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Set-size and chromatic uncertainty in an accuracy visual search task

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Abstract

Thresholds for chromatic differences were measured in a simple visual search task in which the target differed from the distractors in chromaticity only. In Experiment 1, the spatial separation between stimulus elements was varied. Slopes of threshold versus set-size (2–16) for elements in close proximity were somewhat elevated, suggesting non-independence of the stimulus elements. In Experiment 2, chromatic uncertainty was introduced to increase the attentional load beyond that accomplished with the set-size manipulation. The results were accounted for by a model assuming no limit in attention capacity. Furthermore, chromatic uncertainty was successfully modeled as a simple increase in the number of monitored signals.

Keywords: Visual search; Uncertainty; Attention; Color

1. Introduction

Manipulating the number of stimulus elements (set-size) presented simultaneously in a visual search task is both popular and common. Historically, flat set-size functions in plots of reaction time versus set size have been interpreted as evidence for a parallel process underlying the search while positively sloped set-size functions have often been interpreted as evidence for a serial process and hence, some sort of limit in attention capacity (Treisman, 1988; Treisman & Gelade, 1980; although see Duncan & Humphreys, 1989; Townsend, 1990). However, as most clearly pointed out by Palmer (1994, 1998), set-size slopes greater than zero cannot necessarily be interpreted as a limit in attention capacity. Adapting the signal detection theory to an accuracy visual search paradigm (Palmer, Ames, & Lindsey, 1993; Palmer, Verghese, & Pavel, 2000) showed that thresholds are expected to rise with set-size, even when attention capacity is assumed to be unlimited. That is, thresholds (and possibly reaction times as well) are expected to increase with set size because of the noisy nature of coding in the visual system.

In the present study, we asked whether the effects of set-size and chromatic uncertainty could be accounted for by a model adapted from signal detection theory postulating no attention capacity limit. In both Experiments, chromatic difference thresholds for detecting a target that differed from the distractors in chromaticity only were measured as a function of set-size. In Experiment 1, the spatial separation between stimulus elements was tested. In Experiment 2, chromatic uncertainty was introduced to test attention capacity beyond that achieved with the set-size manipulation. Three models of search were tested, all of which assumed the stimulus is represented as a continuous and noisy variable (low-threshold models). That is, according to low-threshold models of signal detection, a non-target element can produce a signal large enough to cause a false alarm. High threshold models, on the other hand, assume a discrete stimulus representation so that the stimulus representation is in either detect or non-detect mode. Moreover, a non-target stimulus can never produce a false alarm. High threshold models

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have been shown to erroneously predict multiple aspects of search performance and were therefore not considered here (e.g. Palmer et al., 2000). For the three low threshold models tested here, the maximum-of-outputs decision rule was adopted since other decision rules, such as the ideal observer, or maximum-of-differences decision rules only slightly differ in their predictions (Palmer et al., 2000). Moreover, the primary aim of the present study was to test attention capacity limits and not which decision rule provided the best prediction. In the next section, three models of search are described. The first assumes attention to be a resource with unlimited capacity while the other two assume two different types of attention capacity limit.

2. Three signal detection models of visual search

2.1. The unlimited capacity model

The unlimited capacity model, derived from signal detection theory and adapted to the visual search task, makes the following assumptions. First, a stimulus element results in an internal representation that is variable or noisy (Green & Swets, 1966). This assumption is the distinguishing feature of low-thresholds models. Second, each stimulus element in a display is assumed to give rise to a single internal representation in each sensory coding channel sensitive to the element. Third, the variability of the internal representation is assumed to be normally distributed and the variance of the noise-alone and signal-plus-noise distributions is assumed to be equal. Variations of assumption 3, such as non-normal distributions, or non-equal variance, have been tested and generally result in little change in the set-size predictions (Palmer et al., 1993; see also Kramer, Graham, & Yager, 1985). Fourth, the internal representations arising from different stimulus elements in a display are assumed to be independent. That is, according to the model, no interaction takes place between internal representations for different stimuli. Fifth, in a two-interval forced choice task, the observer is assumed to select the interval with the largest signal (maximum-of-outputs decision rule). The maximum-of-outputs decision rule is popular in the literature and is often adequate in describing results (e.g. Graham, 1989; Palmer et al., 2000).

