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Measuring the Effect of Attention on Simple Visual Search

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Set-size effects in visual search may be due to 1 or more of 3 factors: sensory processes such as lateral masking between stimuli, attentional processes limiting the perception of individual stimuli, or attentional processes affecting the decision rules for combining information from multiple stimuli. These possibilities were evaluated in tasks such as searching for a longer line among shorter lines. To evaluate sensory contributions, display set-size effects were compared with cuing conditions that held sensory phenomena constant. Similar effects for the display and cue manipulations suggested that sensory processes contributed little under the conditions of this experiment. To evaluate the contribution of decision processes, the set-size effects were modeled with signal detection theory. In these models, a decision effect alone was sufficient to predict the set-size effects without any attentional limitation due to perception.

Attention has long been recognized as contributing to performance in visual tasks (Helmholtz, 1894/1968; James, 1890). What remains unclear is to what extent attention affects perception rather than memory and decision. At one extreme is the position that all of perception is limited by attention (e.g., Posner, Snyder, & Davidson, 1980). At the other extreme is the position that perception is completely preattentive, and attention affects memory and decision (e.g., Shiffrin & Geisler, 1973). In between are a variety of compromises in which perception is affected by attention for complex tasks such as discriminating arbitrary letters but not for simple tasks such as discriminating a single visual attribute such as size, orientation, or luminance (e.g., M. L. Shaw, 1984). We seek to clarify this controversy by determining whether the perception of simple visual attributes is limited by attentional processes.

The Visual Search Task

In a typical visual search task, an observer is asked to determine whether a target stimulus is present among a variable number of distractor stimuli. The total number of stimuli is here referred to as the *display set size* and has often been shown to affect performance. Increasing display set size usually increases response time and/or decreases response accuracy. Such a set-size effect is one of the most commonly cited instances of divided attention. This interpretation is based on manipulating the number of relevant stimuli without changing other aspects of the task.

One of the original motivations for the study of visual search was the desire to isolate the effects of attention on perception from other effects of attention (Estes & Taylor, 1964; Neisser, 1967; for reviews see Smith & Spoehr, 1974; Teichner & Krebs, 1974). The search task does this by minimizing the complexities of response and memory. Consider responses first. In a typical search task, if a target stimulus is in the display, the observer responds *yes*; if only distractor stimuli are in the display, the observer responds *no*. The responses are the same whether the displays have 1 or 100 stimuli. Thus, any effect of display set size cannot be due to difficulty in generating the response as in the case of a full report.

Similarly, the search task minimizes memory requirements (cf. Baddeley, 1964; Palmer, 1990; Sperling, 1960) by requiring that an observer remember only the presence or absence of a target stimulus. Distractor stimuli need not be remembered and, in fact, are not remembered (Brand, 1971; Gleitman & Jonides, 1976). In the search task, the observer need only detect and remember the target alone, and this residual memory requirement is independent of the display set size. Thus in simple visual search tasks, memory requirements will not contribute to set-size effects.

Alternative Search Paradigms

A variety of paradigms have been used to study visual search. These include a variety of eye fixation conditions, stimulus materials, and response measures. We will briefly review the alternative paradigms. Our aim is to test the hypothesis that attention always affects perception by considering possible counterexamples.

Single- and Multiple-Fixation Search

Perhaps the first distinction to make among visual search paradigms is whether they allow the observer to make one or more eye fixations. In the most detailed of multiple-fixation studies, search is modeled as a sequence of perceiving within a single fixation and using peripheral vision to find relevant locations for the next fixation (Bloomfield, 1979; Williams, 1966). To simplify this situation, some

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investigators have sought to mimic sequences of fixations with sequences of brief displays (Eriksen & Spencer, 1969; Sperling, Budiansky, Spivak, & Johnson, 1971; but see Rayner & Fisher, 1987), whereas others have sought to mimic single fixtions with single brief displays (e.g., Estes & Taylor, 1964; Palmer & Ames, 1992; but see Klein & Farrell, 1989). These latter efforts have the advantage of not imposing a performance limit due to the sequential nature of eye fixations. In addition, once eye position is controlled, one can specify the visual stimulus on the retina and control for effects of peripheral vision (e.g., Aulhorn & Harms, 1972). It is under these conditions that visual search experiments show little or no set-size effects for some kinds of stimuli (e.g., Bergen & Julesz, 1983; Egeth, Jonides, & Wall, 1972).

Simple and Complex Search Tasks

A second distinction among visual search paradigms is between simple and complex search tasks. By simple search tasks, we mean the use of targets and distractors that differ on a single, one-dimensional visual attribute such as size, orientation, or luminance. Previous studies of simple search have often shown minimal if any set-size effect (e.g., Teichner & Krebs, 1974). Particularly clear is the special case of detection, in which the small effects of location uncertainty have been modeled as an attentional effect on decision and not on perception (e.g., Davis, Kramer, & Graham, 1983; Graham, 1989). This summary is marred by two complications. When targets and distractors are similar, even simple search tasks show set-size effects, and latency cuing studies with simple stimuli show cuing effects. We will address these complications by building on the previous work of M. L. Shaw (1980, 1982, 1984).

Accuracy and Latency Response Measures

A third distinction among visual search paradigms is whether they primarily measure response accuracy or response latency. Consider latency first. In latency experiments, larger set sizes often lead to longer latencies (Egeth, Atkinson, Gilmore, & Marcus, 1973; Estes & Wessel, 1960), and these set-size effects can be modeled either by serial processing or by capacity limitations in a parallel process (Townsend, 1974, 1990). This makes the interpretation of set-size effects ambiguous for our purpose of determining how attention affects perception. For example, these different causes of set-size effects might be the source of the difference between latency experiments that show set-size effects and others that show no set-size effects (e.g., Egeth et al., 1972, 1973; Egeth & Dagenbach, 1991). When no set-size effect is found, the interpretation is usually for parallel processes with unlimited capacity. But this interpretation is complicated by the fact that even the simplest search tasks have set-size effects when the targets are similar to distractors (e.g., Nagy & Sanchez, 1990). Such results can be interpreted either as a qualitative change in attentional phenomena (Treisman & Gelade, 1980; Treisman & Gormican, 1988) or as a quantitative change due to sensory and decision processes (Duncan & Humpreys, 1989).

In search accuracy experiments, set-size effects are modeled as being directly related to capacity limits on the quality of processing. In particular, if independent processes act on the individual stimuli and are allowed to run to completion, then the set-size effects are unaffected by other aspects of processing such as whether it is serial or parallel. Indeed, the available studies of visual search accuracy show relatively modest set-size effects for simple stimuli (Bergen & Julesz, 1983; Poirson & Wandell, 1990; M. L. Shaw, 1984; and see the detection studies reviewed in Graham, 1989).

The Threshold Search Paradigm

To summarize the review, set-size effects have been minimized by using single fixation displays, simple stimuli, and accuracy measures. To look for set-size effects that depend on attentional factors alone, we further customized such a search paradigm to minimize sensory factors. Brief displays controlled the effects of eye movements and peripheral vision; widely spaced stimuli minimized the effects of stimulus configuration and density; and measuring performance with an accuracy threshold controlled the effect of similarity between target and distractor (cf. Poirson & Wandell, 1990). We called the resulting procedure the *threshold search paradigm.* It adapts some of the useful features of psychophysical detection paradigms to multiple-stimulus search paradigms.

The Two Issues

We must now develop two issues: How one can distinguish sensory from attentional effects and how one can determine if the locus of an attentional effect is within perception rather than within decision.

Distinguishing Sensory From Attentional Effects

In any visual search experiment, the effects of display set size may be due to attentional phenomena or to a variety of sensory phenomena. Several alternative sensory phenomena have already been mentioned such as limited peripheral vision and the need for multiple eye movements. Another possible factor is the common confound between set size and stimulus spacing (density). As stimuli are spaced closer together, they may interfere with or facilitate one another's perception (e.g., Banks, Larson, & Prinzmetal, 1979; Boynton, Hayhoe, & MacLeod, 1977).

Sensory contributions can be eliminated by manipulating the relevant set size while holding constant the display set size. For example, one might always present eight stimuli, but sometimes cue one stimulus and at other times cue all stimuli. The cue provides an instruction that manipulates the set size for stimuli relevant to the task. This *relevant set-size manipulation* can only affect attentionally controlled processes because the stimulus is held constant. It follows a similar manipulation described by Broadbent (1952a, 1952b, 1958) for distinguishing sensory and central contributions: Precuing the relevant ear in selective listening experiments improves performance with no change in the stimuli to the two ears. The common element of these paradigms is to manipulate attention by instruction rather than by the immediate stimulus.

In this approach, a key test is to compare relevant set-size and display set-size manipulations. If they produce different effects, then one has evidence for a nonattentional interpretation of display set-size effects. On the other hand, similar effects would be consistent with a common attentional interpretation. This method has been used in a handful of studies. Some have shown close agreement between display set size and relevant set size (Davis et al., 1983; Grindley & Townsend, 1968), and others have shown disagreement (Eriksen & Lappin, 1967; Eriksen & Rohrbaugh, 1970). In the latter studies, display set size had a larger effect than relevant set size. The differential effects were interpreted as evidence for lateral masking effects in display set-size experiments. We used this method to distinguish sensory and attentional effects within our threshold search paradigm.

Determining the Locus of the Attentional Effect

Attention as defined here can affect both perceptual and decision processes. Thus, after determining that a set-size effect is attentional, the next question is to determine if attention affects perception, decision, or both processes.

Perhaps the first modern statement of this distinction can be found in the development of signal detection theory (e.g., Green & Swets, 1966; Tanner, 1956, 1961). One goal of that theory was to distinguish between perceptual phenomena that affect individual percepts and decision phenomena that affect the mapping of percepts into responses. In this theory, percepts are noisy, and decision processes are necessary to map these variable perceptions into discrete responses. These assumptions alone predict set-size effects in tasks with multiple sources of information even if the sources are independent. In terms of visual search, even if each percept is unaffected by set size, the noise of each percept will give rise to a set-size effect in decision making. In short, each additional distractor gives another chance for a false alarm.

This class of decision models is different from the decision models tested by Bashinski and Bacharach (1980). They distinguished between sensitivity and bias to rule out decision bias being different for different set sizes (response set, Broadbent, 1970). Using receiver operating characteristic (ROC) functions, Bashinski and Bacharach showed an effect on sensitivity that could not be attributed to bias (but see Müller & Findlay, 1987). This bias hypothesis is not the same as the decision model considered here and originally suggested by Tanner. In Tanner's model, decision affects sensitivity by the increased noise from multiple sources of information. Thus, the Bashinski and Bacharach experiment addressed a decision bias hypothesis but not the noise-limited decision hypothesis.

These decision models have been pursued in several domains and with several paradigms (for reviews, see Egeth, 1977; Sperling & Dosher, 1986; Swets, 1984; for early work in audition, see Creelman, 1960; Green, 1961). They have been treated in detail for visual search by M. L. Shaw (1980, 1984), for multiattribute detection by Graham (1989), and for more cognitive tasks by Shiffrin and Geisler (1973; see also Gardner, 1973). In particular, decision models have provided a good description of set-size effects in detection experiments (Cohn & Lasley, 1974; Davis et al., 1983; Graham, Kramer, & Yager, 1987; Kinchla, 1974; Pelli, 1985; Yager, Kramer, M. Shaw, & Graham, 1984). Successful applications of the theory can also be found in the more applied visual search literature (e.g., Swensson & Judy, 1981).

The choice now arises between hypotheses specifying an attentional effect on perception, on decision, or on both. We here follow the approach developed by M. L. Shaw (1980, 1982, 1984), which allows for attention to affect both perception and decision. To model perception effects, one can start from the limited-capacity model introduced by Broadbent (1958); to model decision effects, one needs to assume something about the noise in perception and the rule for decision. Details of definitions and models will be introduced below after Experiments 1 and 2. Although no completely general test of perceptual and decision hypotheses is possible, many specific hypotheses can be eliminated.

Overview of Experiments

The first two experiments measured display set size and relevant set-size effects. Comparing these effects established the size of possible sensory contributions to the set-size effect. The next section addressed the locus of the attentional effects. Set-size effects were compared with models based on both perception and decision phenomena. In a final section, two experiments generalized these results to other stimuli and procedures.

General Method

Subjects

Subjects were selected from a pool of trained young adult observers. Most were graduate students, most were paid \$5–\$10 per hour, and all had normal or corrected-to-normal acuity. The observers were identified by a set of noncontiguous numbers that were the same as those used in related studies (Palmer, 1988, 1989, 1990, 1991; Palmer & Ames, 1992). Observers 1, 17, and 25 were the authors.

