Set-Size Effects in Visual Search: the Effect of Attention is Independent of the Stimulus for Simple Tasks

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In visual search, both attentional and non-attentional sensory processes contribute to set-size effects. Here, non-attentional sensory effects were controlled and the remaining effects matched closely the purely attentional effects measured by a cueing paradigm. Using these controls, set-size effects were measured for five simple and two more complex tasks. The set-size effects were of similar magnitude for all of the simple tasks and larger for the complex tasks. For stimuli in the simple tasks, the results were consistent with the existence of a purely attentional effect on decision processing that is independent of the particular stimulus.

Visual search Attention Texture discrimination Discrimination threshold

INTRODUCTION

Visual search tasks stand at a critical point between psychophysical tasks such as detection and discrimination and more cognitive tasks such as reading and scene recognition. In visual search, the subject must indicate whether or not a target stimulus occurred among some set of visual stimuli that includes distractors as well as possible targets. This task can be as simple as finding a target disk with greater luminance than a set of distractor disks or as complex as finding the letter “q” in this paragraph. For simple cases such as searching for luminance increments, there is a potential for relating the search process to the basic sensory processes of luminance discrimination. This connection can be made by considering manipulations of the number of stimuli, here referred to as the display set size. If there is only one stimulus, then search is a simple luminance discrimination. With more stimuli, performance declines in what is known as the set-size effect. For example, Palmer, Ames and Lindsey (1993) measured search for a longer line among shorter lines and found that the threshold for a discriminable difference in line length doubled as the set size increased from one to eight. In this article, I consider three issues critical to relating this set-size effect to sensory processing: the degree of stimulus dependence, whether the effects are sensory or attentional, and whether the effects are mediated by perception or decision.

Three issues

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Stimulus dependence. The first issue is whether the set-size effect depends on the particular stimulus. It would be particularly interesting to find a situation in which set-size effects are independent of the choice of the stimuli. For such a situation, one can analyze search separately from the details of the stimulus.

Sensory vs attentional effects. The second issue is to distinguish between effects of sensation and attention. By sensory effects, I mean phenomena determined by the immediate stimulus alone such as the effects of eccentricity or masking. Such sensory effects are not under voluntary control. By attentional effects, I mean phenomena influenced by voluntary control such as the effect of cueing a particular stimulus as relevant to a task. In general, increasing the set size in visual search will result in both sensory and attentional effects. The immediate stimulus is different and the number of relevant stimuli is increased. This distinction is particularly relevant here because the dependence of set-size effects on the stimulus is likely to be different for sensory and attentional contributions to the set-size effect.

Perception vs decision. The third issue is to distinguish between the perceptual coding and decision integration hypotheses (Shaw, 1982). By the perceptual coding hypothesis, the quality of the perceptual code for individual stimuli is degraded for displays with larger set sizes. By the decision integration hypothesis, the individual perceptual codes are unaffected but instead the integration of multiple noisy percepts results in worse performance with larger set sizes. From this decision integration hypothesis one can derive that a particular
measure of the set-size effect will be independent of the stimulus.

BACKGROUND

Stimulus dependence

The influence of the choice of stimuli on set-size effects is a basic question for visual search. Unfortunately the answer is obscured by the variety of tasks used to measure search performance. One can measure search over many eye fixations or one, for simple search stimuli such as luminance increments or more complex stimuli such as letters, and for performance measured by latency or by accuracy (for a review see Palmer et al., 1993; for reviews with other perspectives see Egeth, Folk & Mullin, 1989; Teichner & Krebs, 1974; Wolfe, 1992).

For search involving many eye fixations, the effect of set size on latency is sensitive to the exact stimulus and task. For this paradigm, the set-size effect is typically measured by the slope of a linear function and varies widely from 0 to over 100 msec per item (e.g. Treisman & Gormican, 1988).

The variability of set-size effects may be reduced if one equates stimulus discriminability before comparing set-size effects (e.g. Duncan & Humphreys, 1989; Palmer, 1990; Palmer et al., 1993; Pavel, 1990; Pavel, Econopouly & Landy, 1992). This control is necessary because the magnitude of the set-size effect depends strongly on the discriminability between the targets and distractors (e.g. Bergen & Julesz, 1983; Nagy & Sanchez, 1990; Pashler, 1987). This approach changes the issue to whether or not set-size effects depend on the stimulus once the effect of discriminability is controlled.

Systematic measures of set-size effects while controlling for discriminability have been undertaken for search experiments using brief displays to limit eye fixations and measurements of accuracy. Palmer et al. (1993) measured difference thresholds for set sizes one to eight. The results showed that the log threshold increases roughly linearly with log set size. Palmer et al. (1993) summarized the set-size effect using the slope of this linear approximation. This slope measure is independent of the units of both axes. Such a property is essential to make meaningful comparisons between tasks with different stimuli. Using this measure, Palmer et al. (1993) measured line length, line orientation, and shape elongation tasks and found slopes of 0.29, 0.24, and 0.26, respectively. Thus, these three tasks had set-size effects of similar magnitude when measured at a given discriminability and by an appropriately dimensionless measure.

A contrasting result was obtained by Vergheze and Nakayama (1994). They briefly presented stimuli followed by a mask and determined the duration for threshold performance at several levels of discriminability and at several set sizes. These data were used to estimate the tradeoff between duration and discriminability that gave threshold performance. These tradeoff functions were measured for different set sizes to obtain a detailed description of the set-size effect. Using this method, Vergheze and Nakayama compared the set-size effects for stimuli varying in orientation, color and spatial frequency. Their results showed little or no set-size effect for color, intermediate results for spatial frequency, and the largest set-size effect for orientation. Thus, the effects of set size depended strongly on the stimulus for this paradigm.

There are several possible reasons for the different results found by Palmer et al. (1993) and Vergheze and Nakayama (1994). The obvious reasons are the different stimulus spacings (density), the use of a visual mask, and the different ranges of set size and discriminability. Rather than explore these differences, the aim of this article is to pursue conditions under which set-size effects are independent of the stimulus.