Because each element is represented by a noisy internal representation, a non-target or distractor element will sometimes produce a signal large enough to be mistaken for a target. Hence, when information from multiple sources must be integrated, the overall probability for an error will be positively correlated with set-size. In other words, according to the unlimited capacity model, search performance is affected by set-size because of the integration of noisy internal representations; a purely statistical effect independent of any limit in attention capacity. Although the set-size slope prediction for this model in log–log space is not quite linear, the slope of a straight line is a good approximation and is convenient to describe the model's prediction. If a straight line is fit to the set-size prediction over the range tested (2–16) in log–log space, the slope of the line is approximately 0.25 for cued conditions (Fig. 1, left panel, solid line. One assumption of the model is that the difference in the mean responses is proportional to the difference in chromaticity between the distractors and target. See Palmer et al., 1993, 2000 for details and model derivations). The uncued, or chromatic uncertain condition, is described next.

In Experiment 2, chromatic uncertainty was introduced to test attention capacity beyond that achieved with the set-size manipulation. Chromatic uncertainty was hypothesized to force observers to monitor multiple chromatic mechanisms at multiple spatial locations. Chromatic uncertainty was modeled by assuming that signals in additional chromatic mechanisms were monitored for each stimulus. For example, monitoring a single chromatic mechanism at four spatial locations would be identical to monitoring four chromatic mech-

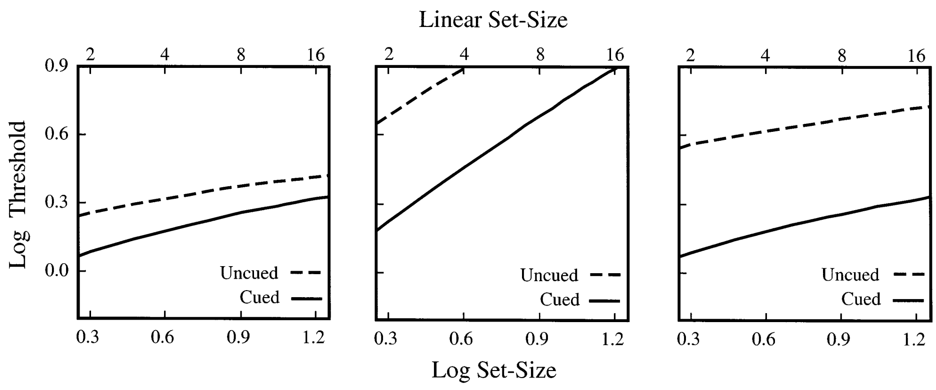

Fig. 1. Log threshold predictions are plotted as a function of log set-size for an unlimited capacity model (left), a limited capacity model (center) and a hybrid model (right). The solid and dashed lines are the cued and uncued predictions, respectively.

anisms at one spatial location. The prediction for the uncued condition was therefore obtained by estimating the number of monitored signals by multiplying set-size and the number of chromatic mechanisms assumed to be monitored in the uncertain conditions. The number of chromatic mechanisms monitored in uncertain conditions was assumed to be four since the chromatic targets were selected from the four cardinal directions, roughly representing red (+L), green (−L), blue (+S), and yellow (−S). Fig. 1 represents the predicted thresholds in the uncertain condition (Fig. 1, left panel dashed line) as a function of set-size for the unlimited capacity model.

2.2. The limited capacity model

The limited capacity model is similar to the unlimited capacity model, except for assumption 4. That is, because the model assumes attention is limited, internal representations arising from stimulus elements are dependent on the number of stimuli presented (set-size). Conceptually, a limit in attention capacity might occur if only a fixed amount of information can be processed or analyzed per unit time. When the amount of information exceeds attention capacity and if the display is present for a long enough interval, a serial monitoring process may occur. If the display is briefly presented, less information from each stimulus may be acquired. For briefly presented displays, the effect of the capacity limit can be estimated using a sample size model (e.g. Palmer et al., 1993). According to the sample size model, a fixed and limited number of samples are available. When a single element is presented in a display, all the samples can be deployed to that single element resulting in a precise estimate of the stimulus. When multiple elements are presented simultaneously for a short time, the samples must be divided among the elements. The resulting estimates for each element will therefore be poorer compared to the estimate in the single element condition. More specifically, the quality, or precision of the representation will be related to the number of stimuli by an inverse square root law. Because of this reduction in the number of samples per stimulus, the limited capacity model predicts larger set-size effects than the unlimited capacity model (see Palmer et al., 1993, 2000 for quantitative predictions and formal derivations of the unlimited and limited capacity models).

