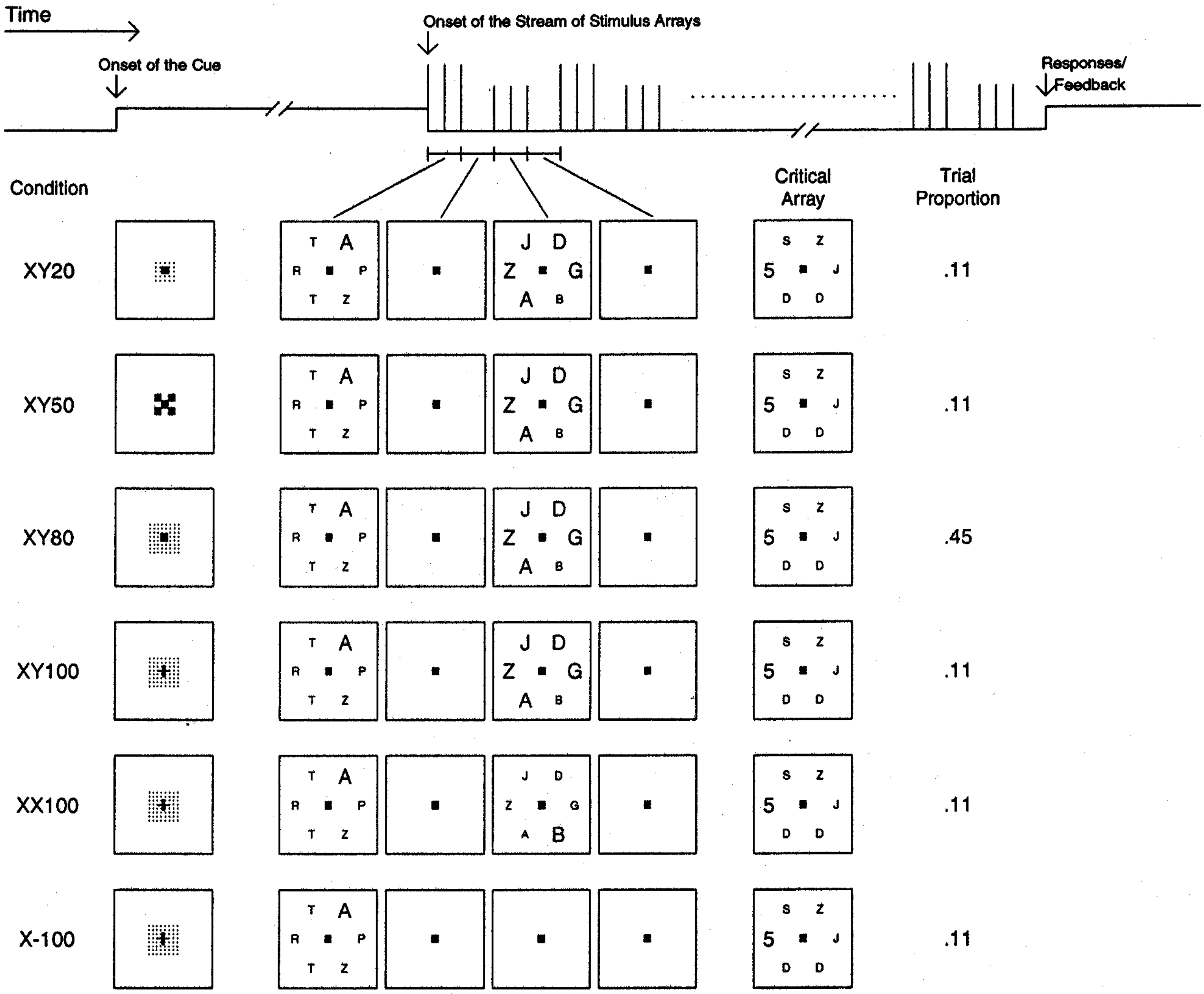

Figure 7. Procedure and representative conditions for Experiment 2. Every array has one item differing in size from the other five. The cued dimension is size (X = "large", Y = "small") and refers to the unique item in each array. A trial is initiated by a keypress (not shown) that produces a visual cue for 2 s (illustrated in leftmost column)—a symbol that indicates to the observer the possible feature values of the target and their probabilities. Then, a series of superimposed stimulus arrays is presented in rapid succession. Each array is exposed briefly (3 refreshes = 67 ms). Arrays are separated by blank screens with a fixation square (also 3 refreshes = 67 ms). The observer searches for an unknown digit (e.g., 5) among letters, typing responses (identity, location, feature value) at the end of the sequence. The central four columns indicate successive arrays prior to the critical array that is shown in the right-most column. Given large (X) targets, the six rows of arrays illustrate, from top to bottom, XY20, XY50, XY80, XY100, XX100, and X−100 conditions, where the numbers 20, 50, 80, and 100 indicate the probability of X targets in the condition. Given an X target, the column "Trial Proportion" indicates the conditional probability of each condition. The critical array is located between the 10th and 17th (or 5th and 9th for X−100) in a sequence. Ten (or 5 for X−100) arrays are presented after the critical array. Complete feedback is given after the responses.

Attention Operating Characteristics

Figures 10 and 11 regraph the data of Figures 8 and 9 in AOCs. Unlike Experiment 1, the three points X, O, and Y representing the three attentional allocations (20/80, 50/50, 80/20) are no longer clustered. Typical AOCs (negative slopes, concave toward the origin) are now observed in most of the data panels. There are costs for misdirected attention and benefits for correctly directed attention. As Table 4 indicated, many of these costs and benefits, taken individually, are not statistically significant. As a whole, however,