Apparatus

The displays were presented with a computer-controlled 14-in. (35.56-cm) cathode-ray tube (Hewlett Packard 35122A). The tube had a P31 phosphor, a 60-Hz refresh, and a 512 × 390 pixel resolution. The displays were created by optically combining the tube with a large, low-luminance disk to produce displays such as illustrated in Figure 1. The tube and disk were both at a distance of 78 cm from the observer. The illuminated disk had a diameter of 22° and a luminance of 5 cd/m^2, which precluded any view of the unilluminated tube. The displays on the tube combined with this field to produce stimuli with a combined luminance of 200 cd/m^2. Outside of the low-luminance disk was a dark $<$ 0.03 cd/m^2 surround that filled the remaining visual field.

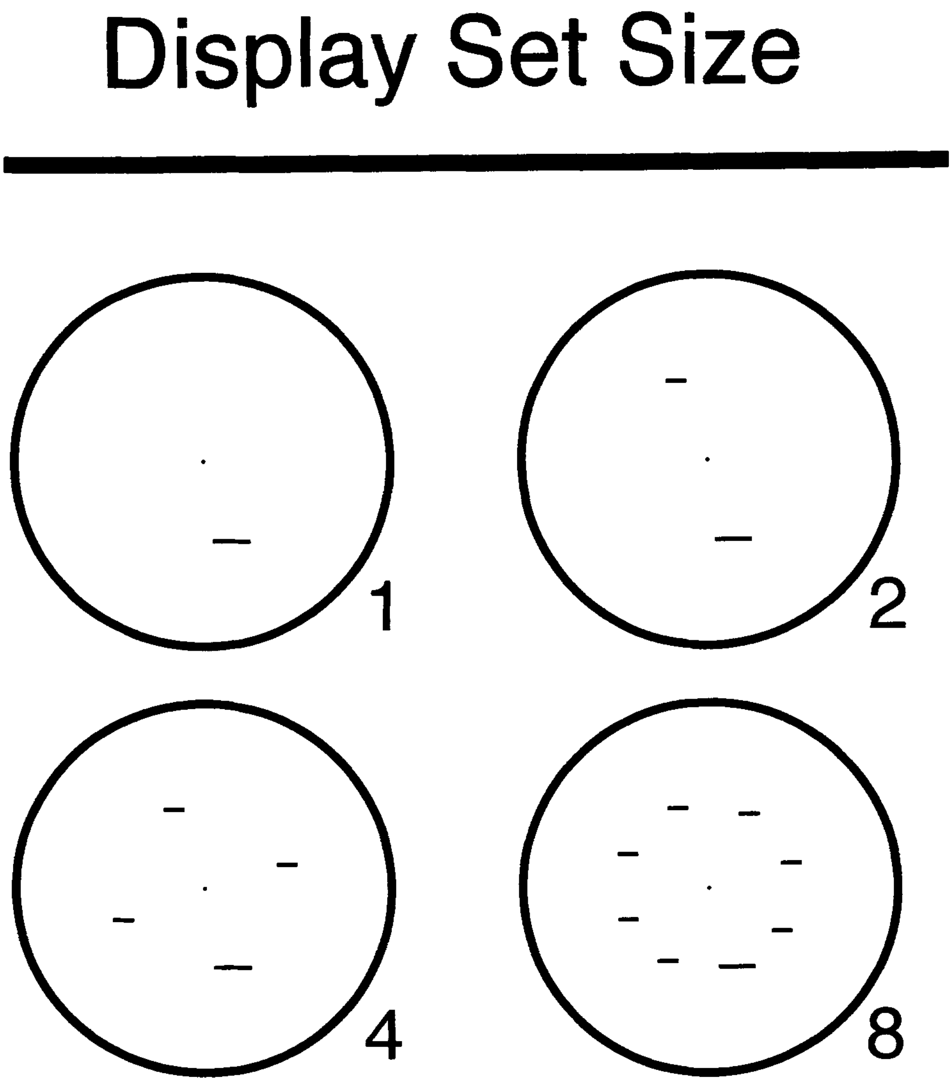

Figure 1. Scale drawings representative of each display set-size condition in Experiment 1. (Each display contains a target whose length is exaggerated to make it clearly visible.)

Stimuli

In most experiments, the distractor stimuli were horizontal lines with a length of 60 arc min. As shown in Figure 1, from one to eight lines were arranged on an imaginary circle with a radius of 5°. The lines were equally spaced and placed to avoid any alignments between lines.

The display sequence of a trial is shown in Figure 2. A warning display was presented for 100 ms followed by a 1,000-ms fixation display; the first stimulus display was presented for 100 ms followed by another 1,000-ms fixation display; the second stimulus display was also presented for 100 ms followed by an empty display until response.

One of the two stimulus displays contained only identical 60 arc min distractor lines. The other stimulus display had identical distractor lines and a single target line that was longer by a few arc min. The exact length of the target line was determined by an adaptive procedure (3:1 rule; Levitt, 1971) restricted to sets of three possible values. For Set Sizes 1, 2, 4, and 8, these lengths were (4, 6, 8), (6, 10, 14), (8, 12, 16), and (8, 12, 16 arc min), respectively. These values were chosen to bracket the difference thresholds in each condition (see definition below).

Procedure

In the first three experiments, observers made a two-interval forced choice discrimination: Was the longer line in the first stimulus display or in the second stimulus display? In the last experiment, observers made a single-interval yes–no discrimination. Responses were indicated by pressing one of two keys. There was no time pressure, and tones were used to provide accuracy feedback on each trial. Trials were presented in blocks of 32 trials, and a day's session consisted of 12 blocks. Each observer participated in at least five sessions of training in related experiments before providing any of the reported data. In addition, each observer had at least one session of specific practice in each experiment. This resulted in at least 3,000 trials of practice per observer.

A psychometric function was formed by calculating the probability of "second interval longer" response as a function of the target length. When the target was in the first display, the sign of the target length was negated to reflect the length change from first to second interval. The observed psychometric function was fit to a cumulative normal function (Finney, 1971), and two parameters were estimated. The difference threshold was defined as half the difference between the stimuli that produced 25% and 75% second interval responses; the point of subjective equality was defined as the stimulus that produced 50% second interval responses.

Experiment 1: Display Set Size

The first experiment measured the effect of display set size. It used the methodology just described to measure line-length thresholds as a function of set size.

Method

Display Set Sizes of 1, 2, 4, and 8 were intermixed from trial to trial. Five observers participated in four sessions with the four set size conditions, yielding 384 trials per condition per observer.

Results

The results are shown in two ways in Figures 3 and 4. In both, the length difference threshold is shown as a function of display set size. The bold curve is the mean threshold for the 5 observers, and the light curves are individual thresholds for each observer. The figures differ in the first using linear scales and the second using logarithmic scales for both axes.

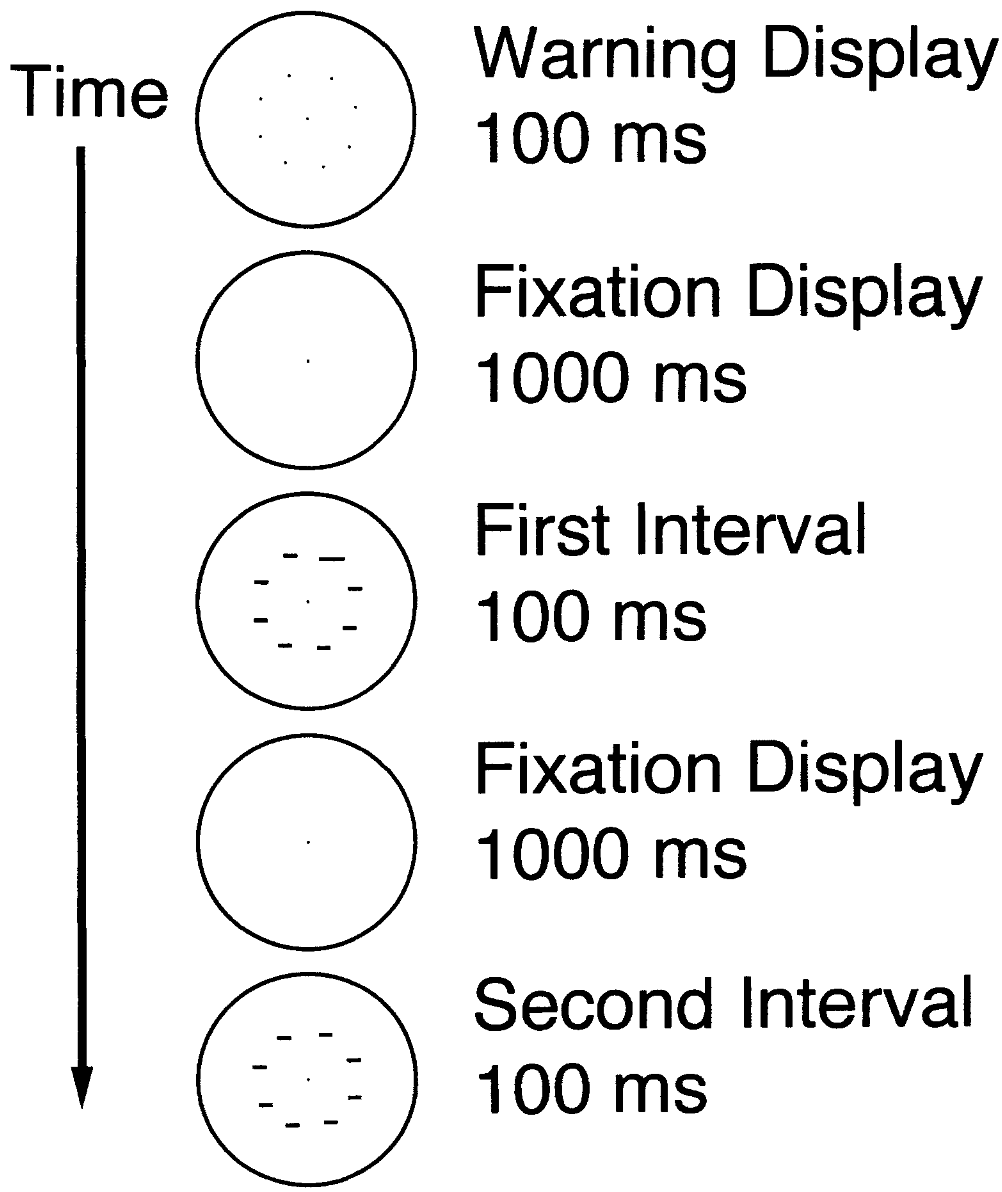

Figure 2. A schematic illustration of the display sequence used in these experiments. (The target appears in either the first or second stimulus display interval. The Set Size 8 condition is shown.)

There is a set-size effect. Examining Figure 3 shows that the threshold increased from around 4 arc min for Set Size 1 to around 8 arc min for Set Size 8. The threshold increases as a negatively accelerating function of set size. The nature of this increase is nicely characterized in the logarithmic plot of Figure 4. Here, the log threshold increases proportionally with log set size. The mean slope of the 5 observers is 0.29 ± 0.06, $t(4) = 5.2$, $p < .01$. Individual observer data are shown by the light curves. All observers showed a reliable effect of set size. For example, Observer 17 had a slope of 0.24 ± 0.08, $t(3) = 3.0$, $p < .05$.[1] In summary, there is a consistently reliable effect of set size on length thresholds.

In addition to the difference thresholds, the point of subjective equality was estimated. This point is the increment in the second display that was equivalent to the homogeneous distractor lengths in the first display. This value may differ from zero because of either a response bias or an order effect between the displays. Over all set sizes, the point of subjective equality was 1.5 ± 0.3 arc min. Though reliable, this effect is a small fraction of the difference threshold (4–8 arc min). Moreover, the point of subjective equality did not systematically vary with set size. For example, a regression of the point of subjective equality against set size yielded a slope of 0.02 ± 0.07 arc min per item. Thus, response bias and order effects do not vary with set size. Because the point of subjective equality was never found to vary with set size, we will not discuss it further in this article.