For the cued condition, the slope of the set-size function predicted by the limited capacity model should be approximately 0.75 (Fig. 1, solid line in center panel). The effect of chromatic uncertainty for the limited capacity model was obtained by estimating the number of monitored signals in the uncued conditions. The estimate was calculated by multiplying set-size and the number of chromatic mechanisms assumed to be monitored in the uncertain conditions (four). The unlimited capacity model predicts a larger effect of the number of monitored signals compared to the unlimited capacity model (dashed line in the center panel of Fig. 1 depicts the limited capacity prediction for the uncertain condition).

2.3. Hybrid feature-based attention limited capacity model

Another possibility for an attention capacity limit is that only a single feature-coding channel can be monitored at multiple spatial locations (e.g. Treisman & Sato, 1990). For example, a single feature-coding channel such as a neural channel coding “redness” might be monitored at multiple spatial locations without exceeding a limit in attention capacity. On the other hand, monitoring multiple feature channels such as channels coding “redness” and “blueness” at multiple spatial locations might exceed a limit in attention capacity. Numerous studies suggest attention capacity is unlimited when the search is limited to a single feature dimension (Foley & Schwarz, 1998; Palmer, 1994, 1998; Palmer et al., 1993; Solomon, Lavie, & Morgan, 1997; Verghese & Nakayama, 1994). On the other hand, attention capacity is often found to be limited when the task involves searching for a target that differs form the distractors along two or more feature dimensions (conjunction searches; Palmer, 1994, 1995; Palmer et al., 1993; Põder, 1999) though some studies suggest that information in different feature coding mechanisms can be combined rapidly and efficiently when feature discriminability is very high (see Eckstein, Thomas, Palmer, & Shimozaki, 2000; Nakayama & Silverman, 1986; Treisman & Sato, 1990; Wolfe, 1994). Treisman’s Feature Integration Theory (e.g. Treisman & Sato, 1990) originally addressed this issue by making the combination of information across feature maps a serial process requiring attention. The hybrid model adopts this idea and hence predicts attention to be unlimited when the search is limited to a single color-coding feature map but to be limited when multiple color feature maps must be monitored simultaneously.

According to the hybrid model, attention is unlimited in cued conditions when a single chromatic mechanism is monitored but is limited when multiple chromatic mechanisms must be monitored, such as in the uncertain conditions. Fig. 1 (right panel) represents the set-size threshold predictions for the hybrid model. Because the hybrid model predicts attention to be unlimited in certain conditions, the cued predictions for the hybrid and unlimited capacity models are identical. The uncued prediction was obtained by assuming a sample size model of the type described earlier for monitoring four chromatic mechanisms. The uncued prediction for the hybrid model is therefore shifted by the log of the square root of 4 (the number of monitored mechanisms) relative to the capacity unlimited uncued prediction (Fig. 1, dashed line, right panel).

2.4. Spatial separation between elements

Although an unlimited capacity model predicts simple searches well, the model sometimes underestimated or overestimated thresholds (Morgan, Ward, & Castet, 1998). Violations of either assumption 2 (the number of internal representations equals the number of elements) or assumption 4 (signal representation independence) may explain these conflicting results. A violation of assumption 4 would occur if, for example, signals from elements in close proximity interact with, or inhibit each other. A violation of assumption 2 might occur if a grouping or texture mechanism is operative and signals from different elements are pooled, summed, or differenced in some way. A factor likely to affect both assumptions is the spatial arrangement of the elements. For example, elements close in proximity are likely to interact (e.g. Verghese & Nakayama, 1994). It is also possible that elements regularly positioned are processed by a grouping mechanism sensitive to discontinuities in the element array (e.g. Julesz, 1984; Nothdurft, 1991, 1993). If an interaction between elements occurs or if a grouping mechanism mediates searches, large set-size effects might be wrongly interpreted as evidence for a capacity limit. In Experiment 1, the effect of the spatial separation between stimulus elements on the slope of the set-size function was systematically investigated.