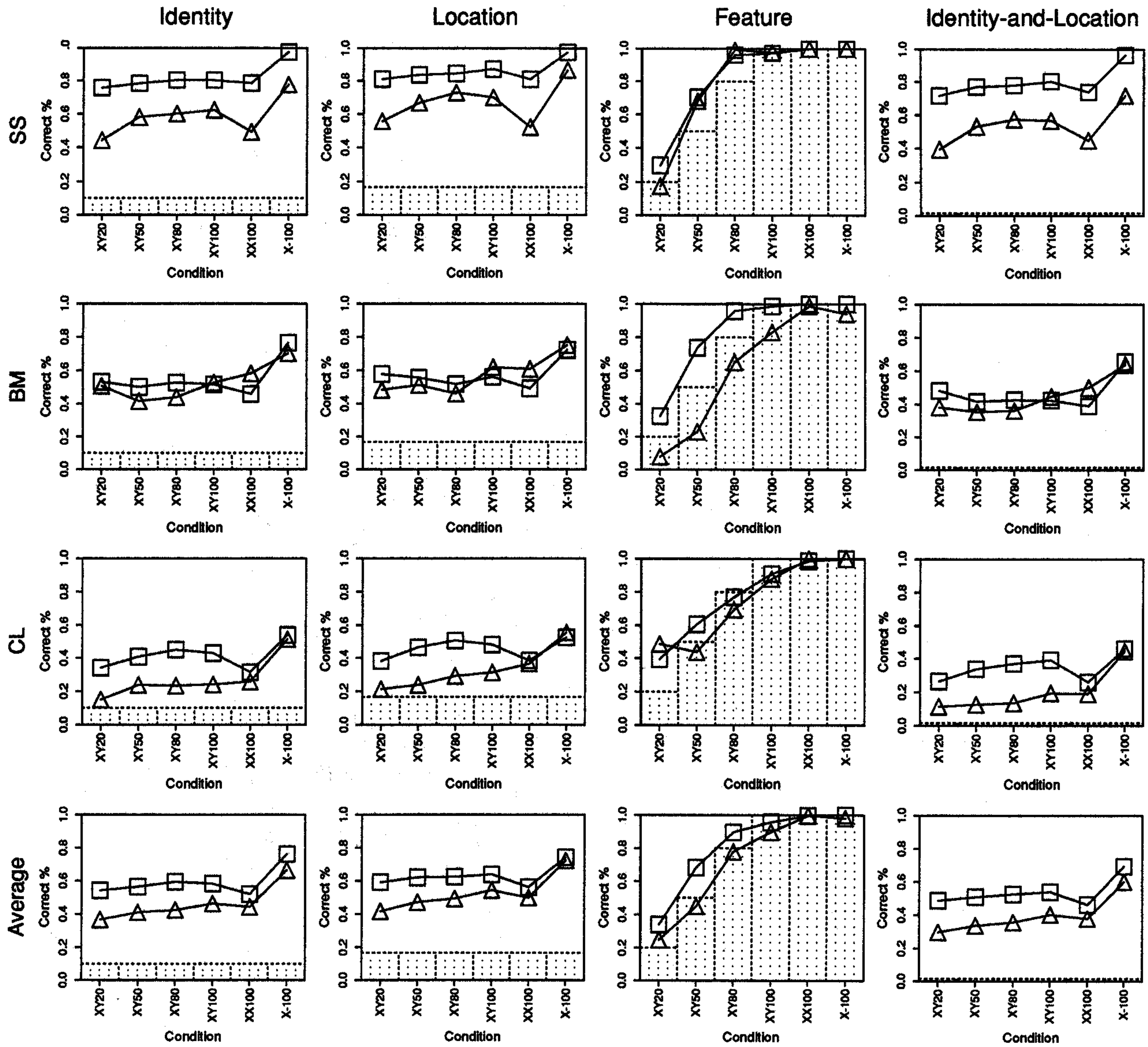

Figure 8. Percentage of correct responses versus experimental conditions for the size dimension in Experiment 2. Target feature value "large" is indicated by squares and "small" by triangles. The ordinate indicates the percentage of correct responses; the abscissa indicates the experimental conditions: XY20 indicates both XY20 and YX20, XY50 indicates both XY50 and YX50, and similarly for XY80, XY100, XX100, X−100. In the notation XYN, the first element, X, indicates the feature value of the target; the second element, Y, indicates the other feature value; and the third element, N, is the expected percentage of first-element targets. The dotted-line histogram below curves represents the expected probability of correct responses by pure chance guessing. Each row represents a different observer, and each column represents a different response category.

the picture is quite compelling, particularly for the color dimension.

To some extent, the stimulus asymmetries are expressed in the equal-attention condition as a bias to attend to the favored feature value. For example, observer S.S. behaved quite similarly in the equal-attention and the attention-to-green conditions. This results in the quite unsymmetric costs and benefits observed in Figure 10 and Table 5. On the whole, however, the results of Experiment 2 show that the same attentional manipulations that yielded no evidence for attention with the stimuli of Experiment 1 yield strong and consistent attentional effects in Experiment 2. Figure 12 shows a summary comparison of the main results of Experiments 1 and 2.