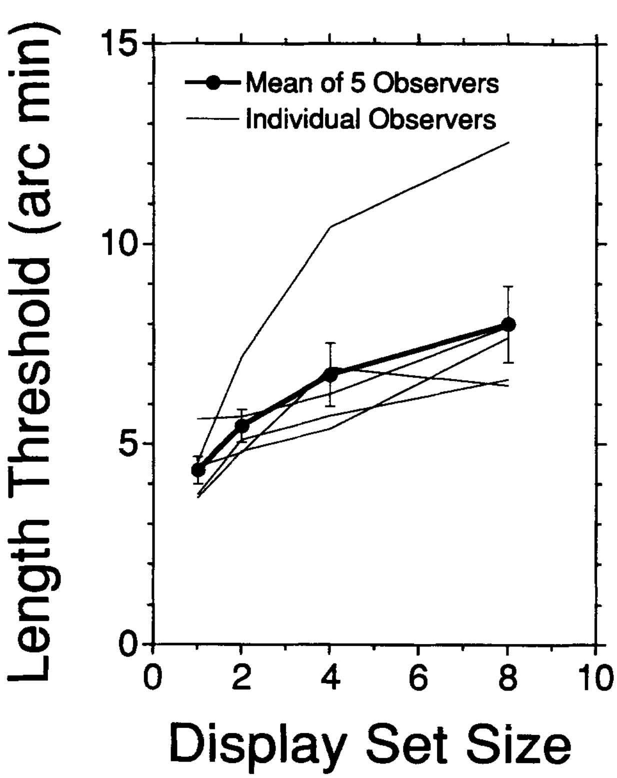

Figure 3. Results of Experiment 1. (The bold curve is the mean length threshold as a function of display set size. The dashed curves are the individual observer thresholds. All error bars are the standard error of the mean.)

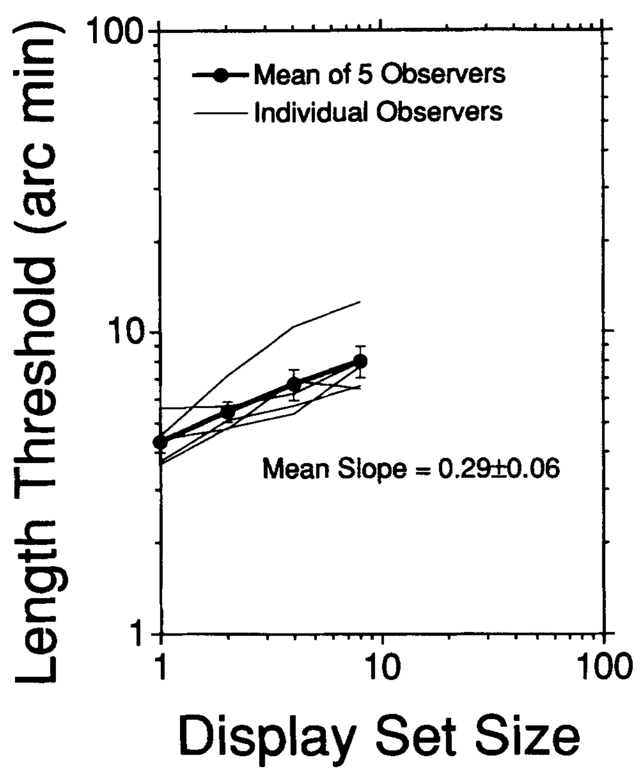

Figure 4. Results of Experiment 1 with the data replotted on a logarithmic axes. (This replot of Figure 3 makes the standard errors more homogenous and yields generally linear functions.)

We will use logarithmic plots such as Figure 4 for the remainder of the article. These plots have the advantages of more homogeneous variability in the threshold estimates and of showing a wider range of values. We will summarize set-size effects by the slope of the best fit line on these logarithmically scaled axes. Summarizing a logarithmic graph by the slope of a linear function is equivalent to summarizing the linear graph by the exponent of a power function. We use the former because it is easier to visualize linear functions than to visualize power functions.

Experiment 2: Relevant Set Size

The display set-size effect obtained in Experiment 1 may be due to attentional phenomena, but it also may be due to nonattentional phenomena such as lateral masking. To address these possibilities, we manipulated relevant set size by using an instructional cue rather than by changing the display. This manipulation is illustrated in Figure 5, where the central lines indicate which of the eight stimuli are relevant. The three displays in the figure illustrate relevant set sizes of 2, 4, and 8. For a relevant set size of 8, the cue becomes simply an indicator that all stimuli are relevant. Any

[1] Statistics for individual observers were based on replications over sessions.

setsize effect that occurs with these stimuli is due solely to attentional phenomena.

Method

Display set size was always eight stimuli. Relevant set sizes of 2, 4, and 8 were presented as illustrated in Figure 5. Set Size 1 was not used because of the tendency of observers to make eye movements when cued to single stimuli on one side of fixation. Relevant stimuli were indicated by the central precues that were 3° long lines. The procedure is illustrated in Figure 6. The precues were displayed before each stimulus for 1,000 ms and remained displayed during the stimulus. In all other respects, the procedure matched that of Experiment 1. The same 5 observers participated in this experiment.

Results

The mean thresholds are plotted as a function of set size in Figure 7. This figure shows the results of Experiment 2 with the open circles and, for comparison, the results of Experiment 1 with closed squares. Relevant set size does have a reliable effect. The slope is 0.21 ± 0.02, $t(4) = 18$, $p < .001$, and is individually reliable for 4 of the 5 observers and marginally reliable for the other observer. For the one marginal case, Observer 17, the slope was still 0.21 ± 0.10. The results of this experiment can also be compared with the display set-size effects of Experiment 1. The observed slope of 0.21 is similar to the 0.28 slope observed in the corresponding conditions of Experiment 1. The difference of slopes was 0.06 ± 0.03 and was not reliable, $t(5) = 2.0$, $p > .1$.

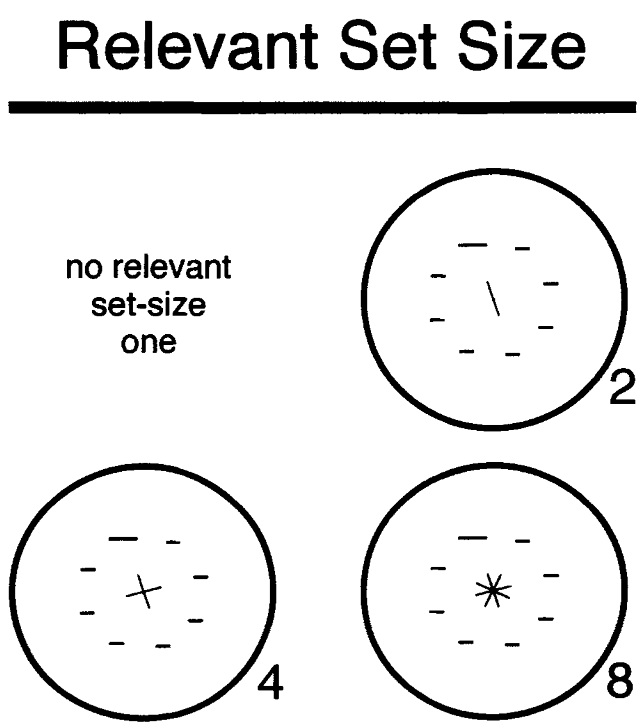

Figure 5. Scale drawings representative of each relevant set-size condition. (The central cue line[s] indicate which stimuli are relevant to the task. The other stimuli can be safely ignored.)

Discussion

The relevant set-size effect is our defining indicator of an attentional phenomenon. The displays were always of eight stimuli, and the task was always to find the one longer line. Because there was a set-size effect, observers had to have used the precue to select the relevant subset of stimuli. Without using the precue, there could have been no variation of threshold with relevant set size. Performance would be constant and equal to the Display Set Size 8 condition. There is no reasonable interpretation of the relevant set-size experiment that does not include attention.

The comparison between Experiments 1 and 2 allows us to consider a second point. If the display set-size effect of Experiment 1 was due to a sensory effect, then the display set-size effect of Experiment 1 should not match the relevant set-size effect of Experiment 2. Thus, this comparison is a test for sensory effects in display set size. No reliable difference was found, and any remaining undetected difference is clearly small relative to the attention effect of Experiment 2. Any such small difference may be due to either imperfect cues specifying the relevant set size or due to sensory interactions with display set sizes. In summary, the agreement between Experiments 1 and 2 is consistent with an attentional interpretation of the display set-size effect of Experiment 1.

The results of this experiment are also relevant to the controversy over whether attention can be distributed over multiple spatial locations. Some have argued that attention is necessarily restricted to a single location (Posner et al., 1980), whereas others have argued that attention can be distributed more generally (M. L. Shaw, 1978; M. L. Shaw & Shaw, 1977). In this experiment, the slope was 0.32 ± 0.04 between relevant Set Sizes 2 and 4 and was 0.11 ± 0.04 between relevant Set Sizes 4 and 8. The relatively large increase in threshold between relevant Set Sizes 2 and 4 demonstrates the effectiveness of the cue for a set size of 2. On the other hand, there was little if any increase in threshold between relevant set sizes of 4 and 8. In addition, observers uniformly complained that the cues in the relevant Set Size 4 condition were difficult to use. This suggests an intermediate hypothesis in which attention can be distributed but not in completely arbitrary fashion (for similar arguments, see Eriksen & Webb, 1989). We also emphasize that it may be easier to distribute attention given plenty of warning time and an unspeeded response.

Alternative Hypotheses for Set-Size Effects

We next address whether the set-size effects are a result of attention modifying decision or to attention modifying perception. In this discussion, we will assume that all purely sensory effects have been controlled. The distinction between decision and perception hypotheses can be illustrated with Figure 8. For both hypotheses, the diagram depicts the flow of stimulus information from four stimuli to a single response. The top part of the diagram depicts the decision hypothesis in which selection is followed by decision processing alone. By this hypothesis, preattentive perception yields a set of percepts, some of which can be selected as the

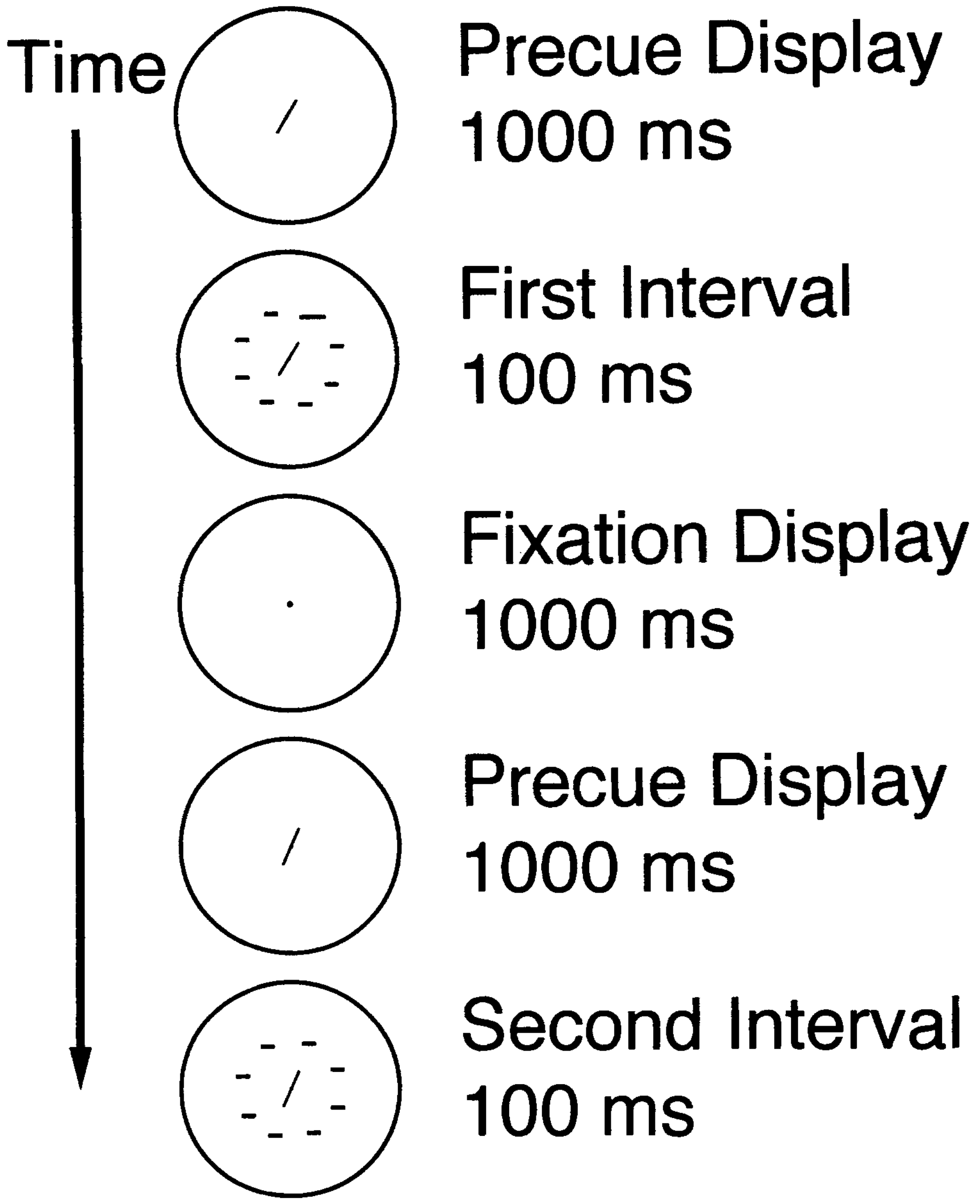

Figure 6. A schematic illustration of the display sequence used in Experiment 2. (The cues were presented well before the stimuli and remained present with the stimuli.)

basis for decision. The bottom of the figure depicts the perception hypothesis in which selection is followed by both perception and decision. Now the output of preattentive perception is selected for processing by attentional perception. These processes produce percepts that are the basis for decision. By both hypotheses, voluntary control enters the picture by controlling the selection of a subset of internal representations for further processing. The hypotheses differ only in the existence of the attentive perception stage.