2.5. Chromatic uncertainty

In Experiment 2, models of attention capacity were tested for simple conditions in which a target differed from white distractors in chromaticity only. Chromatic uncertainty was introduced by intermixing and randomly presenting targets of different chromaticities within a block of trials (Monnier & Nagy, 2001). The target chromaticities were chosen so that they presumably stimulated separate and independent chromatic mechanisms. In the uncertain conditions, the chromaticity of the target, from trial to trial, was therefore uncertain. In cued conditions, similar trials were run, but each trial was preceded by a chromatic cue. The chromatic cue indicated to the observer the target chromaticity he or she was about to be presented. The chromatic cue was spatially neutral so that the only information it provided was about the chromaticity of the target element. Introducing chromatic uncertainty increased the attentional demands beyond that achieved by manipulating set-size alone, because multiple chromatic channels ought to be monitored for each stimulus. Moreover, introducing chromatic uncertainty, as opposed to testing larger set-sizes, makes it less likely that assumptions 2 and 4 will be violated; both assumptions paramount to the signal detection modeling approach. Testing attentional capacity limits beyond that achieved with set-size is important since it might be that attention capacity limits for simple conditions are beyond the range most often tested in the literature (e.g. Palmer, 1994 tested set-sizes up to 8). Additionally, manipulating both set-size and chromatic uncertainty should reveal how attention can be divided among multiple chromatic channels. Pelli (1985) hypothesized that for detection of a threshold stimulus, the relevant variable determining the effect of noise is the total number of attended channels. For example, extending this idea to our conditions, monitoring a single chromatic channel at eight spatial locations ought to be equivalent to monitoring two chromatic channels at four spatial locations.

3. Methods

3.1. Subjects

Three participants, between the ages of 22 and 30, took part in the study. Two participants were paid and the third observer was the first author. The paid participants were naïve as to the purpose of the study. All observers were screened for normal color vision (Ishihara plates) and normal or corrected to normal acuity. The participants were highly trained and practiced observers. The naïve observers performed practice trials for at least 10 h before collecting experimental data. The first author, familiar with similar psychophysical experiments, performed practice trials for at least 4 h prior to experimental data collection.

3.2. Apparatus and stimuli

An Apple Macintosh computer model 8500 was used to generate the stimuli and collect responses. The stimuli were generated using a Radius Thunder 30/1600 video board in 8-bit mode and were presented on a 17 in. Nanao T2-17 color monitor at a resolution of 832 by 624 pixels and at a refresh rate of 74 Hz. The presentation of the stimulus elements on the monitor was done within one frame representing a 14 ms drawing time. The stimulus elements were presented in an annulus centered on a fixation point. The outer and inner annulus diameters subtended 5.6° and 4° of visual angle, respectively. The target and distractors disks were of identical surface area with a diameter subtending approximately 0.21° in visual angle. For a given display, the elements were positioned pseudo-randomly with two constraints. First, each element's spatial position had to be within the annulus and second, a fixed distance separated the elements. In Experiment 1 the stimulus-to-stimulus spatial separations, edge to edge, were 0.11°, 0.21°, 0.42°, and 0.63° (0.5, 1.0, 2.0, and 3.0 times stimulus diameter). In Experiment 2, the stimulus-to-stimulus spatial separation was fixed at the largest spatial separation of 0.63 deg. The resulting displays were somewhat irregular although each element was always presented between 2.0° and 2.8° from the fixation point. Subjects were instructed to keep their gaze on the fixation point, which was present throughout a block of trials. In both experiments, thresholds were measured for set-sizes of 2, 4, 8, and 16.

The distractor and target stimuli were equiluminant (11 cd/m^2) and differed in chromaticity only. The disks were presented on a gray background (CIE coordinates: x, 0.34; y, 0.33) of 5 cd/m^2. The luminance difference between the disks and the background was therefore constant and the difference between the target and distractors was chromatic only. The Derrington, Krauskopf, and Lennie (1984) color space, derived from the chromaticity diagram of MacLeod and Boynton (1979), was used to represent the stimulus chromaticities. In both experiments, the distractors were always at equal energy white represented at the center of the color space. In Experiment 1, target stimuli varied only along the $+$L cardinal axis (reddish). In Experiment 2, target chromaticities were selected from the four cardinal directions ($+$L or reddish, $-$L or greenish, $+$S or bluish, and $-$S or yellowish) thought to activate separate and independent mechanisms (e.g. Boynton & Kambe, 1980).