Sensory vs attentional effects

An important complication to the analysis of set-size effects is that they can be due to both sensory and attentional phenomena. Sensory phenomena are defined as those determined by the immediate stimulus and not under voluntary control. They include effects of eccentricity and masking. Attentional phenomena are defined as those that can be influenced by voluntary control. A typical example is the effect of instructions or informational cues (e.g. Grindley & Townsend, 1968; Palmer, 1990).*

Sensory contributions to set-size effects. Investigations of the sensory contribution to set-size effects have followed three approaches. First, consider studies of sensory variables that are often confounded with set size. These include the effects of multiple eye fixations found with larger set sizes (Ericson & Spencer, 1969; Irwin, 1991; Rayner & Fisher, 1987), eccentricity effects due to using larger displays (Aulhorn & Harms, 1972; Yager & Davis, 1987), masking effects due to changes in stimulus spacing (Breitmeyer, 1984; Gorea, 1987; Kröse & Burbeck, 1989), heterogeneity effects due to more than one kind of distractor (Callaghan, 1989; Farmer & Taylor, 1980), and configuration effects due to changes in the regularity of spacing (Bloomfield, 1972). Second, some studies have sought to measure the interaction between display set size and these sensory variables. For example, some have explicitly modeled the role of sequential eye fixations in search (Bloomfield, 1979; Williams, 1966; Zelinsky, Steinberg & Büllof, 1993). This approach has been elaborated (Chou & Geisler, 1992) by predicting performance in multiple-eye-motion search from the discriminability of the targets and distractors in brief peripheral displays. Third, several studies have tried to minimize these sensory effects. For example, brief displays have been used to eliminate the effects of multiple eye fixations, stimuli have been displayed in a circle around

*For current purposes, I will not consider possible exceptions to this dichotomy such as passive attention (James, 1980; also called stimulus-driven attention, Yantis & Jonides, 1990). For further discussion see Palmer (1993).
fixation to minimize eccentricity effects, and large spacing has been used to minimize spacing effects (Estes & Taylor, 1964; Eriksen & Spencer, 1967; Palmer et al., 1993).

Eliminating sensory contributions. Despite these efforts to minimize sensory effects, there will always remain the potential for sensory contributions as long as different displays are presented to a subject for different set sizes. This problem is resolved using cueing paradigms that measure purely attentional effects (Broadbent, 1958; Eriksen & Lappin, 1967; Grindley & Townsend, 1968; Nakayama & Mackeben, 1989; Palmer, 1990). In these paradigms, the same displays are always presented to a subject and the manipulation is an instruction or cue prior to the critical stimulus. Palmer et al. (1993) used 100% valid cues presented 1 sec before a display to indicate the relevance of two, four, or eight stimuli of an eight stimulus display. This cue manipulation varied the relevant set size while holding constant the display set size. This manipulation of relevant set size had an effect. Moreover, the magnitude of the effect was similar to that found with a corresponding manipulation of display set size. When measured by the slope on a log-threshold by log-set-size plot, the slope was 0.21 for the relevant-set-size condition compared to 0.28 for the display-set-size condition. The difference between these effects was not reliable. The cueing manipulation provides a pure measure of the attentional contribution to the set-size effect. It also suggests that, under the conditions of Palmer et al. (1993) the bulk of the display-set-size effect was attentional and not sensory.

Perception vs decision

Once a set-size effect is determined to be attentional, one can ask what kind of attentional process is responsible. I will review two hypotheses that have been central to theories of attention and then review the evidence distinguishing these theories for the domain of visual search.

The perceptual coding hypothesis. By this hypothesis, the perception of an individual stimulus is affected by the number of stimuli attended. In an early version of this hypothesis, Broadbent (1958) suggested that there is a limit on the total information capacity of the perceptual system. For such a system, the information extracted for each stimulus is inversely proportional to the number of stimuli. One process model for such an account is the sample size model (Lindsey, Taylor & Forbes, 1968; Green & Luce, 1974; Shaw, 1980; for a related approach see Verghese & Pelli, 1992). In this model, perception is constructed from a number of internal samples of sensory representations. If only one stimulus is relevant, then all of the samples can be directed to the representation of that stimulus. On the other hand, if n stimuli are relevant, then the samples must be distributed over the n relevant representations. Given noisy sensory information, the combined percept is less precise for a reduced number of samples. By this mechanism, dividing attention affects the quality of the perception of an individual stimulus.

Perhaps the strongest version of the perceptual coding hypothesis was presented by Posner, Snyder and Davidson (1980) who argued that all percepts are subject to limited-capacity processing. Weaker versions have been presented in which some aspects of processing are subject to capacity limits and others are not (Broadbent, 1971; Neisser, 1967). These variations add more details to the theory to account for a variety of phenomena. They include a revised version of the preattentive/attentive theory (Julesz, 1990), feature integration theory (Treisman & Gelade, 1980) and guided search theory (Wolfe, Cave & Franzen, 1989). All share the concept that some kinds of perceptual processing show capacity limits.

The decision integration hypothesis. By this hypothesis, the perception of an individual stimulus is not affected by the number of stimuli attended. Instead, the effect is on the integration of information from multiple stimuli. Tanner (1956, 1961) and others (Cohn & Lasley, 1974; Green & Birdsall, 1978; Kinchla, 1974; Pelli, 1985; Shiffrin & Geisler, 1973; Swensson & Judy, 1981; and Yager, Kramer, Shaw & Graham, 1984) have pointed out that integrating noisy sources of information will result in a decline of performance with the additional sources. Each additional stimulus contributes a new source of noisy information that results in another chance to make a false alarm. Thus, the many-to-one integration process poses a limit to performance even if the one-to-one coding process does not limit performance.

The decision integration hypothesis has been extensively applied to detection and search (for reviews see Graham, 1989; Shaw, 1982; Sperling & Dosher, 1986; Swets, 1984). For a simple example of its application see Davis, Kramer and Graham (1983). In that article, the simplest form of the decision integration hypothesis was referred to as the "maximum-output version of the multiple-band model" due to its origins in auditory psychophysics.

I consider this effect on decision to be attentional because the subject is assumed to have control over what sources of information are monitored. This usage differs from the usage of others who restrict the term attention to refer to limited-capacity perception and not to limits by decision. The more general definition is used here to be consistent with usage of the term attention in domains such as memory and decision as well as perception.

Critical experiments. Shaw (1980, 1984) distinguished between the perceptual coding and decision integration hypotheses. She calculated the set-size effect expected if one assumes Gaussian variability and a maximum rule in which one responds only to the percept most consistent with the target (for a discussion of more general assumptions see Graham, Kramer & Yager, 1987; Yager et al., 1984). She then calculated the expected effect if one adds a limited-capacity perception coding (the sample size model) before the decision process. Shaw (1984) compared these predictions to measurements of set-size effects for both luminance increments and alphabetical characters. She found that luminance
increments matched the predictions of the decision integration hypothesis and fell short of the predictions of the perceptual coding hypothesis. In contrast, the character task had larger set-size effects that matched the prediction of the perceptual coding hypothesis and exceeded the prediction of the decision integration hypothesis. A similar analysis by Palmer et al. (1993) showed that search for line length, line orientation, and shape elongation all resulted in set-size effects consistent with the decision integration hypothesis. Palmer et al. (1993) derived the decision integration prediction for a log-threshold versus log-set-size function and summarized the effect by the slope of a linear approximation. For set sizes from one to eight, a slope of 0.25 is predicted for yes-no tasks and a slope of 0.31 is predicted for a two-interval forced-choice task. Unless one changes the assumptions about the decision rule or the noise distribution, these predictions will be the same for any stimulus. In summary, once sensory contributions to set-size effects are controlled, the decision integration hypothesis predicts a set-size effect of a particular magnitude that is independent of the stimulus.