To understand the differences between these hypotheses, each component must be defined. By *preattentive perception*, we mean all processes that are driven by the stimulus and not under voluntary control. Under the ideal conditions of widely separated stimuli, preattentive perception has unlimited capacity. By attentive perception, we mean the processes that are jointly driven by the stimulus and voluntary control. In addition, these perceptual processes are usually assumed to have some kind of limited capacity (e.g., the P system of Broadbent, 1958).

Decision processes differ from both kinds of perception in two ways. First, decision is task dependent and not stimulus driven. Depending on the task, an observer may judge a set of stimuli on any of many attributes such as size, shape, or color. Not being stimulus driven also allows decision to be delayed following the offset of a stimulus and to be based on memory rather than perception. Second, perceptual processes can act on a large number of input stimuli and produce a percept that corresponds to each input. In contrast, decision processes for visual search are not one-to-one. These processes combine information from the relevant per-

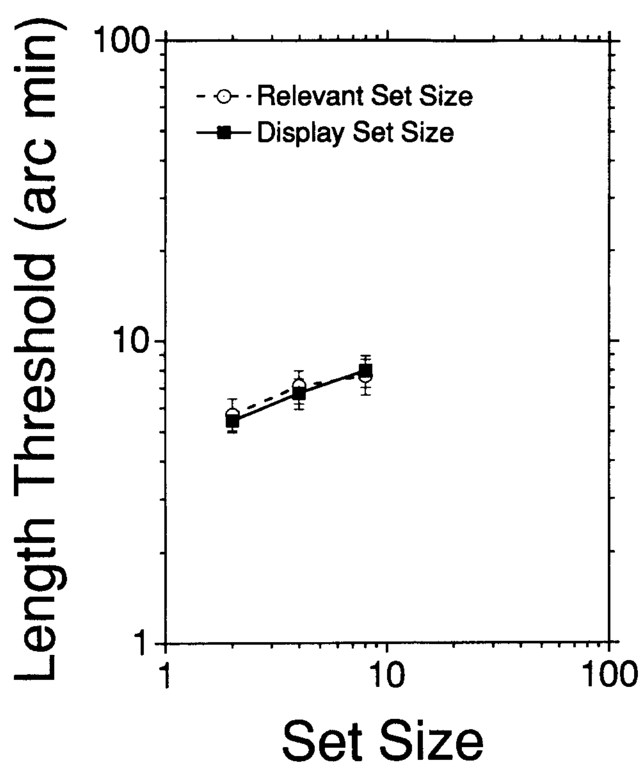

Figure 7. Results of Experiment 2. (The mean threshold is plotted for relevant set size using the open symbols. For comparison, the corresponding mean thresholds as a function of display set size are replotted from Experiment 1.)

cepts to yield a single response. In search, we define decision as a many-to-one process. By this definition, decision processes are being defined relatively narrowly and exclude any perceptual decisions that are part of creating the individual percepts. Decision is defined as task dependent rather than stimulus driven and as many-to-one rather than one-to-one. These restrictions are necessary to make a clear distinction between perception and decision (cf. Navon, 1981, pp. 1179–1180). This particular distinction between perception and decision is described in detail by M. L. Shaw (1982), who dates it to William James.

The Decision Hypothesis

The decision model of set-size effects was initially developed as part of signal detection theory (Green & Swets, 1966; Tanner, 1961). Its essential assumption is that the inputs to decision are noisy.

The consequences of this assumption for a Set Size 1 condition are illustrated in the top panel of Figure 9, which shows the density distributions that correspond to the noisy percepts assumed in signal detection theory. Probability density is shown as a function of percept strength, and percept strength is a function of the stimulus attribute being judged (e.g., line length). For example, suppose that in one display a single distractor line was presented with a length of 60 arc min. When observed, this stimulus produces a percept corresponding to a value sampled from the one-distractor distribution. The length percept is noisy in that its value varies in subjective length. As usual with signal detection theory, these values are assumed to have the unit defined as the standard deviation of the single distractor distribution and a zero defined as the mean of the distractor distribution. In comparison, suppose that another display has a single one-target line with a length of 65 arc min. It produces a percept corresponding to a value sampled from the target distribution.

On any one trial with one stimulus, the observer's percept corresponds to a single value sampled from one of these distributions. For example, on one trial an observer might see a percept with a value corresponding to 1. From the observer's point of view, this percept could have resulted from either a distractor or a target stimulus. It is above average for a distractor and below average for a target. The observer's job in a yes–no search task is to decide whether this ambiguous percept came from a distractor or a target. According to signal detection theory, the observer makes a yes–no decision by adopting a criterion to respond *yes* if the percept is greater than a certain value.

Having described signal detection theory for the case of Set Size 1, we can now describe how it extends to larger set sizes. The observer has to base a decision on a set of percepts resulting from the set of stimuli. For example, if there are eight distractors, then there will be eight percepts all different in value. By chance, one will be the largest and most confusable with the target. This most confusable percept can be quantified by calculating the distribution of the maximum of eight distractors. Such a distribution is shown in the bottom left of Figure 9. Assuming independent Gaussian distributions, the distribution of the maximum of eight distractors is shifted to the right relative to the distribution

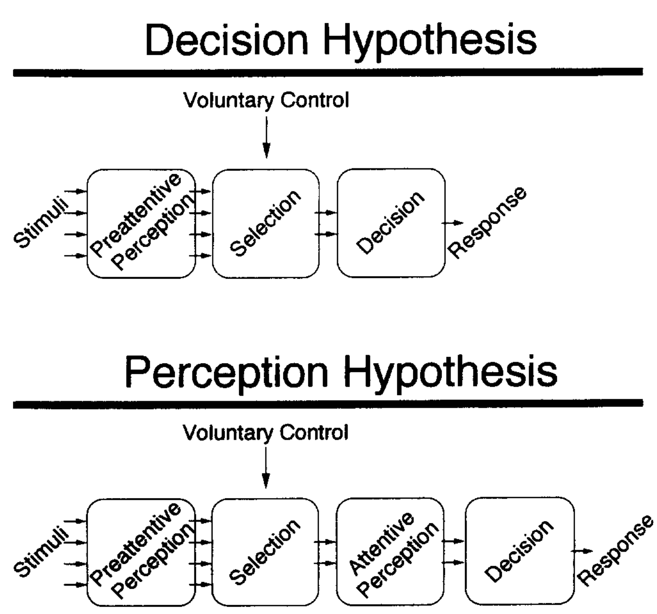

Figure 8. This figure illustrates the decision and perception hypotheses using information-flow diagrams. (Stimulus information and voluntary control interact to yield a response. The upper panel illustrates the decision hypothesis in which attention can affect only decision; the lower panel illustrates the perception hypothesis in which attention can affect both perception and decision.)

of one distractor. The median increases from 0 to 1.39. By comparison, the distribution of the maximum of one target and eight distractors is shifted only a small amount relative to the distribution of one target. The median increases from 2 to 2.15. Having eight stimuli rather than one increases the chances that one distractor will have a percept greater than that expected from a target. That increased probability is the essence of the decision model of set-size effects.

To calculate predictions for the decision model, we assume the signal detection theory as just described and its extention to the two-interval force choice task. In particular, we assume the maximum rule in which the observer indicates the target is in the display with the largest percept. This assumption is commonly adapted for two-interval forced choice because for this task it is both simple and optimal (Green & Swets, 1966). The sometimes-considered sum rule is more appropriate for tasks with multiple targets or a yes–no response (Graham et al., 1987; see below for a comparison). To make specific predictions, we also assume stochastically independent Gaussian distributions and assume that the target distribution is an identically shaped distribution shifted by an amount proportional to the change in the stimulus.[2] This model is formally defined and its predictions derived in the Appendix.

The predicted effects of set size are plotted in Figure 10. The points indicate the mean thresholds from Experiment 1 (repeating Figure 4), and the solid curve indicates the pre-

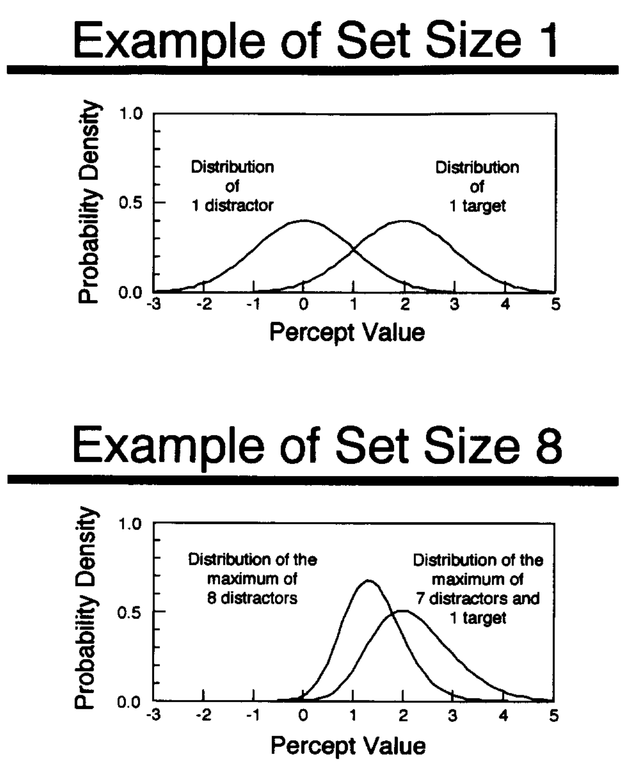

Figure 9. The ideas of the decision model. (The top panel shows the distributions for one distractor and for one target. The bottom panel shows the corresponding distributions for Set Size 8. The distractor distribution is the distribution of the maximum of eight distractors, and the target distribution is the distribution of the maximum of one target and seven distractors.)

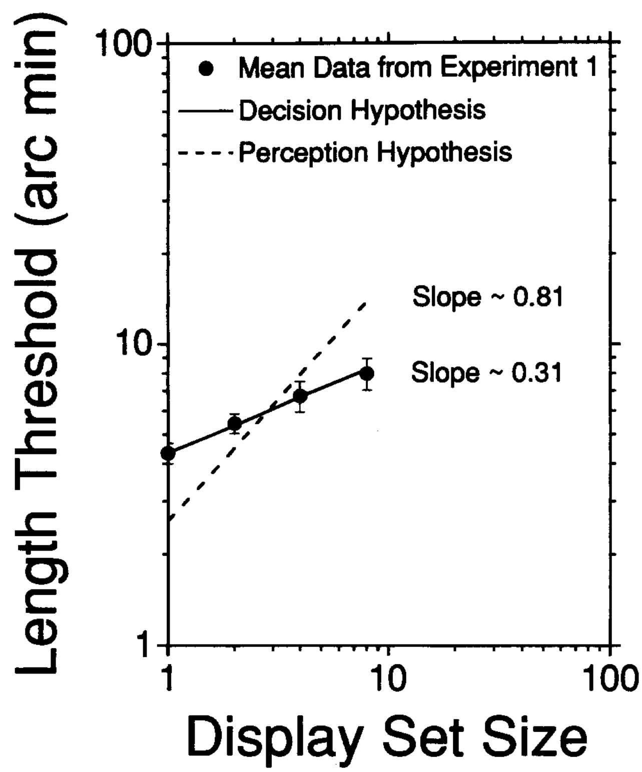

Figure 10. The solid curve is the prediction of the decision model, and the dashed curve is the prediction of the perception model. (Both models have only a single free parameter that shifts the curves vertically without changing their slopes. The solid points are the mean thresholds from Experiment 1.)

diction of the decision model, which is nearly linear in this logarithmic plot. The prediction is concisely summarized by the slope of a best fit line. For independent Gaussian distributions, the decision model predicts a slope of 0.31. This compares favorably with the observed slope of 0.29 ± 0.06.