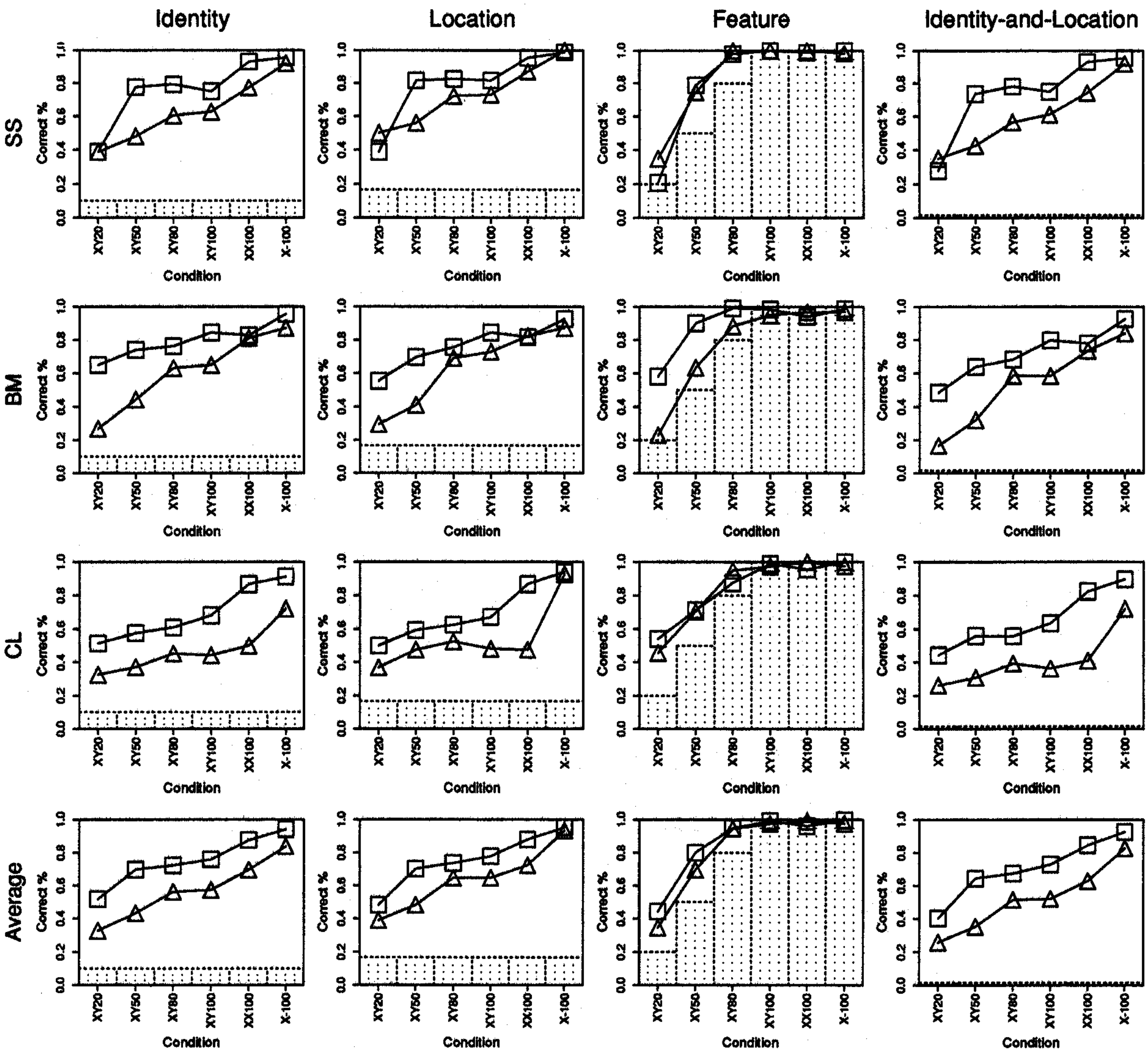

Figure 9. Percentage of correct responses versus experimental conditions for the color dimension in Experiment 2. Target feature value "green" is indicated by squares and "red" by triangles. The ordinate indicates the percentage of correct responses; the abscissa indicates the experimental conditions: XY20 indicates both XY20 and YX20, XY50 indicates both XY50 and YX50, and similarly for XY80, XY100, XX100, X−100. In the notation XYN, the first element, X, indicates the feature value of the target; the second element, Y, indicates the other feature value; and the third element, N, is the expected percentage of first-element targets. The dotted-line histogram below curves represents the expected probability of correct responses by pure chance guessing. Each row represents a different observer, and each column represents a different response category.

Two Anomalous Results and Their Explanations

Costs in Searching for an Odd Item: XY20 in Experiment 1 Versus Experiment 2

Except for the fact that in Experiment 1 each display was homogeneous (contained only one feature value) and in Experiment 2 each display contained five items with one feature value and an odd item with the other value, all other aspects of both experiments were the same: the same observers, display durations, characters, features, arrangements, and so on. Because, in Experiment 2, the observer knows that targets occur only as odd items, only one item in each display needs to be searched. This is potentially very useful information for the observer, and we expected target detection to be better in Experiment 2 than in Experiment 1. Indeed, averaged over all conditions and observers, performance in Experiment 2 was indeed better than in Experiment 1 for every condition except one: XY20.

In the condition XY20, the observer searched for a target with feature Y (which occurs with 80% probability), but the

Table 3
Chi-Square Values for Effects of Attentional Filtering in Experiment 2

Feature/Response category	XY100 versus XX100[a]			XY100 versus X−100[b]			XX100 versus X−100[c]		
	S.S.	B.M.	C.L.	S.S.	B.M.	C.L.	S.S.	B.M.	C.L.
				Size					
Small									
Identity (I)	0.05	1.26	0.02	30.68***	7.49*	9.46**	32.93***	13.65**	9.27*
Location (L)	0.24	1.06	0.81	15.37***	3.03	9.33**	19.02***	7.09*	5.09
I&L	0.00	0.97	0.85	30.10***	8.64*	14.59***	30.62***	14.13***	9.25**
Large									
Identity	0.31	1.20	0.70	6.50*	13.30**	6.28*	4.14	6.30*	3.38
Location	0.01	1.49	0.22	8.69*	9.09*	7.86*	9.19*	2.90	6.17*
I&L	0.11	1.97	0.35	11.02**	12.98**	7.82*	9.19*	4.04	5.59
				Color					
Red									
Identity	3.31	5.60	0.53	15.79***	11.70**	12.64**	5.20	1.23	8.12*
Location	3.90	2.17	0.01	19.65***	5.56	38.47***	8.69*	0.84	39.45***
I&L	2.48	4.13	0.36	17.04***	13.62**	20.30***	7.14*	3.03	15.59***
Green									
Identity	9.87**	0.07	7.21*	13.75**	4.55	11.75**	0.45	5.92	0.67
Location	7.58*	0.21	8.00*	14.51***	2.15	16.72***	1.89	3.84	2.13
I&L	9.87**	0.08	6.63*	13.75**	4.56	13.87***	0.45	6.09*	1.53

Note. S.S., B.M., and C.L. indicate participants.
[a] When XY100 is greater than XX100, it indicates the presence of attentional filtering.
[b] When X−100 is greater than XY100, it indicates that attentional filtering is not perfect.
[c] When X−100 is greater than XX100, the difference indicates the maximum range of possible attentional filtering.
* $p < .05$. ** $p < .01$. *** $p < .001$.

target actually occurs with feature X (20% probability). There are occasional striking cases in which detection in XY20 in Experiment 2 is much worse than detection in Experiment 1; for example, observer S.S., large targets and green targets; B.M., large targets and red targets. How do we interpret such results?