Overview of experiments

Set-size effects were measured for seven tasks to determine their dependence on the stimulus. In Experiments 1 and 2, the manipulations of display and relevant set size were refined and applied to searching for a luminance increment. In Experiment 3, these paradigms were extended to four other similar search tasks. In Experiments 4, 5 and 6, the limits of the analysis were explored for two more complex search tasks, for a forced-choice procedure, and for a larger set size.

GENERAL METHOD

Subjects

Subjects were young adults with normal or corrected to normal acuity. They were paid $10/hr and had previous experience in psychophysical tasks. They were identified by noncontiguous numbers that are the same as those used in related studies (Palmer, 1988, 1990; Palmer & Ames, 1992; Palmer et al., 1993).

Apparatus

The experiments were conducted on either a monochrome or a color display. Both were video monitors controlled by Macintosh computers.

Monochrome display. This video monitor was an Apple Two-Page display with 1152 × 870 pixels and resolution of 30 pixels/cm. It was viewed from a distance of 56 cm, which resulted in 2 arc min per pixel for the central 1° viewing area. The entire display was 38 × 29 cm which subtended 37° × 29°. The stimuli on the video were presented with a gray surround (x = 0.28, y = 0.31, CIE 1931) of 25 cd/m². The dimly lit room also illuminated the display face resulting in a background luminance of 0.25 cd/m². The temporal resolution of this display system was 75 Hz.

Color display. This video monitor was a Barco 6451 display with 640 × 480 pixels and a spatial resolution of 19 pixels/cm. It was viewed from a distance of 61 cm that resulted in 3 arc min per pixel in the central 1° viewing area. The visible field was 34 × 26 cm which subtended 31° × 24°. In the experiments, stimuli were presented within a white appearing surround (x = 0.44, y = 0.40, CIE 1931) with a luminance of 50 cd/m². The dimly lit room also illuminated the face of the Barco display by 0.5 cd/m². The temporal resolution of this display system was 67 Hz.

Stimuli

Stimuli for these experiments included disks, ellipses, Gaussian-luminance profile "blobs", and letter-like forms. Typical spatial dimensions were 1° or smaller. Targets differed from distractors along one dimension such as size or color. For example, in Experiment 1, the distractors were 20% contrast white disks with a diameter of 0.5° and the targets differed in having a higher contrast. In all but the line bisection task of Experiments 4 and 5, the distractors were identical to one another.

Display set size was varied in all of the experiments in the fashion illustrated in Fig. 1. To prevent configurational cues, the display locations were randomized within certain constraints: (a) eccentricity of the center of each stimulus was between 5° and 8°; (b) center-to-center spacing between stimuli was 3° or larger; (c) the density was held approximately constant for set sizes greater than 1 by randomly picking positions within a segment with an area proportional to the set size. For example, stimuli were presented in the entire display area for Set Size 8 but within only one quarter of the area for Set Size 2. The location of these restricted display areas was randomly chosen from trial to trial.

Procedure

In all but the last experiment, subjects made a yes–no response to indicate whether or not the target was present. In the last experiment, a forced-choice response was required. For all experiments, there was no time pressure and tones provided accuracy feedback. Trials were presented in blocks of 48 trials and 12 blocks made up a session. Set size varied between blocks and was always constant within a block. Subjects participated in several sessions of practice before participating in any of the reported experiments.

In each experiment, the discriminability of the target from the distractor was varied to measure a psychometric function. Different targets were run in separate blocks. For example, in Experiment 1, the distractors had a contrast of 20% and the targets had higher contrasts ranging from 28 to 44% (contrast increments of 8–24%). For each subject, a generalized regression analysis was used to fit the observed psychometric function (Finney, 1971) and to estimate the stimulus difference threshold necessary for 75% correct discrimination.
EXPERIMENT 1: DISPLAY SET SIZE

In this first experiment, the display set size was varied. The stimuli were white disks and the task was to search for a target with a higher contrast. This task is illustrated in Fig. 1 with the higher luminance target among the lower luminance distractors.

Method

The sequence of displays is shown in Fig. 2. A fixation display was shown for 1000 msec followed by the test display for 100 msec. After this, the display was blank until the subject responded. The stimuli were 0.5° white disks with distractors of 20% contrast and targets with contrast increments ranging from 8 to 24%. For each subject, contrast increment thresholds were estimated for set sizes 1, 2, 4 and 8. Four subjects (30, 36, 37, 38) participated for eight sessions with 1152 trials per set-size condition per subject.

Results

As shown in Fig. 3, display set size has an effect on the increment contrast threshold. In this graph, both axes are logarithmically scaled and span one log unit. The bold curve indicates the mean difference threshold for four subjects and the light curves indicate the individual subject thresholds. The effects of log set size on log contrast threshold are approximately linear with a mean slope of 0.30 ± 0.03. The slope is also reliably different from zero for all of the individual subjects. Subjects 30, 36, 37, and 38 have slopes of 0.31 ± 0.08, 0.27 ± 0.07, 0.39 ± 0.10, and 0.40 ± 0.15, respectively.*

In summary, the effect of set size is robust and similar across subjects.

Discussion

This experiment quantified the set-size effect for luminance increments. The magnitude for this task was the same as reported previously for line length tasks (Palmer et al., 1983). Moreover, for this yes–no task with set sizes 1 to 8, a slope of 0.25 is predicted by the decision integration hypothesis (Palmer et al., 1983). In this hypothesis, it is presumed that sensory processes do not contribute to set-size effects. The next experiment tests this assumption.

EXPERIMENT 2: RELEVANT SET SIZE

In this experiment, I turn to distinguishing between sensory and attentional contributions to the set-size effect. In any manipulation of display set size, the changes in the display may introduce sensory effects. In contrast, the manipulation of relevant set size...
(Palmer et al., 1993) uses constant displays to prevent any sensory effect. Experiment 2 used both the display-set-size manipulation of Experiment 1 and a corresponding relevant-set-size manipulation. Targets and distractors were the same as Experiment 1. For the relevant-set-size conditions, eight stimuli were always displayed and either two or all eight were cued as relevant. The cue was always 100% valid. When two stimuli are cued, the subject is instructed to attend to only those two stimuli.

Method

The experiment employed four conditions. The first two replicated Display Set Size 2 and 8 of Experiment 1 in all respects. The second two conditions held constant the display set size and manipulated the relevant set size. The method of cueing the relevant set size is shown in Fig. 4. An initial cue display was presented for 250 msec followed 750 msec later by the test display. The test display was identical to the test displays in Display Set Size 8 condition. The new feature is the cue display. In the Relevant Set Size 2 condition, dark crosses appeared at each of the relevant locations and white crosses appeared at each of the irrelevant locations. The cues were always on roughly opposite sides of the display. This cue display takes advantage of the strong segregation between black and white to provide an easy-to-use cue. The fourth condition was the Relevant Set Size 8 condition in which all eight stimulus locations are cued with dark crosses. In this condition the cue was presumably useless but it can be compared to the Display Set Size 8 condition to confirm that a cue presentation has no general effect on performance.