The predicted slope depends on no free parameters. It is completely determined by assuming the maximum decision rule and the independent Gaussian distributions. However, there is one free parameter in the creation of Figure 10. The predicted thresholds depend on a proportionality constant between stimulus and percept. For a logarithmic graph such as Figure 10, this parameter will simply slide the predicted curve up and down and not change the slope. In summary, the decision hypothesis is sufficient to account for the results of Experiments 1 and 2.

The Perception Hypothesis

The alternative to the decision hypothesis is to assume that perception is not independent of set size even under the ideal conditions of these experiments. Although there are many possible perceptual hypotheses, the most fundamental

[2] Two distributions are stochastically independent if there is no correlation between their values from trial to trial. This is reasonable for widely separated objects that do not show sensory interactions.

and best defined is one that assumes that perception as a whole is a limited-capacity process. More than one thing can be perceived, but at a cost. Capacity can be defined in several ways, with the most concise being the original definition based on information theory (Broadbent, 1958, 1971; Taylor, Lindsay, & Forbes, 1967). This information theory model is equivalent to both the sample-size model (Lindsay, Taylor, & Forbes, 1968; M. L. Shaw, 1980) and certain information integration models (Kinchla, 1980). The easiest model to describe is the sample-size model (see Appendix for details). In this formulation, perception is based on sampling the input information some fixed number of times. If only one input is relevant, then all the samples can be directed at that input. Otherwise, the samples will be distributed among all of the relevant inputs. Fewer samples of a given input result in a poorer estimate of the input. In particular, if the input is one dimensional and noisy, then additional samples will reduce the standard deviation of the mean estimate. If one assumes Gaussian distributions, then the standard deviation will be inversely proportional to the square root of the number of samples. This is the familiar sample-size effect of statistical inference about means. This analysis predicts that the set-size manipulation affects the signal-to-noise ratio of a percept by a square root relation. For example, increasing the set size by a factor of four will reduce the signal-to-noise ratio by a factor of two. If such percepts could be measured directly, this would be seen in a corresponding decrease in d' or a corresponding increase in the threshold. From this model, one can derive that the effect of log set size on log threshold results in a slope of 0.5.

This, however, is not yet a complete hypothesis. As long as the percepts are noisy, then there will be an effect of decision. Accordingly, the sample-size model must be combined with the decision model. When the perceptual effects are combined with the decision effects, the effects are multiplicative (cf. Palmer, 1989). For log threshold measures, this makes the effect due to perception and the effect due to decision have additive effects on the slope measure (see Appendix). Thus, the combined prediction is for a slope of $0.5 + 0.31 = 0.81$. This limited-capacity perception hypothesis is clearly rejected by the data. It predicts an effect of set size that is several times larger than observed.

Other Hypotheses

Though the limited-capacity perception hypothesis can be clearly rejected, not all perceptual hypotheses with attentional effects can be rejected. Because both decision and perception components contribute to a response, both must be considered. The following discussion considers alternative perceptual and decision hypotheses.

Alternative Decision Assumptions

The only decision hypothesis with considerably smaller effects is one that assumes no noise in the percept. This high-threshold hypothesis predicts no set-size effect from decision processes. Such a hypothesis is not usually considered realistic because it makes many faulty predictions. It wrongly predicts the shape of the ROC curve, the shape of the psychometric function, rating scale data, differences between yes–no and forced choice tasks, and second-choice data from multiple-alternative tasks (Green & Swets, 1966). The other well-known variation in the decision hypothesis is to use a sum rule instead of a maximum rule. In this context, the sum rule predicts larger set-size effects with slopes of 0.5. Thus, it does not fit these results.

More appropriate are decision hypotheses that include different distributional assumptions. If one assumes an unequal-variance Gaussian model in which the variance of the signal increases proportionally with the stimulus (target standard deviation equals $1 + d'/r$), the predicted set-size effects are somewhat reduced. Graham et al. (1987) have used models with $r = 3$ or 4 to account for uncertainty effects in contrast detection. Such a model predicts log set-size slopes in Experiment 1 of 0.25 for $r = 4$ and 0.23 for $r = 3$. In summary, the reasonable decision models in the literature predict log set-size slopes of 0.23 or more. Using the predicted slope of 0.23 leaves room for 0.06 effect of perception on the slope. This is but 12% of the 0.50 predicted by the limited-capacity model.

Alternative Perception Assumptions

There are many ways that attention might affect perceptual processing. One might combine capacity limits with some notion of supercapacity (Kahneman, 1973) or introduce limits on processing time (Müller & Humphreys, 1991; Townsend, 1974) or consider qualitative changes in attentive processing (e.g., Stelmach & Herdman, 1991). With appropriate adaptations, these kinds of assumptions may result in predictions of the small set-size effects observed here. However, one should be cautious in evaluating these alternatives. There are conditions, such as M. L. Shaw's (1984) letter search experiment, that do produce the larger set-size effects predicted by the limited-capacity model. In our own pilot studies, we have found logarithmic slopes near the predicted 0.81 for the task of searching for tilted Ts among tilted Ls (cf. Beck & Ambler, 1973). Thus, even though one may be able to create alternative perceptual models that predict cases with small set-size effects, they will need further assumptions to explain cases with large set-size effects. In summary, the simple decision model is sufficient to account for set-size effects in simple search, whereas the combined perception and decision model may well be needed to account for the larger effects found with more complex search tasks.

Experiment 3: Stimulus Generalization

The next experiment addressed the issue of generalizing the results of Experiment 1 to other stimulus materials. Are the modest display set-size effects found with the line-length task representative of other simple visual judgments? In this experiment, we measured display set-size effects for the shape of rectangles and the orientation of line segments. We chose to measure display set-size effects rather than relevant set-size effects because the display effects are the more common measure in the literature.

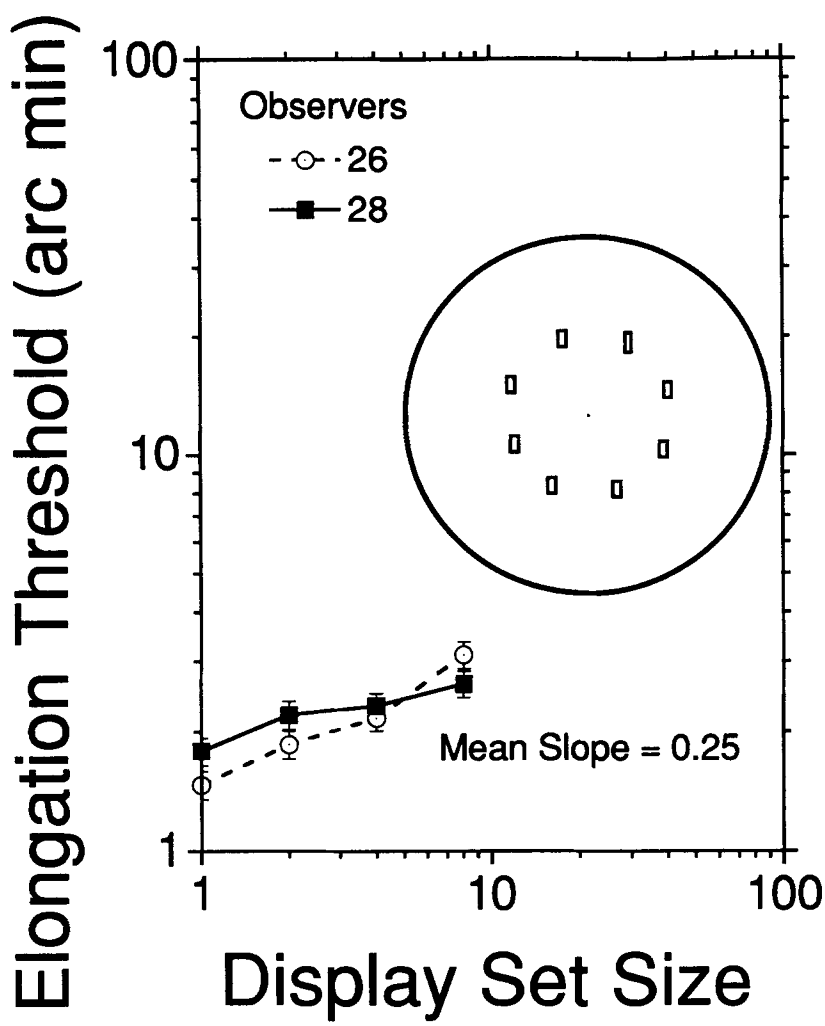

Figure 11. Results of Experiment 3. (Elongation thresholds as a function of display set size for Observers 26 and 28. The insert illustrates a representative display for the Set Size 8 condition.)

Method

Rectangle Shape Task

A representative stimulus display is shown in the insert within Figure 11. As with the previous experiment, stimuli were arranged around a fixation point. In this example, eight rectangles are shown, with one being a target rectangle with a vertically elongated shape. The distractor rectangles were all vertically oriented with 60 arc min height and 30 arc min width. The target rectangle was changed in shape by increasing the height and decreasing the width by an equal amount. Specifically, the dimensions were changed by 2, 4, or 6 arc min for Set Sizes 1 and 2, and by 4, 8, or 12 arc min for Set Sizes 4 and 8. From these conditions, an elongation threshold was estimated in units of arc min change in each dimension. This measure of shape was used to facilitate comparisons to Experiment 1.

Line Orientation Task

A representative display is shown in the insert in Figure 12. In this example, eight line segments are shown, with one being a target line with a more vertical orientation. The distractor lines were all oriented 27° from vertical, with a horizontal run of 16 arc min and a vertical rise of 32 arc min. The target line was changed in orientation by increasing its vertical run and decreasing its horizontal rise by an equal number of pixels. Specifically, the dimensions were changed by 2 and 4 arc min for Set Sizes 1 and 2, and by 2, 4, and 6 arc min for Set Sizes 4 and 8. This resulted in changes of target orientations of approximately 3°, 8°, and 12°. Thresholds are reported in terms of the change in rise and run dimension to facilitate comparisons to the line-length and rectangle shape experiments. All three thresholds are reported in terms of arc min of linear displacement.

Procedure

The procedure was essentially the same as that of Experiment 1. The judgment was a two-interval forced choice discrimination of elongation or orientation. For each task, two observers participated in both tasks for four sessions with four set-size conditions, yielding 384 trials per condition per observer.

Results

Rectangle Shape

In Figure 11, thresholds are plotted as a function of display set size for 2 observers. There was a reliable set-size effect for both observers. For Observer 26, the slope on this logarithmic plot was 0.33 ± 0.07, $t(3) = 4.5$, $p < .05$; for Observer 28, the slope was 0.20 ± 0.04, $t(3) = 5.0$, $p < .01$. The average slope of 0.26 was indistinguishable from the 0.29 ± 0.06 slope observed in Experiment 1.

Line Orientation

In Figure 12, thresholds are plotted as a function of display set size for 2 observers. For Observer 17, the slope on this logarithmic plot was 0.30 ± 0.04, $t(3) = 6.9$, $p < .01$; for Observer 21, the slope was 0.18 ± 0.07, $t(3) = 2.6$, $p < .05$. Again, the average slope of 0.24 was indistinguishable from the 0.29 ± 0.06 slopes observed in the line-length and rectangle shape experiments.

Discussion

This experiment demonstrated that both shape and orientation tasks show similar display set-size effects as the line-length task. The effects were all compatible with a decision model of attention effects, and the effects were much too small for a limited-capacity perceptual model. We suggest that this generalization may extend to all judgments of single dimensions.

Such similar set-size effects in different tasks have not been obtained in previous visual search experiments that did not control similarity (e.g., Treisman & Gormican, 1988). We suspect that finding consistent set-size effects depends on the control of stimulus factors and target–distractor similarity. The threshold search paradigm was designed with these issues foremost, but even so, we suspect that yet more sophisticated controls will be necessary for some kinds of stimuli. In any case, it is only with these kinds of controls that there is any hope of set-size effects being identical for a range of visual attributes.