A two-interval forced-choice (2IFC) accuracy search task was used to measure chromatic difference thresholds. A trial consisted of two 200-ms temporal intervals; a signal interval in which one of the elements was a target and a noise interval in which only distractor elements were presented. The observer's decision indicated whether the target was seen in the first or second interval. Several levels of chromatic difference between the target and distractors were tested to obtain a psychometric function. Weibull functions were fit to the data and detection thresholds were estimated at 75% correct.

3.3. Procedure

In a typical block of trials, an observer was first presented with practice trials showing each of the target chromaticities to be tested in the block of trials. The practice targets were presented with white distractors. As opposed to the experimental trials where the interval displays were presented for 200 ms, the presentation time for the practice displays was under the observer's control. This was done to ensure that the targets could be clearly and unambiguously identified. Following the practice trials, an auditory signal warned the observer that the experimental trials were about to begin. For the entire duration of the block of trials, the observer was instructed to remain fixated on the fixation cross located at the center of the display.

In the first experiment, a block of trials contained target chromaticities selected from the cardinal $+$L axis (reddish). Chromatic uncertainty was introduced in Experiment 2 by intermixing and randomly presenting several target chromaticities ($+$L or reddish, $-$L or greenish, $+$S or bluish, $-$S or yellowish) within a block of trials. The targets within a block of trials were approximately equated in difficulty based on pilot work. In the uncued conditions, the observer was uncertain as to what target chromaticity would be presented in a given trial. Although the target chromaticity in a given trial was uncertain, observers were aware that only four target chromaticities ($+$L, $-$L, $+$S, $-$S) were tested in a block of trials. To evaluate the effects of chromatic uncertainty, conditions identical to those run in uncertain conditions were run again with the addition of a pre-trial chromatic cue. The pre-trial cue indicated to the observer the target chromaticity for the next trial and hence removed chromatic uncertainty. The chromatic cue was presented in such a way as to provide no information about the spatial location of any elements. The chromaticity of the cue was always much more saturated than the target to clearly indicate to the observer the chromatic direction tested in a given trial. Fig. 2 illustrates a cued trial sequence on the left and an uncued sequence on the right. First, the fixation cross appeared at the center of the monitor and in cued blocks; the pre-trial cue was presented as well. The pre-trial cue consisted of a triangular arrangement of three disks centered on the fixation cross with the target above two white distractor stimuli. The cuing display remained visible for 500 ms and was followed by a fixation display. After a 1-s delay, the first interval was presented for 200 ms followed by a 1-s fixation display. The second interval was presented next for 200 ms. After the presentation of both intervals, the observer was required to press one of two keyboard keys. Pressing the key "a" indicated the target was seen in the first interval and pressing the key "l" indicated the target was seen in the second interval. Accuracy feedback was provided in the form of an auditory signal.

The order in which the blocks of trials within an experiment were completed was randomized. Experiment 1 was conducted first, followed by Experiment 2. The room in which the study was conducted was dark and participants were dark adapted for at least 5 min before data collection was initiated. During data collection, observers sat 125 cm away from the monitor. A chin rest was used to stabilize the observer's head and keep the viewing distance constant.