If, in Experiment 2, observers simply had been unable to locate the odd item in the XY20 displays, they would have had to process all six items, as in Experiment 1. However, the fact that they do worse in Experiment 2 than in Experiment 1 indicates that, at least sometimes, they find the location of the odd item and, because it has the not-to-be-attended feature value, they suppress the information from that location—a true cost! Experiment 1 showed that it was not possible to enhance (or to suppress information) from all six locations simultaneously. Experiment 2 shows that it is possible to enhance and also to suppress information from a single location.

Consistent Versus Inconsistent Odd Items

In both the XY100 and XX100 conditions, observers know with 100% certainty that the target will occur with feature value X. In the XY100 condition, features alternate in successive displays. Therefore, attentional selection at

Table 4
Chi-Square Values for Effects of Cue Validity in Experiment 2

Response category	Small targets			Large targets		
	S.S.	B.M.	C.L.	S.S.	B.M.	C.L.
Identity (I)	7.62	6.30	6.59	9.76	9.45	9.27
Location (L)	9.28	10.88*	2.34	21.04***	7.51	10.80*
I&L*	12.74*	9.14	4.11	17.39**	11.12*	5.74
	Red targets			Green targets		
Identity	15.23**	39.49***	5.63	51.08***	7.33	4.87
Location	19.44***	57.84***	6.99	66.85***	17.25**	5.37
I&L	16.74**	55.79***	6.35	74.55***	16.17**	5.79

Note. Each chi-square test is performed across XY20, XY50, XY80, and XY100 conditions. S.S., B.M., and C.L. indicate participants.
* $p < .05$, $\chi^2_{(.95,4)} = 9.49$. ** $p < .01$, $\chi^2_{(.99,4)} = 13.28$. *** $p < .001$, $\chi^2_{(.999,4)} = 18.47$.

Table 5
Chi-Square Values for Cost–Benefit Analyses in Experiment 2

Feature/Response category	Cost: XY20 versus XY50			Benefit: XY80 versus XY50			Benefit: XY100 versus XY50		
	S.S.	B.M.	C.L.	S.S.	B.M.	C.L.	S.S.	B.M.	C.L.
Size									
Small									
Identity (I)	—	—	—	—	—	—	—	—	—
Location (L)	3.94	1.58	—	0.07	1.68	—	0.07	1.55	—
I&L	5.23	1.84	—	0.32	1.21	—	0.13	0.67	—
Large									
Identity	1.20	3.92	5.42	0.08	0.03	0.07	4.79	0.00	0.02
Location	1.58	—	6.34*	4.37	—	0.09	8.31*	—	0.12
I&L	2.09	2.75	—	1.95	0.70	—	6.88*	0.64	—
Color									
Red									
Identity	1.35	5.55	—	3.81	9.80**	—	3.08	7.01*	—
Location	0.56	2.46	—	7.44*	22.68***	—	4.51	16.81***	—
I&L	0.96	5.39	—	4.69	19.02***	—	4.86	11.56**	—
Green									
Identity	22.91***	—	—	0.11	—	—	0.13	—	—
Location	28.27***	3.05	—	0.06	1.04	—	0.00	4.07	—
I&L	31.19***	3.31	—	0.73	0.51	—	0.03	4.12	—

Note. Cost–benefit analyses are only performed for the observer × feature value × response category that show significant and marginally significant effect of attentional instructions presented in Table 7.
* $p < .05$, $\chi^2_{(.95,2)} = 5.99$. ** $p < .01$, $\chi^2_{(.99,2)} = 9.21$. *** $p < .001$, $\chi^2_{(.999,2)} = 13.82$.

any stage could exclude one half of the items (the Y items) from further processing and thereby facilitate the remaining X items. In the XX100 condition, all of the displays have the same features, and there is no comparable role for selective attention. We might expect the XY100 conditions to be at least equal or superior to the XX100 conditions.

In Experiment 1, in which attention conditions apparently had no effect, XY100 and XX100 produced statistically indiscriminable data. In Experiment 2, there is a weak trend for XX100 to exceed XY100 in the case of size features. The data show, surprisingly, a highly significant superiority of XX100 over XY100 in the color dimension (3 Observers × 2 Feature Values). This surprising observation requires an explanation, and we consider two.

Two Possible Roles for Attention

The two following plausible attentional strategies in Experiment 2 are considered: (a) Attention acts after odd items have been located. In processing each individual item during the subsequent detection–decision process, attention allocates more weight or more processing resources to those items that have the to-be-attended feature value; and (b) attention acts before the odd item is located. The effect of an attention is to facilitate locating those odd items that have the to-be-attended feature value.

Does attention act after odd items have been located? Suppose that attention had its effect only after the odd item had been located (e.g., at a decision stage). We consider two related observations: the number of items being processed per unit time at the decision stage and the XY100 versus XX100 anomalous results.

The time from the onset of one display to the onset of the next is never less than 133 ms for any participant or condition. If only one (odd) item were delivered to the decision stage from each display, the detection stage would never have to process more than one item per 133 ms. The data of Sperling, Budiansky, Speelman, and Johnson (1971) and of Shiffrin and Schneider (1977) have suggested that 133 ms is enormously more—perhaps 10 times more—time than necessary to discriminate an unknown digit from a letter. On this basis, a decision stage would seem to be an unlikely bottleneck in which attention might make a difference.

Consider the superiority of XX100 versus XY100. If attention could exclude some of the Y items from consideration at the decision stage, XY100 performance should have been better than XX100, but it was not. Even if we suppose that excluding useless items when there is no bottleneck is not an advantage, however, it fails to explain the positive advantage of XX100 over XY100 in Experiment 2. These considerations mitigate strongly against a decision-stage explanation of selective attention.