In all conditions, the distractors had a contrast of 20% and the targets had contrast increments ranging from 10 to 30%. Four subjects (30, 35, 36, 37) participated in four sessions with 576 trials per set-size condition per subject.

Results

As shown in Fig. 5, set size had a similar effect on contrast increment thresholds for both display-set-size and relevant-set-size conditions. For display set size the mean slope is 0.26 ± 0.02 and for relevant set size it is 0.25 ± 0.02. The difference between the observed slopes is not reliable at 0.01 ± 0.07. The slope estimates for this experiment are somewhat less than with Experiment 1. To some extent this is predicted by the decision integration model that predicts a slope of 0.22 when restricted to set sizes 2 and 8 compared to 0.25 for set sizes 1 to 8. Neither of the observed slopes in this experiment are reliably different from the predicted 0.22 slope. The two slope measures are shown for individual subjects in Table 1.* For all subjects, set-size effects were always reliably different from zero for both display and relevant set size. In summary, there was an effect of relevant set size and the magnitude was similar to that found for display set size.

Discussion

There are two points to discuss. First, the relevant-set-size manipulation had an effect even though the different conditions had identical test displays in

*The display and relevant set size slope values were not correlated across subjects. A further analysis of the reliability indicated that there was little consistent subject variability in these data. Instead, the variability was largely due to day to day and trial to trial variability. Under these circumstances, one does not expect the two slope estimates to be correlated even if they are produced by the same mechanism.
all respects. They only differed in the cues presented a second earlier. Thus while a sensory explanation is possible for the display-set-size effect, no reasonable sensory explanation is possible for the relevant-set-size effect. It must be an attentional phenomenon.

Second, the magnitude of the relevant-set-size effect was similar to the magnitude of the display-set-size effect. If sensory processes such as lateral masking were contributing to the display-set-size effect, then one would expect that the effect of display set size would be larger than the effect of relevant set size. The small standard error of the difference between these conditions implies that any additional sensory effect due to the display set size was no more than a fraction of the size of the attentional effect due to the relevant set size.

This result needs to be put into a larger context. The equivalent magnitude of the effects of display set size and relevant set size is probably a relatively unusual outcome. It has been shown to fail with letter stimuli even at fairly large separations (Eriksen & Rohrbaugh, 1970). In preliminary studies, I also found the two effects to be quite different in magnitude. For example, in an initial experiment I tried to generalize the results from Palmer et al. (1993) to disk stimuli using regularly arranged displays rather than randomized displays. With these regular displays, the effect of display set size was much smaller than the effect of relevant set size. One subject even had thresholds that decreased with increases in display set size. This subject reported using the configuration of the disks to detect a change in the
pattern. Larger display set sizes created denser patterns in which it was easier to detect a change in the pattern (cf. Bloomfield, 1972). In Experiment 2, this configuration effect was eliminated by the use of displays with randomized positions and constant density. In summary, the effects of display set size are likely to be attentional only after controlling for sensory contributions.

**EXPERIMENT 3: STIMULUS GENERALITY**

Thus far, attentional effects have been measured for two search tasks: the contrast increment search of Experiment 2 and the line length search of Palmer et al. (1993). By controlling for sensory factors and measuring effects at threshold, one may eliminate many of the stimulus specific effects usually found in visual search. In Experiment 3, four additional search tasks were considered to determine if set-size effects are independent of the particular stimulus.

**Method**

The method of Experiment 2 was repeated for 4 new stimuli: Gaussian blobs varying in luminance, Gaussian blobs varying in color, disks varying in size, and ellipses varying in orientation. A sample display from each is illustrated in Fig. 6. Four subjects participated in this experiment. They had 4 sessions in the size and orientation conditions and 8 sessions in the luminance blob and reddish blob conditions.

**Blob luminance.** The stimuli were low-pass luminance increments in space and time. They had a Gaussian luminance profile with a half-height diameter of 0.5° and Gaussian temporal envelope with a half-height duration of 100 msec. The distractors had a peak contrast of 14% that was twice the detection threshold measured for these stimuli. The targets were luminance blobs with contrast increments ranging from 5 to 13%.

**Blob color.** The stimuli were reddish blobs with the same spatial and temporal parameters as the luminance blobs. The blobs were isoluminant to the surround for the CIE standard observer (Judd, 1951) and varied in saturation. Specifically, the color varied along a line from the color of the “white” surround to the color of our “red” phosphor (x = 0.61, Y = 0.34, CIE 1931). The distractor color had a chromatic contrast of 32% of the available gamut. This value was twice the measured detection threshold for these stimuli. The targets had higher chromatic contrast increments ranging from 10 to 40% of the gamut. These targets appeared as a more saturated red than the distractors.

**Disk size.** The distractors were black disks with a 30 arc min diameter. The targets had size increments ranging from 4 to 8 arc min.*

**Ellipse orientation.** The stimuli were 50%-contrast white ellipses with a major axis of 32 arc min and a minor axis of 16 arc min. The distractors were oriented vertically. The targets varied in orientation by tilting to the right (clockwise) from 5 to 20°.

**Results**

There were set-size effects for all conditions and for all subjects. The mean thresholds are shown as a function of set size in Fig. 7. Each panel contains a different stimulus condition and the two curves illustrate display-set-size and relevant-set-size conditions. The slope measure on these logarithmic graphs is given for each condition in Table 2. Also included are the slopes measured in Experiment 2 for disk luminance. The slopes for display set size range from 0.18 to 0.26 and for relevant set size range from 0.17 to 0.25. The mean slopes observed are 0.21 and 0.22 for display and relevant set size, respectively. These means match closely the 0.22 predicted by the decision integration model for these set sizes. There are no reliable differences between display and relevant set size for any of the stimuli. While there are no significant pairwise differences in slopes for different tasks, a general test for differences between tasks is significant $F(4,31) = 3.7, P < 0.05$. The disk luminance task from Experiment 2 has the largest slope of 0.04 above the average and the blob luminance task has the smallest slope of 0.03 below the average.

### Table 1. Slopes for individual subjects in Experiment 2

<table>
<thead>
<tr>
<th>Subject</th>
<th>Display set size</th>
<th>Relevant set size</th>
<th>Difference in slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.45</td>
<td>0.26</td>
<td>0.20</td>
</tr>
<tr>
<td>35</td>
<td>0.18</td>
<td>0.30</td>
<td>-0.12</td>
</tr>
<tr>
<td>36</td>
<td>0.17</td>
<td>0.18</td>
<td>-0.02</td>
</tr>
<tr>
<td>38</td>
<td>0.25</td>
<td>0.25</td>
<td>0.00</td>
</tr>
<tr>
<td>Mean</td>
<td>$0.26 \pm 0.07$</td>
<td>$0.25 \pm 0.02$</td>
<td>$0.01 \pm 0.07$</td>
</tr>
</tbody>
</table>

The values are slopes defined by log threshold vs log set size. Differences in slope were calculated for each subject individually resulting in a rounding error of up to 0.01 between the mean slopes and the mean difference between the slopes.