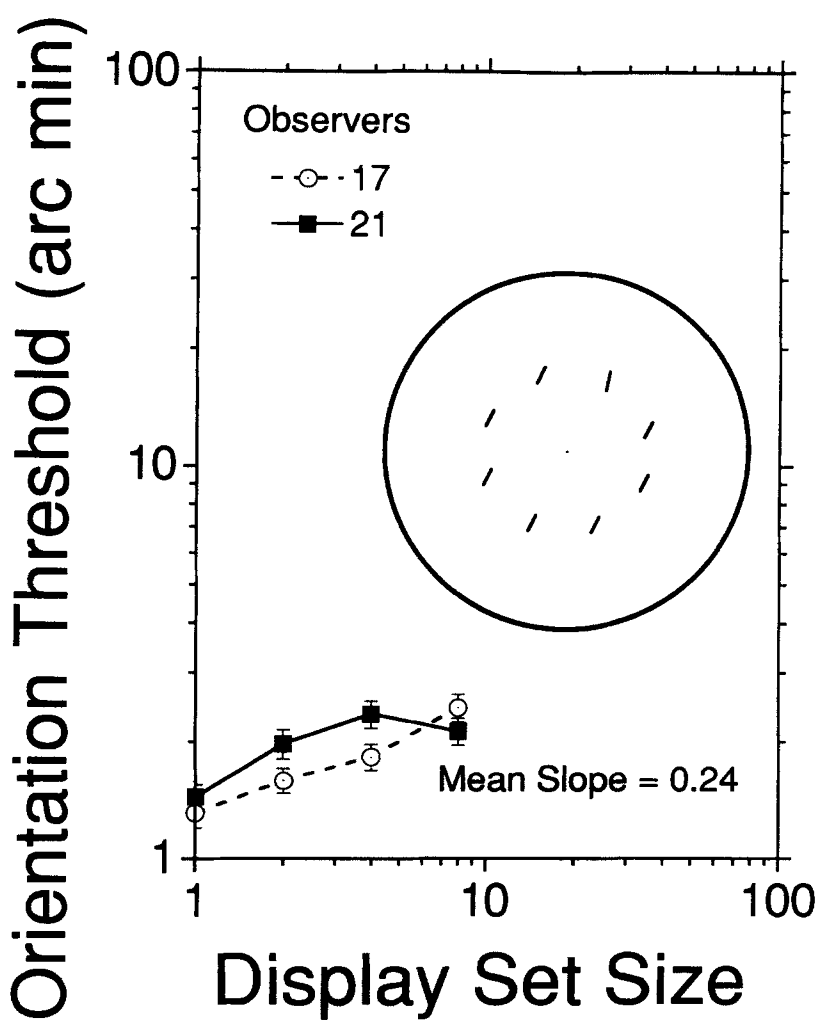

Figure 12. Results of Experiment 3. (Orientation thresholds as a function of display set size for Observers 17 and 21. The insert illustrates a representative display for the Set Size 8 condition.)

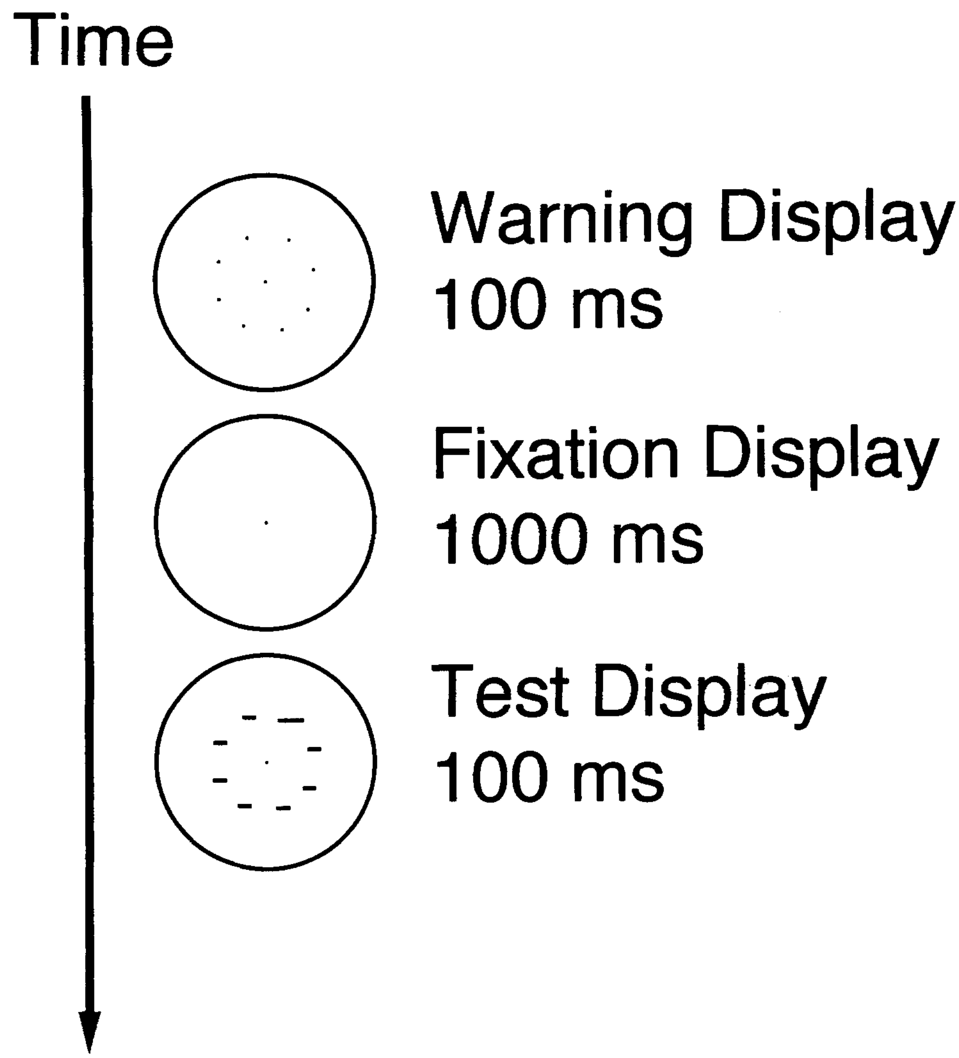

Figure 13. A schematic illustration of the display sequence used in the yes–no procedure of Experiment 4. (A target stimulus appeared on 50% of the trials.)

Experiment 4: Procedure Generalization

Up to now, the two-interval forced choice procedure has been used because it minimizes possible effects of response bias on performance. In this final experiment, we generalized our study to a yes–no procedure. Observers viewed a single display and then made a yes–no decision about the presence of a target as illustrated in Figure 13. This generalization is important for two reasons. First, the yes–no response has been the most commonly studied response in previous search experiments. Second, two-interval forced choice introduces a possible memory load on the observer. In principle, observers might try to remember all the stimuli from the first display and compare them with the second display. In practice, observers report remembering just the largest stimulus from the first display and comparing it with the largest from the second. This strategy makes the memory load independent of set size. Showing similar set-size effects for yes–no and forced choice procedures will eliminate the concern that two-interval forced choice may have inflated the set-size effects by introducing a memory requirement. The following experiment pursued the yes–no procedure, and the ensuing discussion introduces the appropriate decision model.

Method

This experiment introduced several changes from Experiment 1. First, only a single display was presented, and observers made a yes–no response. Second, each set size and target line length was presented in a separate block to allow for separate estimation of hits and false alarms. Each block began with instructions indicating the set size and a display of one target and one distractor. Third, the unbiased, 75% correct threshold was estimated from a d' psychometric function by linear regression. The d' statistic was calculated by the constant-variance Gaussian model of signal detection theory (Green & Swets, 1966). This calculation was made separately for each session, and the standard error was calculated for the mean across sessions. As in Experiment 1, there were Set Sizes 1, 2, 4, and 8. Two observers participated in four sessions, yielding 576 trials per condition per observer.

Results

In Figure 14, thresholds are plotted as a function of set size for 2 observers. There was a reliable set-size effect for both observers. For Observer 17, the slope on this logarithmic graph was 0.23 ± 0.05, $t(3) = 5.1$, $p < .01$; for Observer 26, the slope was 0.27 ± 0.03, $t(3) = 11$, $p < .001$. The average slope of 0.25 was indistinguishable from the 0.29 ± 0.06 slope found in Experiment 1. This result replicated the modest set-size effects found with Experiment 1. Clearly, the magnitude of the set-size effects was not due to using two-interval forced choice.

Discussion

Quantitative predictions can be derived for this experiment based on the same theory introduced earlier for two-interval forced choice. The general theory assumes signal detection theory, the maximum decision rule, and stochastic independence between percepts. To get specific predictions, we also assume constant-variance Gaussian distributions. This model is described in the Appendix. It predicts a set-size effect that is slightly smaller than the one predicted for two-interval forced choice. The predicted slope on a logarithmic graph is 0.25 for the yes–no procedure compared with 0.31 for the two-interval forced choice procedure. This prediction matches exactly the average observed slope of 0.25. In summary, the decision model yields a prediction for a yes–no search task that fits the observed data.

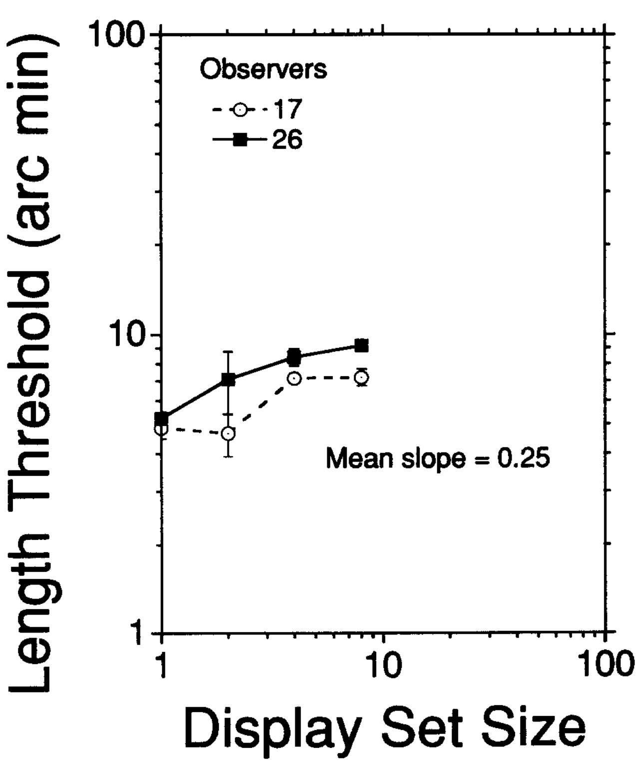

Figure 14. Results of Experiment 4. (Length thresholds as a function of display set size for Observers 17 and 26. In this experiment, a yes–no procedure was used instead of a two-interval forced choice procedure.)

General Discussion

Summary

In this research, we investigated three questions about set-size effects in visual search. The first was to distinguish attentional contributions from nonattentional contributions; the second was to determine if the attentional effects were due to decision or perceptual processes; and the third was to address the generality of the results to other instances of simple visual search. We have results relevant to each question.

Attention

When care is taken to avoid sensory contributions, one can find a set-size effect that is largely or entirely attentional. This was established by the relevant set-size paradigm in which set size is manipulated through instructions alone. Although set-size effects may usually involve both sensory and attentional phenomena, the relevant set-size paradigm is a way to isolate the attentional componant.

Decision

For visual search tasks that use targets defined on a single simple dimension, decision processes are sufficient to account for the entire attentional effect. The set-size effect was less than half that expected if perception had a limited capacity in the information sense. Moreover, the magnitude of the set-size effect was predicted by the decision hypothesis that included noisy percepts and the maximum decision rule. For all of the experiments, there was no indication that attention affected the perception of individual attributes. The decision hypothesis was sufficient.

Generality

Set-size effects can be caused by sensory, perceptual, or decision processes. Our conclusions about attention and decision processes as the cause of our observed set-size effects depends critically on the visual search task. Others have shown sensory effects that are correlated with set-size manipulations (e.g., Eriksen & Rohrbaugh, 1970). Similarly, others have demonstrated perceptually mediated attentional effects for more complex stimuli such as letters (e.g., M. L. Shaw, 1984). The key research objective is to determine the boundary conditions that result in sensory versus perceptual versus decision contributions to set-size effects.