Does attention act before odd items have been located? Both Experiments 1 and 2 showed that selective attention does not filter out items with unattended features to reduce a subsequent processing load. This constraint and the constraint that attention does not act after odd items have been located seem to leave attention only a very narrow range

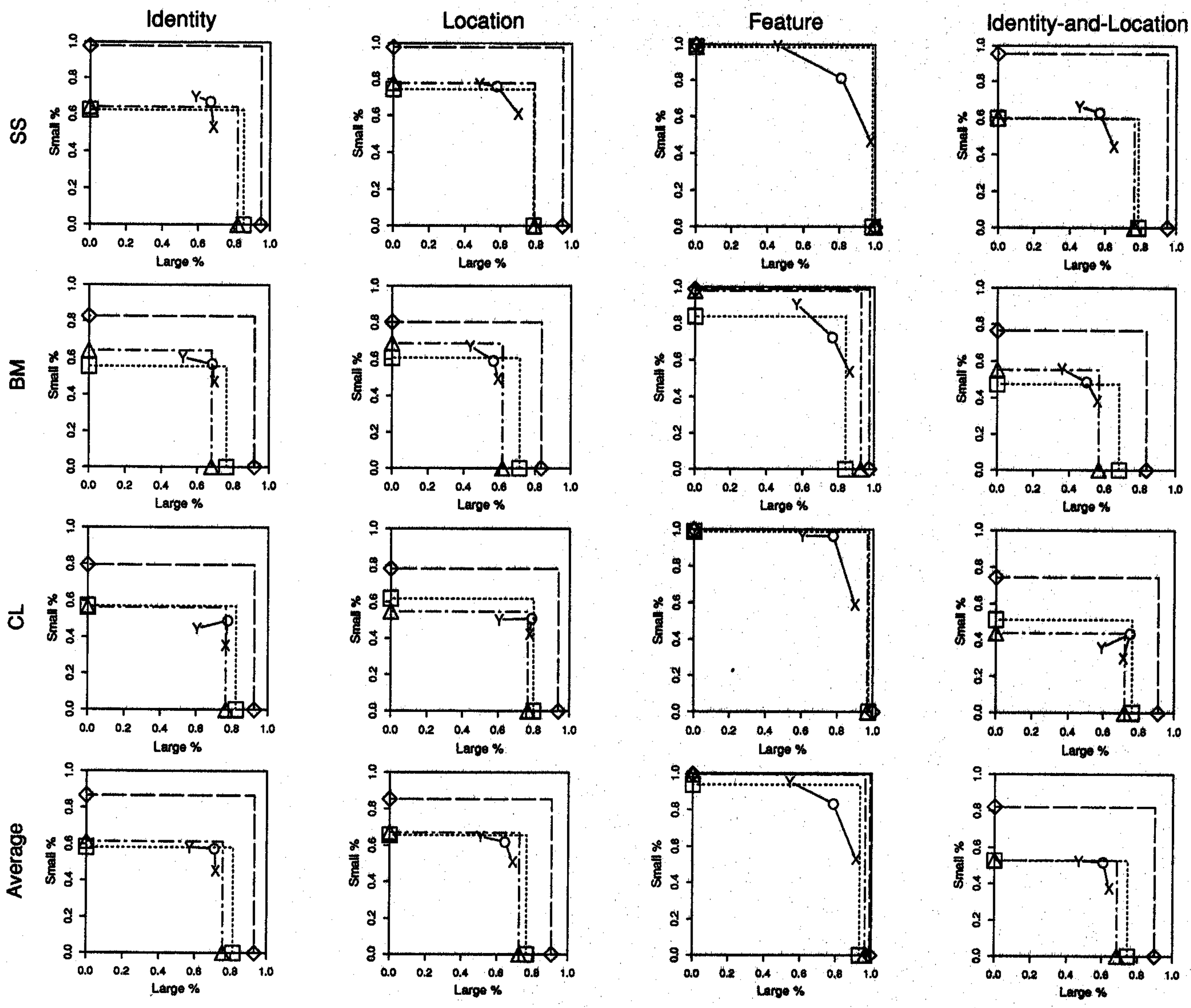

Figure 10. Attention operating characteristics for the size dimension in Experiment 2. The *x* axis is the percentage of correct responses for large targets and the y axis is for small targets. Each row represents data from a different observer; each column represents a different response category. The *x* axis is the percentage of correct responses for large targets. The *y* axis is for small targets. X indicates the joint performance for the XY80 and YX20 (attend to X); O indicates XY50 and YX50, Y indicates XY20 and YX80 (attend to Y), where X = large and Y = small. Triangles indicate performance for the XY100 and YX100 conditions; squares for XX100 and YY100; diamonds for X−100 and Y−100. Three borders are indicated: The outermost border (long-dash lines), defined by X−100 and Y−100, represents the upper limit of expected performance. The innermost border (dotted lines), defined by XX100 and YY100, represents the lower limit of expected performance. The intersection of the middle-dash lines, defined by XY100 and YX100 is the independence point—the performance that would be achieved in divided attention tasks if there were no costs for dividing attention.

within which to operate (i.e., in the process of locating the odd items). We propose that selective attention causes preferentially finding the location of odd items with to-be-attended features and that information from the selected locations is advanced to further processing.

At the level of discovering the locations to be searched, we consider two possible theories to explain how XX100 can yield equal or better performance that XY100. One possibility is that attention to X items in XY100 yields up to five X-item locations in odd-Y-item arrays, but only one X