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*This condition was the first to be conducted of the experiments reported in this article and differed slightly from the others in using points as cues rather than crosses.
Discussion

This experiment demonstrates similar set-size effects for four more search tasks. Display and relevant set size have similar effects when sensory phenomena are controlled. In addition, the magnitude of these effects was consistent with the predictions of the decision integration hypothesis. The consistency of these results reinforces the previous results of Palmer et al. (1993). Perhaps the relative consistency found here compared to that found for Verghese and Nakayama (1994) was due to eliminating sensory effects by the use of widely separated stimuli.

The other side of this issue is the variation that was observed among all of the tasks. Considering all of the 10 measures from Experiments 2 and 3, the slopes varied from 0.17 for blob luminance to 0.25 for disk luminance. This variation was statistically significant but not systematic enough to establish its origin. The best candidate for such an effect is a comparison between disk and blob luminance (and color). The mean slope for the two disk luminance tasks was 0.26 and the mean slope for the four blob luminance/color tasks was 0.19. This 0.07 difference is ±16% of the predicted slope of 0.22. One approach to accounting for these apparent differences is to modify the distributional assumptions of the decision integration hypothesis (Pavel et al., 1992). Unequal variances of the target and distractor distributions will cause a change in the predicted magnitude of the set-size effect.

In summary, the observed variation among the slopes measured for different search tasks was within ±25% of the value predicted by the simplest decision integration model and is compatible with simple variations on that model.

EXPERIMENT 4: MORE COMPLEX SEARCH TASKS

For the six search tasks studied thus far, the set-size effects have had a fairly consistent magnitude. Next, the generality of this result will be extended by considering two more complex search tasks. In distinguishing between simple and more complex tasks, my goal is to identify a subset of tasks that are simple from a wide variety of perspectives. Specifically, I consider a task to be simple if it depends on only one attribute, the attribute has plausibility as a relevant psychological variable, the attribute is of a single object rather than a relation among objects, and the task introduces no distractor heterogeneity. Such tasks seemed the most plausible candidates for not introducing additional phenomena unique to each task. Experiment 4 leaves the domain of such simple tasks to consider two more complex tasks that have been previously shown to produce large set-size effects. One of these tasks is more complex because it introduces distractor heterogeneity and the other is
more complex because it requires a judgment of a relation between two distinct objects.

The line bisection task was modeled after the rotated Ts and Ls task that has been used in a variety of search studies. For example, one may search for a rotated T target among distractors that are rotated Ls. Beck and Ambler (1973) introduced the task in an early demonstration of large set-size effects. Since then Bergen and Julesz (1983) suggested that this task depended on attentive rather than preattentive processes; Treisman and Paterson (1984) suggested that the task was an instance of conjunction search; Duncan and Humphreys (1989) suggested that the task was an instance of high target similarity and distractor heterogeneity; Wolfe et al. (1989) suggested that the task was an example of “serial-like” search; and Egeth and Dagenbach (1991) explicitly argued that the task depends on serial search processes. I consider it a more complex search task because it introduces distractor heterogeneity and may introduce differences between targets and distractors on more than one dimension. This is perhaps the most studied example of a search task that produces large set-size effects on latency.

The point separation task is an example of a search task requiring the judgment of spatial relations between distinct objects. In general, such spatial relation tasks depend on the judgment of the orientation or separation between objects in the visual field. For example, distractors might be pairs of points with one separation and targets might be pairs with a larger separation. I consider such tasks more complex because they depend on relations between objects rather than on attributes of a single object. Several investigators have reported relatively large set-size effects for such spatial relation tasks (Enns & Rensink, 1991; O’Connell & Treisman, 1990; Steinman, 1987).

Method

The method of Experiment 2 was repeated again for the two more complex search tasks. The same four subjects participated in 4 sessions for each task with 576 trials per condition per subject.

Line bisection task. The stimuli were black letter-like forms made up of two line segments, as illustrated in the top panel of Fig. 8. The line segments were 60 arc min long and 6 arc min wide (3 pixels). The distractors were T-like stimuli that were oriented either vertically or rotated 90°, 180° or 270°. The targets differed from the “T” distractor, in having the point of intersection deviate from a bisection. At the extreme deviation, the two line segments make an L-like form. As with distractors, the targets could occur at any of 4 orientations. Performance was measured by the threshold deviation from a perfect bisection. The T-like distractors had a perfect bisection with deviation of 0 arc min and the L-like targets had deviations from 10 arc min to the maximum deviation of 30 arc min.

Point separation task. The stimuli were pairs of small, black-and-white squares on a gray field as illustrated in the bottom panel of Fig. 8. The squares were horizontally arranged with the white square on the left and the black square on the right. They were 12 arc min in width and height, and had 100% contrast. The distractors had a center-to-center spacing of 60 arc min that was 5 times their size. These conditions minimized grouping of the squares (cf. Zucker & Davis, 1988). The targets had separation increments ranging from 30 to 90 arc min. One detail of the display was changed to maximize the separation between these stimuli. Rather than maintain a minimum center-to-center separation of 3°, a minimum separation of 2.5° was maintained between all parts of the different stimuli. For these horizontally arranged points, this resulted in pairs of stimuli staying well separated horizontally as well as vertically.

Results

Line bisection task. In the top-left panel of Fig. 9, the mean bisection threshold is shown as a function of both

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Display set size</th>
<th>Relevant set size</th>
<th>Difference in slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disk luminance</td>
<td>0.26 ± 0.07</td>
<td>0.25 ± 0.02</td>
<td>0.01 ± 0.07</td>
</tr>
<tr>
<td>Blob luminance</td>
<td>0.19 ± 0.03</td>
<td>0.17 ± 0.03</td>
<td>0.02 ± 0.05</td>
</tr>
<tr>
<td>Blob color</td>
<td>0.18 ± 0.04</td>
<td>0.22 ± 0.03</td>
<td>-0.03 ± 0.04</td>
</tr>
<tr>
<td>Disk size</td>
<td>0.24 ± 0.04</td>
<td>0.21 ± 0.04</td>
<td>0.03 ± 0.03</td>
</tr>
<tr>
<td>Ellipse orientation</td>
<td>0.19 ± 0.05</td>
<td>0.23 ± 0.04</td>
<td>-0.03 ± 0.08</td>
</tr>
<tr>
<td>Mean</td>
<td>0.21</td>
<td>0.22</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The values are slopes defined by log threshold vs log set size. Differences in slope were calculated for each subject individually resulting in a rounding error of up to 0.01 between the mean slope and the mean difference between the slopes.
display and relevant set size. The slope is $0.32 \pm 0.04$ for the display-set-size condition and is $0.47 \pm 0.06$ for relevant-set-size condition. The difference is reliable at $-0.16 \pm 0.03$ (display-set-size condition minus relevant-set-size condition). Such a difference was not found for the simple tasks under comparable conditions.