Toward that end, we have specialized our experimental conditions to demonstrate set-size effects for which attention affected the decision process alone and did not affect perception. This result was found for three stimulus judgments and for both two-interval and yes–no procedures. The next step for the future is to define more clearly what kinds of visual search tasks produce set-size effects with sensory, perceptual, and/or decision contributions.

Specific Implications

Reject Models With Limited Capacity for All of Perception

There has been a persistent debate regarding the effect of attention on perception. Some have argued for little effect (e.g., Duncan, 1980; Egeth, 1977; Graham, 1989; Shiffrin & Geisler, 1973), and others have argued for a significant effect for all kinds of perception (e.g., Posner et al., 1980). For the perception of simple visual attributes, the results found here require little or no effect of attention on perception. Our results extend previous results with luminance increment detection that showed no sign of an attentional component (Davis et al., 1983; Graham, Kramer, & Haber, 1985; M. L. Shaw, 1984; Yager et al., 1984). We argue that these results are enough to establish that perception is not always limited by attention.

Conditions With Limited-Capacity Perception

Previous indications of attentional effects on perception were largely for more complex stimuli and tasks. Search for characters among characters often shows signs of attentional limitations (e.g., Eriksen & Yeh, 1985; Hoffman & Nelson, 1981; Jonides, 1980; Kröse & Julesz, 1987; M. L. Shaw, 1984). The main line of results showing attentional effects for simple stimuli are the cuing studies of Posner and his colleagues (Posner, Nissen, & Ogden, 1978; Posner et al., 1980). Unfortunately, for these kinds of latency experiments distinguishing the role of perception and decision remains uncertain. Extensive assumptions are necessary about the stochastic processes that introduce a decision set-size effect (e.g., Pavel, 1990), and existing detailed models of latency effects on visual search do not explicitly distinguish perceptual and decision components (e.g., Wolfe, Cave, & Franzel, 1989). Distinguishing these components is further confounded by the use of partially valid cues. When partially valid cues are used, one must make assumptions about the interpretation of the cue probabilities as well as about the stochastic processes.

Despite the difficulties, several researchers have pursued variations on the cuing paradigm to find other predictions that might distinguish decision and perception accounts (Downing, 1988; Hawkins et al., 1990; Müller & Findlay, 1989; Müller & Humphreys, 1991). It seems likely that attention affects perception under some conditions. The most likely conditions are the following.

Perception of letter identity. Attention limits the identification of letters under some circumstances (M. L. Shaw, 1984, and many others).

Perception requiring memory. Attention almost certainly limits complex perceptual tasks that require memory across multiple fixations or over fractions of a second (Irwin, 1991; Palmer, 1988, 1990; Palmer & Ames, 1992; Sperling, 1960). This memory phenomenon may also explain the effects found with postcues (Downing, 1988; Hawkins et al., 1990).

Perception contributing to dual tasks. Certain dual tasks may require attention to coordinate multiple perceptions. Although dual tasks using detection show little interference (e.g., Graham et al., 1985), other discrimination tasks do show such effects (e.g., Bonnel, Possamaï, & Schmitt, 1987). This dual-task effect may account for the attention effects reported by Müller and Humphreys (1991). Why these dual tasks show attention effects is unclear. It may be implicit memory demands such as measured by Palmer (1990), or it may be something specific to coordinating multiple tasks.

Perceptual processing time. It is possible that perception has unlimited capacity but shows effects of attention on processing time. This distinction is well developed by Townsend (1974, 1990). Processes may combine serial and parallel processing with either limited or unlimited capacity. Backus and Sternberg (1988) have argued that cuing studies of simple attributes may have uncovered a case with unlimited capacity and serial processing.

In summary, there is plenty of evidence that attention affects perception under some conditions.

Question Models With Qualitative Effects of Similarity

In visual search, the similarity of targets and distractors has a profound effect on performance. Increased target and distrctor similarity results in less accuracy, longer latencies, and larger set-size effects. Results of this kind were interpreted by Treisman and Gormican (1988) as indicating a qualitative shift from unlimited-capacity, parallel processing to limited-capacity, serial processing. Alternatively, Duncan and Humphreys (1989) have interpreted this same phenomena as a quantitative effect of similarity (see Pavel, 1990, for a model). In their view, an unlimited-capacity parallel processing system will show set-size effects for targets that are similar to distractors because of noise-limited decision. This possibility is well illustrated by the experiments of Nagy and Sanchez (1990), in which a steady increase was observed in latency set-size effects with increases in similarity between target and distractor.

These two interpretations led to different predictions in the current experiments. Our experiments measured set-size effects at a discrimination threshold of 75% correct response. To reduce performance to threshold, the current experiments used highly similar targets and distractors. Treisman and Gormican propose that such similar targets can only be detected by attending individual stimuli. Such a limited-capacity system predicts much larger set-size effects than observed here. Consequently, our result argues against the limited-capacity model and supports the Duncan and Humphreys alternative. However, this result says nothing about the serial or parallel nature of the processes. It says only that all stimuli are processed without overall capacity limitations.

A closer look at our experiments suggests that although similarity has a large effect on overall performance, it has only a small effect on the magnitude of set-size effects as quantified by our slope measure. When threshold is defined at 75% correct, thresholds nearly doubled when set size increased from 1 to 8. A slightly smaller set-size effect can be seen if one defines threshold at 90% correct. This change in the size of the effect is predicted by the decision model. The maximum decision rule predicts a change in the combined noise distribution that changes the shape of the psychometric function at large set sizes (e.g., Pelli, 1985). In particular, increasing set size from 1 to 8 predicts that the 75% correct threshold will increase by 1.9 and predicts that the 90% correct threshold will increase by 1.5. In summary, although there probably is a small quantitative effect of similarity on set-size effects as measured here, there is no sign of a qualitative effect of similarity.

Relation to Search Latency Experiments

It is natural to ask what would have happened in our experiments if we had measured latency instead of accuracy. Speculating on this question will illustrate the relation between these two paradigms. The biggest difference is that there were far more errors made under the conditions of this experiment than would ever be allowed in a latency study. We manipulated stimulus differences to measure a psychometric function and estimate threshold. For the largest stimulus differences, accuracy reaches 90% correct, and our stimulus differences were similar to some of the most difficult conditions in Treisman and Gormican (1988, pp. 39–40) and Nagy and Sanchez (1990). Under these conditions, both accuracy and latency studies show set-size effects. The results change if one further increases the stimulus differences. Then accuracy becomes perfect, and the set-size effects on latency decline to near zero, at least for very large color differences (Nagy & Sanchez, 1990). We argue that these results can be modeled by an unlimited-capacity but noisy parallel process (cf. Pavel, 1990). The set-size effects on latency arise from a noise-limited decision process that integrates information from the parallel processes. As the stimulus differences grow, the noise becomes less significant, and set-size effects are reduced.

General Implications

Defining Attention Phenomena by Voluntary Control

A cornerstone of the analysis in this article is our definition of attention. It derives from the peripheral–central contrast made by Broadbent (1958, pp. 11–14). In general terms: Attentional phenomena are changes in performance that are under voluntary control and not determined by the immediate stimulus. The key word is *control.* This general definition gives rise to operational definitions that use instructional manipulations such as precues and relevant set size.

This definition emphasizes what William James called *voluntary attention* and ignores what he called *passive attention* and what others have called *stimulus-driven attention.* There are two ways to accommodate this definitional issue. One is to agree with James and to restrict our definition to voluntary attention. The other is to look more closely at stimulus-driven attention. Perhaps the closest study is that of abrupt visual onsets (Yantis & Jonides, 1984, 1990). In these visual search experiments, set size had little effect when the target had an abrupt visual onset and the distractors had camouflaged onsets. To demonstrate that this was an attentional effect, Yantis and Jonides (1984) compared abrupt onsets and camouflaged onsets when voluntary attention was directed to the target. This eliminated the difference between these classes of target. This result is consistent with there being no sensory contribution to the differences in processing of these targets. Furthermore, when the abrupt onsets were reliably always distractors and never the target, subjects could ignore them entirely (Yantis & Jonides, 1990). This method of distinguishing stimulus-driven attention from sensory effects is remarkably similar to the logic of using relevant set-size experiments to distinguish attentional and sensory effects. The relevant stimuli, not all of the displayed stimuli, determine the attentional effect even for this example of stimulus-driven attention. Thus, stimulus-driven attention may be moderated by voluntary control. This makes plausible the idea that all attentional phenomena may be identified by the possibility of voluntary control.

There are important advantages to a specific definition of attention. In this article, defining attention by instructional control led to procedures that help distinguish between attentional and nonattentional phenomena. Such distinctions are critical to go beyond treating all set-size effects as attentional.

The Selection Model

The issues addressed in this article can be put into a larger context through a generalization of Broadbent's selection model. The ideas are illustrated in the information-flow diagram of Figure 8. For both hypotheses, it shows the flow of information from some number of distinct stimuli to a single response. In preattentive processing, each stimulus is processed without voluntary control; in selection, some of these representations are chosen for further attentive processing, which in turn yields the response. Selective processing is under instructional control and is not determined by the immediate stimulus. The one specific assumption made here is that proper instructions can exclude some stimuli from further processing. This stark model is enough to capture the qualitative results of the current experiments. The selection process predicts the equivalent effects of display and relevant set size. In addition, this general model allows the specific decision model discussed earlier as a special case. The decision model specifies the output of the early processing in terms of random variables corresponding to noisy percepts and specifies the later processing as a simple decision rule.

This characterization is an instance of the preattentive–attentive distinction with a stress on the selective aspect of attentive processing (Neisser, 1967). It is more general than specific models that specify capacity limitations and the dynamics of processing as serial or parallel. This characterization is also ambiguous about early versus late selection. It is an early selection model if later processing is necessary for more complex perceptions. For conditions studied here, selection is relatively late. It is after the relevant sensory and perceptual processing of simple visual attributes. For other conditions, this general model makes no predictions. In summary, the present results highlight the successful selection of relevant percepts. This interpretation is compatible with a wide range of models that include a selection mechanism for attention.

Measuring the Size of Attentional Effects

Another aspect of the current work was the effort to measure the size of attentional effects. In particular, a quantitative measure needs to be independent of the details of stimulus and procedure. Several aspects of the threshold search paradigm were designed to create such a measure. First, the elimination of nonattentional contributions was necessary. The details of stimuli and procedure were chosen to avoid sensory effects, and success was confirmed by comparing display and relevant set size. Second, performance was measured in terms of a stimulus threshold—an isoresponse measure—rather than a variable response measure. By measuring what set of stimuli produce equivalent responses, the details of the response scale become largely irrelevant. Third, set-size effects were quantified in terms of the slope on the log threshold by log set-size graph. This results in a dimensionless value that is independent of the units. For example, switching from size thresholds to orientation thresholds with completely different units will not change these slope values. Through this analysis, simple decision-based attention models predict that all stimuli should result in set-size effects of the same magnitude. Such formulations are necessary to move attention research beyond qualitative demonstrations and on to quantitative measurements.

Conclusion

Our goal was to measure the effect of attention on visual search for attributes such as size and orientation. A search paradigm was described that minimizes a variety of nonattentional contributions to set-size effects. The success of these efforts was confirmed by the correspondence between the display set-size experiment and the relevant set-size experiment. The observed set-size effect was found with three stimulus conditions and two response procedures. The magnitude of the set-size effect was consistent with hypotheses in which attention affects only decision processes and not perceptual processes. In these tasks, the perception of simple attributes is not limited by attentional processes.

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Appendix

Two-Interval Forced Choice Task

The decision hypothesis of set-size effects was developed as part of signal detection theory (Green & Swets, 1966; Tanner, 1961). We will introduce the hypothesis by briefly describing the relevant aspects of signal detection theory, the maximum rule, and then the hypothesis itself.

Consider first the Set Size 1 condition in which a distractor stimulus is presented in one interval and a larger target stimulus is presented in the other interval. The observer must decide which interval contains the target. Observing these stimuli is assumed to result in noisy percepts. The aspect of each percept that is relevant to the decision is assumed to correspond to a one-dimensional, real-valued random variable. Usually, it is further assumed that the mean of these random variables is proportional to the stimulus magnitude. For distractors and targets, denote the random variables by D and T, respectively. Denote their density distributions by $f(x)$ and $g(x)$ and their cumulative distributions by $F(x)$ and $G(x)$, respectively. For this two-interval forced choice task, the optimum decision rule is to choose the interval with the largest percept (Green & Swets, 1966). By this maximum rule, the probability of a correct decision is

$$P(\text{correct}) = P(T > D). \tag{A1}$$

By assuming that T and D are stochastically independent, the probability correct can be determined by integrating the product of target values and smaller distractor values,

$$P(\text{correct}) = \int_{-\infty}^{\infty} g(x)F(x)dx \tag{A2}$$

(Green & Swets, 1966, p. 46).