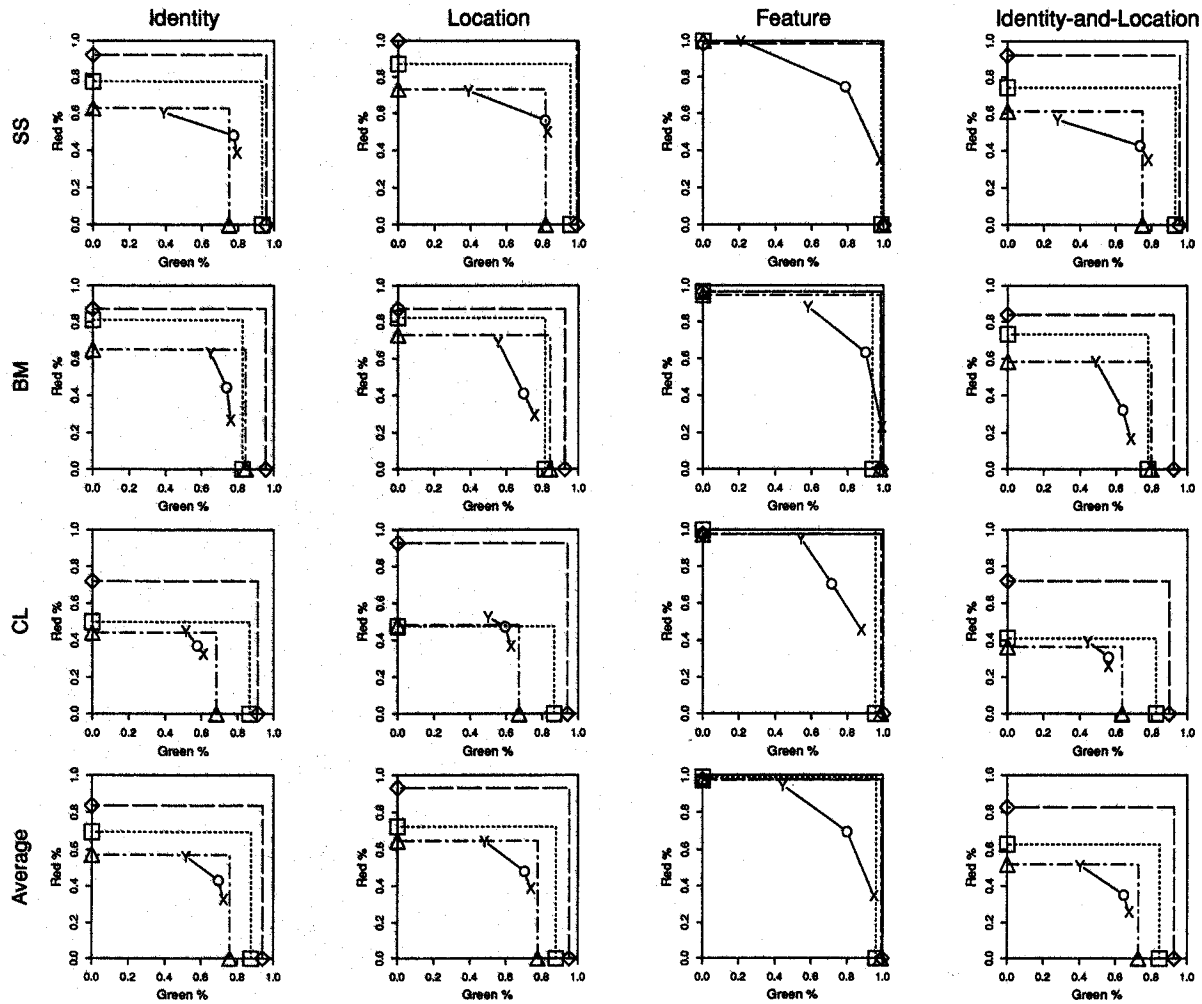

Figure 11. Attention operating characteristics for the color dimension in Experiment 2. The *x* axis is the percentage of correct responses for green targets and the *y* axis is for red targets. Each row represents data from a different observer; each column represents a different response category. The *x* axis is the percentage of correct responses for large targets. The *y* axis is for small targets. X indicates the joint performance for the XY80 and YX20 (attend to X); O indicates XY50 and YX50, Y indicates XY20 and YX80 (attend to Y), where X = large and Y = small. Triangles indicate performance for the XY100 and YX100 conditions; squares for XX100 and YY100; diamonds for X−100 and Y−100. Three borders are indicated: The outermost border (long-dash lines), defined by X−100 and Y−100, represents the upper limit of expected performance. The innermost border (dotted lines), defined by XX100 and YY100, represents the lower limit of expected performance. The intersection of the middle-dash lines, defined by XY100 and YX100 is the independence point—the performance that would be achieved in divided attention tasks if there were no costs for dividing attention.

location per array in the XX100 condition. The larger number of target-eligible X locations in XY100 search impairs performance relative to XX100. Alternatively, partial attention might be involuntarily drawn to odd items in XY100 sequences. Alternating attention between red and green would not be as successful in extracting only odd green items (the targets) as the constant green-attention strategy in the XX100 condition. These possibilities cannot be resolved with the data at hand.

Guided Search Theory

No Selective Filtering for Feature but Odd Items with the Cued Feature are Selected

Experiment 2 used the same stimulus presentation conditions, task, and observers as Experiment 1. The only difference was that, in Experiment 2, one of the six characters in each array had a different feature value from the other five,