*Point separation task.* In the top-right panel of Fig. 9, the mean separation threshold is shown as a function of both display and relevant set size. The slope is $1.35 \pm 0.26$ for the display-set-size condition and is $0.64 \pm 0.02$ for relevant-set-size condition. The difference of $0.70 \pm 0.24$ is reliable and is in the opposite direction of that found for the line bisection task. For the first time in these studies, the most discriminable targets did not reach threshold for all subjects so that the threshold had to be extrapolated from the observed psychometric functions. For Display Set Size 8, probability correct for the largest separation (90 arc min) was 0.65, 0.78, 0.76 and 0.63 for Observers 30, 35, 36, and 37 respectively. In pilot studies, further increases in the separation increment did not improve performance. Subjects reported that it became harder to group the points together with extremely large separations. Performance was improved with the Relevant Set Size 8 condition presumably because the precues helped subjects to group the points.
unchanged. The targets were defined by rotating the two points around one another while maintaining a constant 1° center-to-center separation. For these targets, the right point was always above the left point. Performance was measured in terms of the orientation change from the horizontal standard. The change in orientation ranged from 8° to 64° depending on the condition.

Four subjects participated, three were the same as in Experiment 4 (35, 36, 37) and one was not (38). Subject 30 was unavailable for this study. For both tasks, 8 sessions were conducted with 1152 trials per condition per subject. The number of sessions was increased because of the smaller effects obtained with only changing set size from 2 to 4.

Results

Line bisection task. The results are shown in the bottom-left panel of Fig. 9. The mean slope is $0.29 \pm 0.04$ for the display-set-size condition and is $0.34 \pm 0.08$ for the relevant-set-size condition. The difference of $0.06 \pm 0.06$ is not reliable. These set-size effects are smaller than those found with Experiment 4 and are only slightly larger than those found with the simpler search tasks. Furthermore, the discrepancy between display and relevant set size is smaller and not reliable.

Point orientation task. The results for this task are shown in the bottom-right panel of Fig. 9. The mean slope is $0.49 \pm 0.04$ for the display-set-size condition and $0.52 \pm 0.06$ for the relevant-set-size condition. The difference of $-0.03 \pm 0.03$ is not reliable. These set-size effects are smaller than those found with Experiment 4 but remain clearly larger than those found with the simpler search tasks. In addition, there was little if any discrepancy between display and relevant set size.

Discussion

Line bisection task. In Experiment 4, there was a discrepancy between the effects of display set size and of relevant set size. In particular, the Display Set Size 2 condition had a higher threshold than the Relevant Set Size 2 condition. This difference was largely eliminated in Experiment 5 with the larger spacing. The discrepancy in Experiment 4 may have been due to the use of texture cues across stimuli as well as the attributes of individual stimuli. According to this texture cue hypothesis, subjects might be able to use either kind of cue depending on which is the better source of information. Such cues would be present in the more closely spaced displays but absent in either the widely spaced displays or in the displays with only two stimuli. This would have put the Display Set Size 2 condition at a disadvantage relative to the other 3 conditions in Experiment 4.

The texture cue hypothesis also provides an alternative interpretation of the relevant-set-size effects in Experiment 4. Assume the more closely spaced display of 8 stimuli was discriminated by a texture cue. If so, the

EXPERIMENT 5

The previous experiment was modified in two ways to further minimize sensory contributions to the set-size effects. First, for both tasks the minimum separation between stimuli was increased from 3° to 6°. To allow this larger spacing the maximum set size was reduced from 8 to 4. Second, the point separation task was replaced by a similar point orientation task. The change was motivated by the concern that increasing the separation between points made it more difficult to group the points. Thus, the targets may have been particularly hard to group. This concern is avoided by switching to an orientation judgment for which the separation remains constant.

Method

Experiment 4 was repeated with the 6° minimum separation and a point orientation task instead of a point separation task. The distractors for the point task were
cue manipulation was affecting the spatial uncertainty of the texture cue rather than manipulating the relevant set size. The relevant set size becomes irrelevant because the judgment is based on the texture across space rather than on the individual stimuli. The possibility of such texture cues will be discussed again following Experiment 6.

While the texture cue hypothesis is speculative, it makes clear that there are alternative interpretations of the large set-size effects found in Experiment 4. When the discrepancy between effects of display and relevant set size was eliminated in Experiment 5, the set-size effects were in the range predicted by variations on the decision integration hypothesis. Thus, it does not appear that the line bisection task is a good example of a task that demands limited-capacity as in the perceptual coding hypothesis.

**Point separation and orientation tasks.** In Experiment 4, there was a large discrepancy between the effects of display and relevant set size. The Display Set Size 8 condition had much higher thresholds than the corresponding Relevant Set Size 8 condition. This difference was eliminated in Experiment 5. One account of this pattern of results is that the grouping of these stimuli as pairs was affected by the spacing and the cue. For the relatively close spacing of Experiment 4, grouping of the stimuli in the Set Size 8 condition was difficult unless the cues were present. This unexpected benefit of the cues was not found in Experiment 5 with the larger spacing between stimuli.

The point separation and orientation tasks have persisted in producing larger set-size effects than the other tasks investigated. In addition, the similar magnitude of the effects of display and relevant set size is compatible with an attentional interpretation of the effects. The use of opposite polarity points was important in producing this result. Similar search tasks with line orientation did not yield unusually large set-size effects in Palmer et al. (1993). In addition, a pilot experiment with same polarity points yielded results intermediate between the results found with line orientation and with opposite polarity points. One interpretation is that searching for relations among distinct objects requires qualitatively different processing than searching for an attribute of a single object.

**EXPERIMENT 6: PROCEDURE GENERALIZATION AND LARGER SET SIZES**

In this final experiment, I tested the generality of Experiment 1 in two additional ways. The first generalization is the use of a forced-choice procedure rather than yes–no. Previous work has often generalized results across these two procedures (Green & Swets, 1966; Palmer et al., 1993) and a failure of this generalization would indicate that the results depend on some particularity of the response procedure. The second generalization is to measure thresholds for the larger set size of 24. Previous work with large set sizes mostly used paradigms that allow multiple eye fixations and there is evidence that large and small set sizes can yield different results (cf. Pashler, 1987).