Consider next the larger set sizes in which one interval will contain n identical distractors and the other interval will contain one target and $n - 1$ identical distractors. Denote the random variables for the all-distractor interval by $D_{d1}, D_{d2}, \ldots, D_{dn}$ and the random variables for the target interval by $T, D_{t2}, D_{t3}, \ldots, D_{tn}$. Using the maximum rule, the probability of a correct response is

$$P(\text{correct}) = P(\max(T, D_{t2}, \ldots, D_{tn}) > \max(D_{d1}, D_{d2}, \ldots, D_{dn})). \quad \text{(A3)}$$

This result can be expressed more easily in terms of the probability of an incorrect response as follows:

$$\begin{aligned} P(\text{incorrect}) &= P[\max(D_{d1}, \ldots, D_{dn}) \geq \max(T, D_{t2}, \ldots, D_{tn})], \\ &= \int_{-\infty}^{\infty} P[\max(D_{d1}, \ldots, D_{dn}) = x] \\ &\qquad P[\max(T, D_{t2}, \ldots, D_{tn}) < x]dx, \\ &= \int_{-\infty}^{\infty} nf(x)F(x)^{n-1}G(x)F(x)^{n-1}dx, \\ &= n \int_{-\infty}^{\infty} f(x)G(x)F(x)^{2n-2}dx. \end{aligned}$$

Now the probability of a correct response is

$$P(\text{correct}) = 1 - n \int_{-\infty}^{\infty} f(x)G(x)F(x)^{2n-2}dx. \quad \text{(A4)}$$

This result closely follows a result by M.L. Shaw (1980) for a localization task.

Although Equation A4 is sufficient to predict the effect of set size on probability correct, a further assumption is necessary to predict the effect of set size on threshold. One must specify how probability correct varies with changes in the stimulus. Here we will follow the simplest version of signal detection theory and assume that increasing stimulus values causes a proportional shift in the target distribution $T = D + ws$. By this assumption, the target distribution is $g_s(x) = P(T = x) = P(D + ws = x)$, where $g_s(x)$ is the signal distribution for a target that differs from the distractor by an amount s, and w is a free parameter for perceptual sensitivity. This can be manipulated to give

$$g_s(x) = P(D = x - ws), \qquad g_s(x) = f(x - ws). \quad \text{(A5)}$$

The corresponding cumulative distribution is similarly $G_s(x) = F(x - ws)$. Next, define $s_t(n)$ as the stimulus threshold that is defined by .75 probability correct. This threshold and $G_s(x)$ can also be substituted into Equation A4 to yield

$$.75 = 1 - n \int_{-\infty}^{\infty} f(x)F(x - ws_t(n))F(x)^{2n-2}dx. \quad \text{(A6)}$$

This equation was solved numerically for $s_t(n)$, assuming that $f(x)$ was a Gaussian distribution. For $w = 1$, s_t equals 0.95 with $n = 1$ and equals 1.82 with $n = 8$. This is a 1.9-fold set-size effect and is equivalent to a slope on a logarithmic graph of 0.31. Changing the value of parameter w changes the absolute performance but does not change the predicted slope.

Yes–No Task

To make a quantitative analysis of Experiment 4, one must derive the predictions of the decision model for a yes–no threshold experiment. This derivation was based on the same signal detection theory that was used to derive predictions for the two-interval forced choice task. As before, let D and T be the random variables for the distractors and targets, respectively. Also let $f(x)$, $g(x)$, $F(x)$, $G(x)$, be the density and cumulative distributions as before. Finally, let the target distribution $G(x)$ be defined by a shifted family of distractor distributions $F(x - ws)$ as in Equation A5.

Consider first a Set Size 1 condition. In a yes–no task, there is a single stimulus that can be either a target or a distractor. The observer must respond *yes* if the stimulus is a target and *no* if it is a distractor. According to signal detection theory, the observer responds *yes* if the random variable of the stimulus is greater than a decision criterion c. Let a denote the *false alarms*, which are the probability of responding *yes* to a distractor, and let b denote the hits, which are the probability of responding *yes* to a target. With these definitions, the false alarms and hits are

$$\begin{aligned} a &= F(D > c) = 1 - F(c), \\ b &= F(T > c) = 1 - F(c - ws). \end{aligned} \quad \text{(A7)}$$

Consider next a set size n. Using the maximum rule as before, an observer responds yes if the maximum percept of the n stimuli surpasses the decision criterion c. Let $a(n)$ and $b(n)$ be the false alarm and hit probabilities for a set size n. In this notation, Equation A7 gives false alarms and hits for $a(1)$ and $b(1)$. Assuming that all the distractor and target distributions are stochastically independent, the general false alarm and hit probabilities can be expressed as a function of $a(1)$, $b(1)$, and n (Graham et al., 1986, p. 380):

$$\begin{aligned} a(n) &= 1 - [1 - a(1)]^n \\ b(n) &= 1 - [1 - b(1)][1 - a(1)]^{(n-1)}. \end{aligned} \quad \text{(A8)}$$

To estimate set-size effects on threshold, we must combine Equation A8 with Equation A7 for $a(1)$ and $b(1)$. Making this substitution and simplifying yields

$$\begin{aligned} a(n) &= 1 - F(c)^n, \\ b(n) &= 1 - F(c - ws)F(c)^{n-1}. \end{aligned} \quad \text{(A9)}$$

This system of equations can be solved for the threshold stimulus $s_t(n)$ defined by false alarms $a(n) = .25$ and hits $b(n) = .75$:

$$.25 = 1 - F(c)^n, \quad \text{(A10)}$$

and

$$.75 = 1 - F(c - ws_t(n))F(c)^{n-1}. \quad \text{(A11)}$$

To solve for $s_t(n)$ as a function of set size n and the free parameter w, first use Equation A10 to solve for $F(c)$ and c:

$$F(c) = (.75)^{1/n}, \quad \text{(A12)}$$

and

$$c = F^{-1}[(.75)^{1/n}]. \quad \text{(A13)}$$

Next, rearrange Equation A11,

$$F(c - ws_t(n)) = .25/F(c)^{n-1}.$$

Take the inverse,

$$c - ws_t(n) = F^{-1}[.25/F(c)^{n-1}],$$

and solve for $s_t(n)$,

$$s_t(n) = (1/w)\{c - F^{-1}[.25/F(c)^{n-1}]\}.$$

Next, substitute $F(c)$ and c using Equations A12 and A13,

$$s_t(n) = (1/w)\{F^{-1}[(.75)^{1/n}] - F^{-1}[.25/[(.75)^{1/n}]^{n-1}]\}.$$

This expression simplifies to the final result:

$$s_t(n) = (1/w)\{F^{-1}[(.75)^{1/n}] - F^{-1}[(.75)^{1/n}/3]\}. \quad \text{(A14)}$$

As before, this equation predicts set-size effects to a proportionality constant w, which is the single free parameter. Assuming Gaussian distributions and $w = 1$, solving for s_t with $n = 1$ yields 1.39 and for $n = 8$ yields 2.27. This is a 1.6-fold set-size effect and is equivalent to a slope on a logarithmic graph of 0.25. As with the two-interval forced choice model, the predicted slope is unaffected by w. Thus the yes–no model predicts a slope slightly less than the 0.31 slope predicted for the two-interval forced choice task.

The Perception Hypothesis

The perception hypothesis follows closely the work of Broadbent (1958; 1971) and Lindsay et al. (1968). By this hypothesis, set-size effects are due to both perception and decision processes. We will first describe a general version of the perception hypothesis with a general version of the sample-size model (Shaw, 1980). Following that general treatment, the usual sample-size model will be described as applied to our paradigm.

As before, let D and T denote the random variables that correspond to the percepts of the distractor and target, respectively. In the previous development, the random variables were subscripted to denote individual stimuli; in what follows, those subscripts will be dropped to ease the notation. In the sample-size model, each percept depends on the mean of multiple samples of an underlying sensation. The random variables corresponding to this sensation will be denoted D^* and T^* for distractor and target, respectively. For k samples of a distractor sensation, the distractor percept will be defined as

$$D = (D_1^* + D_2^* + \ldots + D_k^*)/k, \quad \text{(A15)}$$

where D_j^* is the random variable corresponding to the jth sample of the sensation D^*. Each sensation D_j^* is defined as independent and identically distributed with a density function of $f^*(x)$ and a cumulative function of $F^*(x)$. Next, consider the number of samples k. By the sample-size model, there are a fixed number of samples that can be distributed over sensations. Denote the total number of possible samples by m, and assume that they can be equally distributed over n stimuli to yield an integer number of samples per stimulus, m/n. With this assumption we can derive the distribution of D as

$$f_n(x) = (1/k)F^{*k}(x). \quad \text{(A16)}$$

Where $k = m/n$, $F^{*k}(k)$ is the k-fold convolution of $f^*(x)$ with itself, and $f_n(n)$ is the density distribution of D for a particular n.[3] Similarly, the distribution of T is

$$g_n(x) = (1/k)G^{*k}(x). \quad \text{(A17)}$$

From the definition of convolution, one can express themean and variance of D and T in terms of D^* and T^*, respectively:

$$E(D) = E(D^*),$$
$$\text{var}(D) = (1/k)\text{var}(D^*),$$
$$E(T) = E(T^*),$$
$$\text{var}(T) = (1/k)\text{var}(T^*). \quad \text{(A18)}$$

In these kinds of signal detection models, one usually fixes the variance of the distractor distribution to 1 without loss of generality. This can be done here for the distractor percept distribution for a set size of 1 by defining $\text{var}(D^*) = m$. Then for $k = m/n$, $n = 1$, and Equation A18, we have $\text{var}(D) = 1/(m/n)\text{var}(D^*) = 1$, and more generally for any n, we have $\text{var}(D) = 1/(m/n)\text{var}(D^*) = n$. If T and D are similarly distributed, then a similar result holds for T. Thus, the effect of set size is to proportionally increase the variance of the percepts.

To complete this general model, we can take the derived perceptual distributions and use them as the inputs to the decision model. In particular, the $f_n(x)$ and $g_n(x)$ distributions of Equations A16 and A17 can be substituted for $f(x)$ and $g(x)$ in Equation A4:

$$P(\text{correct}) = 1 - n \int_{-\infty}^{\infty} f_n(x)G_n(x)F_n(x)^{2n-2}dx. \quad \text{(A19)}$$

From this equation, predictions can be calculated for any particular distributional assumption. Similar substitutions can be made in Equations A5 and A6.

Previous work with the sample-size model has assumed that the sensory distributions are Gaussian. In particular, we will assume that D^* is a Gaussian distribution with a mean of zero and a variance of m. From Equation A16, D is also Gaussian but with a variance of n. This distribution can be substituted into Equation A6 and solved numerically as for the decision model. For $w = 1$ as before, $s_t = .95$ with $n = 1$ and equals 5.14 with $n = 8$. This 5.4-fold increase is equivalent to a slope on a logarithmic graph of 0.81.

A final comment may help clarify the relation between the perception and decision models. The models are decomposable in the sense that the perception model simply changes

[3] Suppose X and Y are independent random variables having respective cumulative distributions of F and G. Then the distribution of $X + Y$, which is called the convolution $F * G$, is given by $F * G(x) = \int_{-\infty}^{\infty} F(x - z)g(z)dz$, where g is the density distribution corresponding to G. In addition, the n-fold convolution of x with itself is the distribution of the sum of n independent random variables each having the distribution F.

the variance of all perceptual distributions by a common factor. These distributions are then the inputs to the decision model. When the predictions of these models are expressed in terms of thresholds, there is a close relationship between the variance of the percepts and the predicted thresholds. If the standard deviations of all percepts increase by the square root of n, then the threshold will increase by the square root of n. The decision model predicts a similar multiplicative effect of n on threshold. Thresholds will increase by a multiplicative amount that is independent of the performance at any given set size. These two independent multiplicative factors can be combined to predict overall performance in the perception model. In terms of logarithmic slopes, the multiplicative factors become additive. The square-root-of-n effect on the percepts becomes a 0.5 slope; the decision model factor becomes a 0.31 slope; and the two factors add to yield a combined prediction of a 0.81 slope. In general, these kinds of multiplicative models make additive predictions about logarithmic thresholds (Palmer, 1989).

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