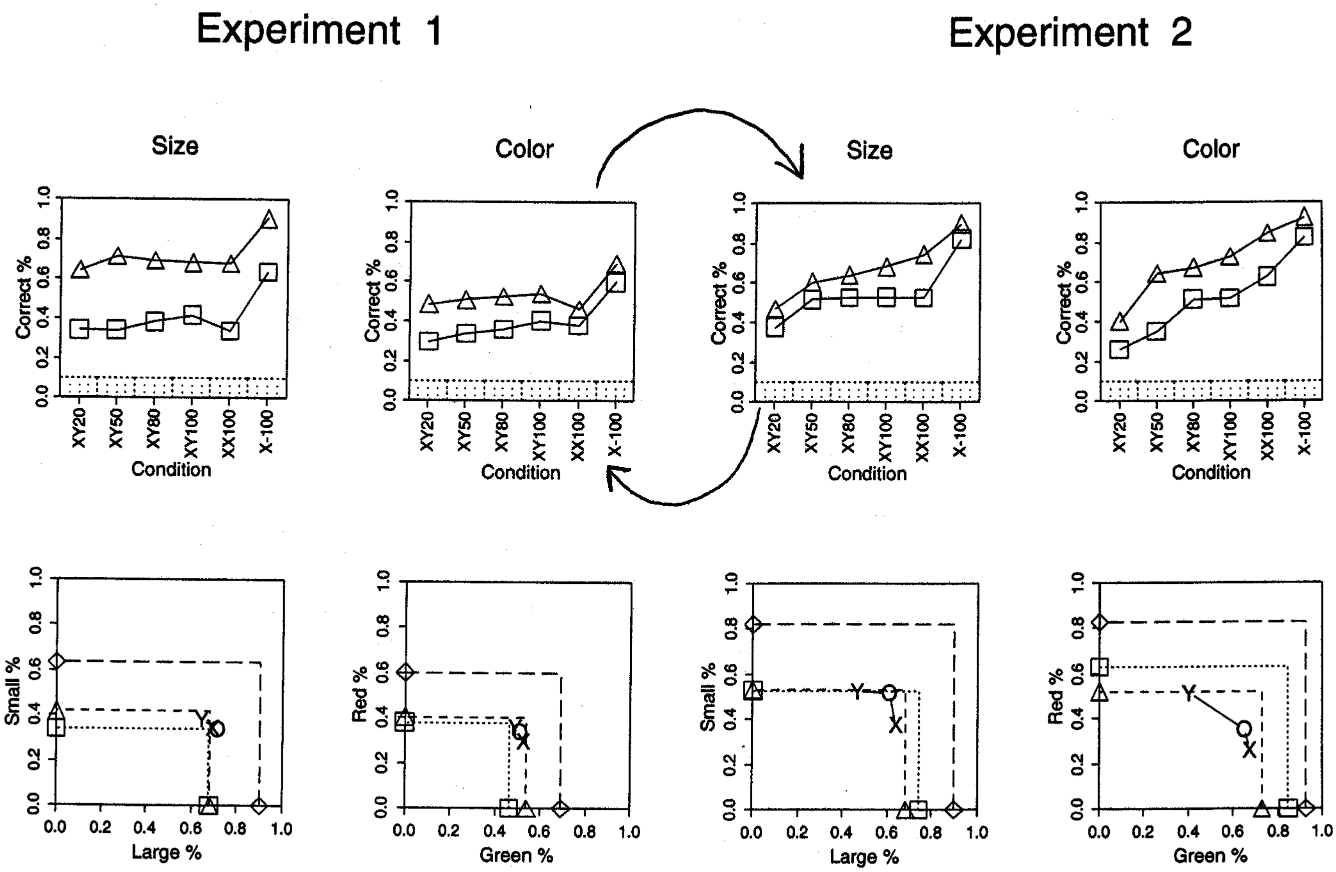

Figure 12. Summary graphs for Experiments 1 and 2. Data are averages of all observers of the item-and-location scores. Top row: Percentage of correct responses versus experimental conditions. Target feature values *large* and *green* are indicated by squares, *small* and *red* by triangles, XY20 indicates both XY20 and YX20 (20% probability of target), XY50 indicates both XY50 and YX50, and similarly for XY80, XY100, XX100, X−100. In the notation XYN, the first element, X, indicates the feature value of the target; the second element, Y, indicates the other feature value; and the third element, N, is the expected percentage of first-element targets. The dotted-line histogram under curves represents the expected probability of correct responses by pure chance guessing. Bottom row: attention operating characteristics (AOCs). The *x* axes are the percentage of correct responses for *large* and for *green* targets. The *y* axes represent correct responses for *small* and for *red* targets. X indicates the joint performance for the XY80 and YX20 (attend to X); O indicates XY50 and YX50; Y indicates XY20 and YX80 (attend to Y), where X = *large* or *green*; and Y = *small* or *red.* Triangles indicate performance for the XY100 and YX100 conditions, squares indicate performance for XX100 and YY100, and diamonds indicate performance for X−100 and Y−100. Three borders are indicated: The outermost border (long-dash lines), defined by X−100 and Y−100, represents the upper limit of expected performance. The innermost border (dotted lines), defined by XX100 and YY100, represents the lower limit of expected performance. The intersection of the intermediate-dash lines, defined by XY100 and YX100 is the independence point—the performance that would be achieved in divided attention tasks if there were no costs for dividing attention.

and the target was always an odd character. Unlike Experiment 1, in which the attentional conditions had no effect, Experiment 2 showed consistent costs for misdirected attention and benefits for correctly directed attention. The conclusion of Experiment 1 was that attention did not act to selectively filter items. This conclusion was further confirmed in Experiment 2. Analysis of apparently anomalous results suggested that, in Experiment 2, attention operated at the stage in which the location of odd items was discovered prior to the items being passed on to a decision stage for detection.

This view of the role of attention is highly consistent with the guided search theory originally proposed by Cave and Wolfe (1990) and again by Wright and Main (1996). In this theory, feature strengths are computed for each item in a multi-item array. The strengths determine the order in which items are scanned by subsequent processes. Uniqueness, relative to neighbors, is assumed to be a strong contributor to strength; this is how the theory explains the quick search of unique items. Having features similar to a known target contributes to strength. Finally, internal noise perturbs the strengths, adding a randomness to the search order.

Elaborated Guided Search

We would add one further assumption to the guided search theory: Attention adds to (or multiplies) the inherent strength of features, so that an attended feature has more strength and an unattended feature has (less strength) than the same feature in an attentionally neutral state.

In Experiment 1, according to this elaborated guided search theory, characters are searched in an order that (except for internal noise) corresponds to their similarity to the digit targets. There is not time to search all of the items, so successful performance is an (unknown) combination of number of items searched and the success in arriving at an optimum search order. In Experiment 2, all of the targets are odd items. Whereas odd items are presumed to have a higher search priority, performance in Experiment 2 is generally better than in Experiment 1. Indeed, we can estimate the value of oddness per se by comparing performance under equal attention conditions (XY50) in which attention is essentially unconstrained. There is only a slight benefit for Experiment 2 relative to Experiment 1, suggesting that oddness, by itself, in these displays, confers only a very modest benefit. However, correctly directed attention to an odd item significantly improves the search order, producing a benefit; incorrectly directed attention away from an odd item impairs the search order, producing a cost.