**Method**

In this experiment, I returned to measuring the display-set size effect on the contrast increment task as studied in Experiment 1. There were, however, two significant changes in the method. First, the single display procedure was replaced by a sequential two-display procedure that is illustrated in Fig. 10. After the same fixation display as in Experiment 1, the first 100 msec test display was followed by a 500 msec interval and then a second 100 msec test display. The subject made a forced-choice response that indicated whether the target was in the first or the second display.

The second change was the inclusion of a set size of 24 along with set sizes of 1, 2, and 8. Figure 11 shows schematic drawings of these 4 set-size conditions. To accommodate the large set size, eccentricity was allowed to vary from 5 to 13° rather than from 5 to 8°. Within this new constraint, randomized positions were chosen as in previous experiments to maintain constant stimulus density and a minimum center-to-center separation of 3°. The resulting configurations for the Set Size 24 condition filled the display while the Set Size 8 condition only filled one-third of the display. The distractor contrast was 14% and the target had contrast increments ranging from 3 to 12%. In other respects the same methods were followed. Four subjects participated for four sessions with 576 trials per condition per subject.

**Results**

In Fig. 12, the contrast increment threshold is shown as a function of display set size. The bold curve indicates the mean of four subjects and the light curves indicate the performance of individual subjects. For Set Size 1 to Set Size 8, the display-set-size effect yielded a slope of 0.37 ± 0.04. This value is larger than the slope of 0.30 found in Experiment 1. If one only considers Set Size 2 and Set Size 8 as in Experiment 2, the observed slope is 0.32 ± 0.03. This value is larger than the slopes of 0.30 and 0.26 found in the corresponding conditions of Experiments 1 and 2. In both comparisons, the forced-choice procedure results in a larger slope than the yes–no procedure. Such a difference is predicted by the decision integration hypothesis. For set sizes 1 to 8, the slope predicted for forced-choice is 0.31 and for yes–no is 0.25. Thus, part, if not all, of the difference between the procedures is predicted by the decision integration hypothesis.

The other new aspect of this experiment is Set Size 24. Surprisingly, there is little effect of increasing the set size from 8 to 24. The difference in the log constrast increment threshold is 0.03 ± 0.03. In other terms, the slope from Set Size 8 to 24 is 0.06 ± 0.07 compared to the slope of 0.20 predicted for the decision integration model. Thus, from all perspectives, the Set Size 24 condition shows little of the expected increase in threshold.
The effect of display set size found in all previous experiments did not generalize to a set size of 24. There is little if any effect of increasing set size from 8 to 24. It is unclear if this is related to previous reports of different effects for larger set sizes (e.g., Pashler, 1987). Subjectively, subjects reported that the task seemed different with these large set sizes. It seems that one cannot attend to all 24 stimuli. Instead subjects reported that they noticed the target by changes in texture. It may be that for a single fixation, more than a certain number of stimuli are more efficiently perceived as a texture rather than as individual stimuli. Once considered as a texture, the number of "microelements" (display set size) is no longer relevant value for set size. Instead one must consider the spatial uncertainty of the texture detection task. In summary, the analysis of Palmer et al. (1993) does not extend to a larger set size.

**GENERAL DISCUSSION**

*Summary of results*

The results are summarized in Fig. 13. This plot shows set-size effects in terms of the slope measured for the seven tasks considered here. Filled symbols denote relevant set size and open symbols denote display set size. I will emphasize 5 points.

1. **Stimulus independence.** For the five simple tasks shown in Fig. 13, set-size effects were independent of the stimulus. These simple tasks included contrast increments of luminance disks, luminance blobs, and reddish blobs along with increments in disk size and changes of ellipse orientation.

2. **Attentional effects.** Relevant-set-size effects were found for all conditions. This effect is strong evidence for attentional phenomena in visual search. Because the displays are identical for the different relevant-set-size conditions, it is impossible to propose any sensory explanation.

3. **Similar effects of display and relevant set size.** For the five simple tasks, the set-size effects were similar for display and relevant set size. In addition, the two more complex tasks yielded a similar effect for display and relevant set size. However, these results depend critically on the separation of the stimuli. For the more complex tasks, the separation had to be at least 6°.

4. **The decision integration hypothesis was sufficient.** For the five simple tasks, the decision integration hypothesis was sufficient to account for the effects of set size. In addition, the line bisection task had set-size effects only slightly larger than predicted by the decision hypothesis. In Fig. 13, the prediction of the decision integration hypothesis is shown by the vertical line at a value of 0.22 and the prediction of the perceptual coding hypothesis is shown by the vertical line at a value of 0.72.

5. **Limitations.** Results differed for one of the two complex tasks and for Set Size 24. For the point orientation task, the observed slope of 0.5 was midway between the predictions of the decision integration and
perceptual coding hypotheses. In addition, something not shown in Fig. 13 is the failure to find an increase in the threshold for Set Size 24 as compared to Set Size 8.

**Stimulus dependence**

**Simple tasks**. This study extends Palmer et al. (1993) by showing that the magnitude of the set-size effect is independent of the choice of stimulus over the range of simple stimuli tested. This is the simplest result one can hope for. It suggests that a simple model of the interaction between sensation, perception, decision, and attention will be sufficient for the idealized conditions of these experiments. It also stimulates an interest in identifying the domain of stimuli over which stimulus independence holds. The experiments of Verghees and Nakayama (1994) suggest some of the conditions under which stimulus independence will not hold.

![Graph](image1.png)

**FIGURE 12.** Results of Experiment 6 are shown as the contrast increment threshold as a function of set size. In this graph, both axes span 2 log units compared to the 1 log unit in previous graphs.

![Graph](image2.png)

**FIGURE 13.** Experiments 2, 3, and 5 are summarized by the slope measured for display and relevant set size. The vertical line at a slope of 0.22 marks the prediction of the decision integration hypothesis and the line at a slope of 0.72 marks the prediction of the perceptual coding hypothesis.
More complex tasks. The more complex tasks demonstrated both larger attentional effects and notable sensory effects. One surprise of the current experiments was the difficulty of controlling the sensory contributions to these more complex tasks. It may be that these tasks are more complex because of introducing additional sensory features rather than in requiring limited-capacity perception.

Sensory vs attentional effects
The demonstration that an instructional cue can modify the relevant set size and change performance is a clear indication of attentional phenomena. The logic of this approach dates to Broadbent (1958) and has been used in a variety of studies (see Palmer, 1990 and 1992 for reviews). The use of identical stimulus displays is crucial. It is only with identical stimuli that one can rule out sensory contributions.