The guided search theory does not explain why performance on XX100 is better than on XY100 in Experiment 2. It would require an ad hoc elaboration such as those proposed above: Interference from nonodd X items selected for search from Y displays or involuntary attention switches to odd not-to-be-attended Y items.

In its original formulation, the computations of the guided search theory are indifferent as to the stage at which guidance is occurring. There were no operations to distinguish decision from selection processes—the formalism would be the same. Experiments 1 and 2 provide independent evidence that search guidance mechanisms actually do operate at the point at which items are selected for further processing—not earlier at the level of perceptual filtering or later at the level of detection–decision processes.

Summary and Conclusions

Experiment 1 investigated the possibility of selecting items on the basis of the physical features, size, or color. An RSVP search task was used in which successive arrays were perfectly superimposed. All six items in an array were presented with the same feature value (e.g., red). Successive arrays alternated in feature value (e.g., red, green or small, large). The task of the observers was to detect a target numeral among letter distractors. Before each trial, the observer was informed about the probability of the feature value with which the target would occur. The role of attention in Experiment 1 was to filter items containing the not-to-be-attended feature at an early processing stage so that one half of the arrays could be eliminated from processing. The results showed that attending to the feature value of the target (e.g., red or large) did not improve detection accuracy. The manipulation of cue validity yielded no costs for misdirected attention nor benefits for correctly directed attention. Under the conditions of Experiment 1, selective attention had zero efficiency as a filter for excluding items with the not-to-be-attended feature value from subsequent processing.

Experiment 2 used the same procedures, conditions, display durations, and observers as Experiment 1, except that each array contained an odd item differing in feature value from the other five. The target was always the odd item in the array. The role of attention in Experiment 2 was to direct processing to the location of the odd item so that only one item would need to be processed in each array. In contrast to Experiment 1, the manipulation of cue validity now yielded costs and benefits in response accuracy. Attending to the feature value of the target now facilitated target detection, and misdirected attention impaired target detection. Under similar presentation conditions to Experiment 1, attention could direct processing to the single location that contained the item with the to-be-attended feature value.

In conclusion, Experiment 1 showed that attention did not operate as a filter to exclude items from subsequent processing on the basis of the features size and color. The data of Experiment 2 were easily subsumed under a guided search model, in which attention operates by differentially directing perceptual processing to a location that contained the to-be-attended feature value. On the basis of these results, we conclude that where effects of attention to features had been found in visual search tasks, it was most likely not because items lacking the attended feature value were attentionally excluded at early processing stages but because the attended feature guided search processes to the likely location of the target.

References

Bravo, M., & Blake, R. (1990). Preattentive vision and perceptual groups. *Perception, 19,* 515–522.

Bravo, M., & Nakayama, K. (1992). The role of attention in different visual-search tasks. *Perception & Psychophysics, 51,* 465–472.

Broadbent, D. E. (1958). *Perception and communication.* London: Pergamon Press.

Cave, K. R., & Kosslyn, S. M. (1989). Varieties of size-specific visual selection. *Journal of Experimental Psychology: General, 118,* 148–146.

Cave, K. R., & Pashler, H. (1995). Visual selection mediated by location: Selecting successive visual objects. *Perception & Psychophysics, 57,* 421–432.

Cave, K. R., & Wolfe, J. M. (1990). Modeling the role of parallel processing in visual search. *Cognitive Psychology, 22,* 225–271.

Cheal, M., & Lyon, D. R. (1992). Attention in visual search:

Multiple search classes. *Perception & Psychophysics, 52,* 113–138.

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review, 96,* 433–458.

D'Zmura, M. (1991). Color in visual search. *Vision Research, 31,* 951–966.

Egeth, H., Jonides, J., & Wall, S. (1972). Parallel processing of multielement display. *Cognitive Psychology, 3,* 674–698.

Holliday, I. E., & Braddick, O. J. (1991). Pre-attentive detection of a target defined by stereoscopic slant. *Perception, 20,* 355–362.

Larsen, A., & Bundesen, C. (1978). Size scaling in visual pattern recognition. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 1–20.

Moraglia, G., Maloney, K. P., Fekete, E. M., & Al-Basi, K. (1989). Visual search along the colour dimension. *Canadian Journal of Psychology, 43,* 1–12.

Nissen, M. J. (1985). Accessing features and objects: Is location special? In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 205–219). Hillsdale, NJ: Erlbaum.

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

Rock, I., & Gutman, D. (1981). *Journal of Experimental Psychology: Human Performance and Perception, 7,* 275–285.

Shiffrin, R. M. (1988). Attention. In R. A. Atkinson, R. J. Herrnstein, G. Lindzey, & R. D. Luce (Eds.), *Stevens' Handbook of experimental psychology: Vol. 2. Learning and cognitive* (pp. 739–811). New York: Wiley.

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

Sperling, G., Budiansky, J., Spivak, J. G., & Johnson, M. C. (1971, October 15). Extremely rapid visual search: The maximum rate of scanning letters for the presence of a numeral. *Science, 174,* 307–311.

Sperling, G., & Dosher, B. A. (1986). Strategy and optimization in human information processing. In K. Boff, L. Kaufman, & J. Thomas (Eds.), *Handbook of perception and performance: Vol. 1* (pp. 1–65). New York: Wiley.

Sperling, G., & Melchner, M. J. (1978, October 20). The attention operating characteristic: Examples from visual search. *Science, 202,* 315–318.

Sperling, G., Wurst, S. A., & Lu, Z.-L. (1992). Using repetition detection to define and localize the processes of selective attention. In D. E. Meyer & S. Kornblum (Eds.), *Attention and performance, XIV* (pp. 265–298). Cambridge, MA: MIT Press.

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics, 51,* 599–606.

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,* 15–48.

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

Tsal, Y., & Lavie, N. (1993). Location dominance in attending to color and shape. *Journal of Experimental Psychology: Human Performance and Perception, 19,* 131–139.

Wright, C. E., & Main, A. M. (1996). *Selectivity searching for conjunctively defined visual targets* (Institute for Mathematical Behavioral Sciences, Tech. Rep. Series MBS-96-14). University of California, Irvine.

Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). A modified feature integration model for visual search. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 419–433.

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