The correspondence of these set-size effects allows one to reject several hypotheses. If one assumes that the effect of relevant set size provides a good estimate of the effect of attention, then one can reject the possibility of any significant sensory contribution to the effect of display set size. Given the close match between effects of display and relevant set size, any residual sensory effect must be small. Alternatively, if one assumes that the display-set-size conditions achieved their goal of minimizing sensory effects, then one can reject any significant underestimation of the attentional effect by the cue manipulation in the relevant-set-size condition. The effect of an irrelevant stimulus is similar to the absence of a stimulus. The one alternative hypothesis that cannot be completely rejected is that the relevant-set-size conditions underestimate the attentional effect because of imperfect cues and that the display-set-size conditions underestimate the attentional effect because of a residual sensory effect facilitating performance at larger set sizes. These two effects could, in principle, cause the two set-size manipulations to match coincidentally. Such a coincidence seems unlikely because the match was eventually found for all 7 different stimuli and for two procedures. In particular, any residual sensory contributions would not be expected to remain constant over the diverse stimuli investigated here. Thus, while one cannot reject all alternative interpretations, a common attentional explanation seems likely for the two kinds of set-size effects.

Perception vs decision
Simple stimuli and the decision integration hypothesis. The magnitude of the set-size effects found for all of the simple stimuli can be accounted for by the decision integration hypothesis. This hypothesis has had considerable success predicting uncertainty effects in detection (Tanner, 1961; Graham, 1989). The crucial assumption in these hypotheses is that the percept is noisy. Given this assumption, decision will have an effect that is dependent on only the details of the noise and the decision rule. Such a decision explanation of the set-size effect goes a long way toward explaining how the set-size effect can be independent of the stimulus because the effect is mediated by decisions made after the initial perceptual processing. Thus, the details of perceptual processing have no effect once one has equated the information available for decision.

Simple stimuli and the perceptual coding hypothesis. This study adds to the growing body of evidence that perceptual coding is not always limited by attention (cf. Posner et al., 1980). When sensory contributions were eliminated, the set-size effect was consistent with an attentional effect on decision and not consistent with an additional attentional effect on perception. This article adds five more stimuli for which this result appears to be true to the one described by Palmer et al. (1993). This evidence, combined with the related search experiment by Shaw (1984), makes a strong case that perception does not always have capacity limitations. In addition, a similar argument has been made for detection accuracy (reviewed by Graham, 1989) and for dual-tasks involving detection (Bonnel, Stein & Bertucci, 1992; Oltak & Thomas, 1981). Thus, one can reject general claims about the necessity of limited-capacity perceptual coding.

Other hypotheses depending on limited-capacity perception. The consistent lack of attentional effects on perceptual coding challenges many of the details of existing search theories. For example, according to feature integration theory, set-size effects for difficult feature search tasks are due to limited-capacity perceptual coding of stimuli with low signal-to-noise ratios (e.g. Treisman & Gormican, 1988; Wolfe et al., 1989). The work reported here is inconsistent with that interpretation and instead suggests that difficult feature search tasks introduce a larger attentional effect on decision rather than on perception. While this particular issue is not central to feature integration theory or guided search, it undermines the inference that larger set-size effects imply a different kind of attentional process (see also Townsend, 1974, 1990).

Another point of controversy among existing theories is whether target-distractor discriminability (or similarity) is as important as qualitative stimulus differences. For example, Duncan and Humphreys (1989, 1992; but see also Treisman, 1991) argue that discriminability can account for much of the variation in the magnitude of set-size effects for different stimulus conditions. Here, discriminability was controlled and much of the variation in set-size effects was eliminated. Discriminability is clearly important. Consequently, one must equate discriminability to make meaningful comparisons of the set-size effects in different stimulus conditions.

More complex tasks. The two more complex tasks had larger set-size effects than the simple tasks. Consider first the line bisection task that was based on the rotated Ts and Is task. The use of widely spaced stimuli in Experiment 5 eliminated the sensory effects found in Experiment 4 and reduced the magnitude of the set-size effects. The resulting set-size effects were only slightly larger than those predicted by the simplest version of the decision integration hypothesis. One can modify this
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decision hypothesis to account for the larger magnitude of effects observed. For example, the distractor heterogeneity of this task is consistent with assuming larger variability of the noise distribution relative to the signal distribution. Such an assumption will increase the magnitude of the set-size effect (cf. Graham et al., 1987). Thus, the task that shows some of the most convincing evidence for serial processing in latency search experiments does not convincingly indicate limited-capacity processing when sensory phenomena are controlled. This result was not expected.

Consider next the point orientation task. This task produced the largest set-size effects once non-attentional sensory effects were controlled. The magnitude of the set-size effect was more than twice that predicted by the simplest version of the decision integration hypothesis. The magnitude of the effect fell short of the prediction of a limited capacity perceptual system followed by decision integration but, curiously, matched the prediction of a limited-capacity system when the entire system, including decision, was considered together. These larger set-size effects suggest either a modified version of the decision integration hypothesis or some degree of limited-capacity perceptual processing. There are two other tasks in which set-size effects have been analyzed to distinguish contributions due to nonattentional sensory processes, perceptual coding, and decision integration. One is the letter search task investigated by Shaw (1984) and the other is a visual memory task investigated by Palmer (1990). For these cases, the set-size effects were larger than could be accounted for by any version of the decision integration hypothesis. It remains to be understood why these three tasks distinguish themselves from those with smaller set-size effects.

Texture and visual search

In Experiment 6, Set Size 24 did not show any additional effect of set size beyond that observed for Set Size 8. This is not consistent with the decision integration hypothesis and requires an explanation. One way to explain it is to consider texture phenomena. Others have remarked on differences between texture discrimination and visual search (Wolfe, 1992). Suppose that displays with large set sizes depend on a perception based on texture that is more sensitive than a perception based on individual stimuli. Under these circumstances, the individual stimuli become microelements in the texture. One would now expect performance to depend on properties of the texture as a whole rather than on the number of microelements (display set size). This may also be at the root of the stimulus specific effects found by Vergheese and Nakayama (1994). Such a texture cue hypothesis was suggested in the discussion of Experiment 5 to account for the effect of spacing found for the line bisection task. Such spacing effects are consistent with texture gradient phenomena and inconsistent with many search models (cf. Landy & Bergen, 1991; Nothdurft, 1985). This issue is related to the larger problem of identifying the relevant mechanisms mediating performance. For example, consider the issue of separate mechanisms for different spatial scales as discussed in Farell and Pelli (1993). In summary, to investigate this texture cue hypothesis, one must distinguish judgments mediated by the perception of individual stimuli from those mediated by the perception of larger regions of the stimulus array.

SUMMARY

In most visual search paradigms, set-size effects vary dramatically with the details of the stimulus. Here, sensory contributions were eliminated by measuring performance at threshold and by using cues to manipulate relevant set size. For luminance, color, size, and orientation tasks, a purely attentional set-size effect was found and shown to be independent of the stimulus. All of these simple search tasks required the discrimination of a target that differed in only one attribute from a homogeneous set of distractors. For two more complex tasks, the set-size effects were larger. The results for simple tasks can be understood using the decision integration hypothesis. The results for the more complex tasks will require an elaboration of the decision integration hypothesis or an additional attentional effect on perception. In closing, this study has identified a range of conditions under which set-size effects are independent of the stimulus.

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