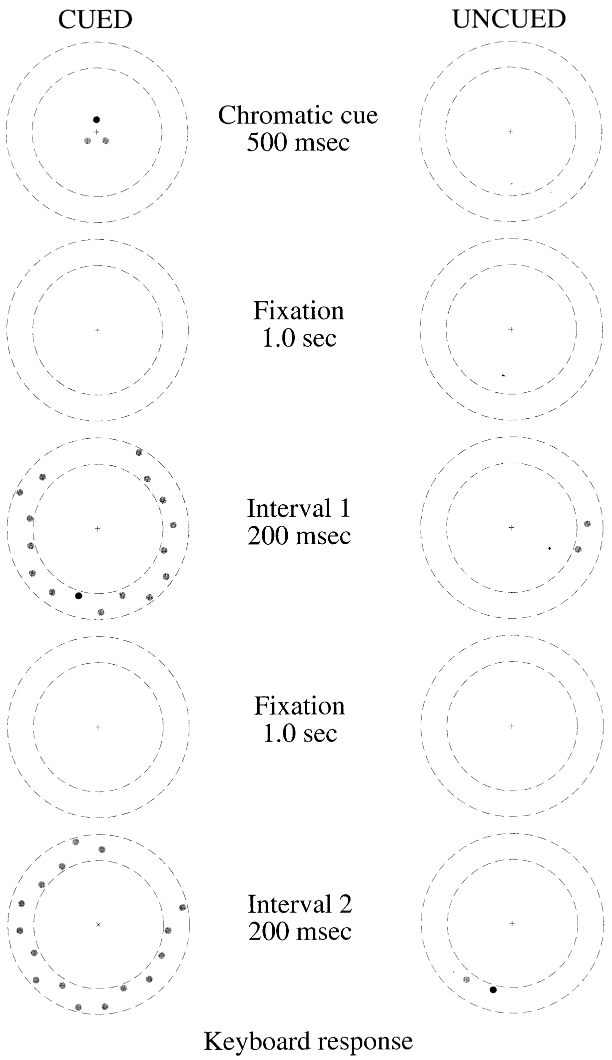

Fig. 2. The temporal sequence for cued (left) and uncued (right) two-alternative forced-choice trials.

4. Results

4.1. Threshold normalization

Because the units along the + L, − L, + S, − S chromatic directions are arbitrary in the chromaticity diagram, units for each chromatic direction were normalized. The normalization was performed as follows: First, linear fits were obtained for set-size functions for the + L, − L, + S and − S chromatic directions separately. Estimated set-size 2 cued thresholds were subsequently obtained for each chromatic direction using the linear fits. The set-size 2 threshold was estimated using this fitting procedure to weight all set-size thresholds equally in the estimate. Next, the units for each chromatic direction were normalized by the respective estimated cued set-size 2 thresholds. Finally, the logarithm of the normalized thresholds was taken. Because of this normalization procedure, set-size thresholds across chromatic directions are directly comparable. Furthermore, in normalized units, the three models of attention predict detection performance for all set-sizes and for cued and uncued conditions with no free parameters. To assess the models' goodness of fit, root-mean-squared (RMS) errors were computed.

4.2. Experiment 1: spatial separation

The unlimited capacity and limited capacity models of attention make distinct set-size predictions. Over set-sizes 2–16, an unlimited capacity model predicts a set-size slope in log–log coordinates of approximately 0.25 while a limited capacity model predicts a set-size slope of approximately 0.75. As mentioned, both the limited capacity and unlimited capacity models of attention assume a one-to-one mapping between the number of elements and the number of internal representations. The models, as presented here, therefore predict no effect of spatial separation on set-size thresholds. To test this assumption, the spatial separation between stimulus elements was systematically varied. Separations of 0.11°, 0.21°, 0.42°, and 0.63° between elements, edge-to-edge, representing one half, one, two and three times the diameter of a single element, were tested.

Fig. 3 represents the slopes of the set-size functions obtained for each observer plotted as a function of the level of stimulus-to-stimulus separation. The solid and dashed gray lines represent the unlimited capacity and limited capacity slope predictions, respectively. The predictions are straight horizontal lines since the models

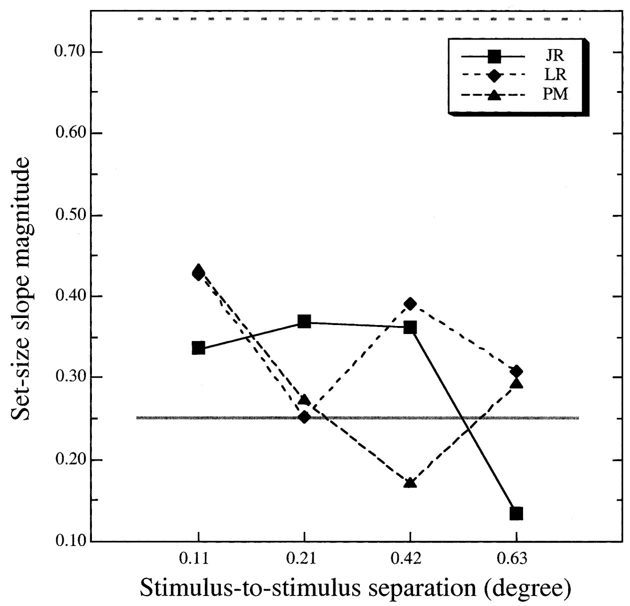

Fig. 3. The set-size slopes are plotted for the four levels of stimulus-to-stimulus separation for each observer. The gray solid and dashed straight lines represent the unlimited and limited capacity predictions.

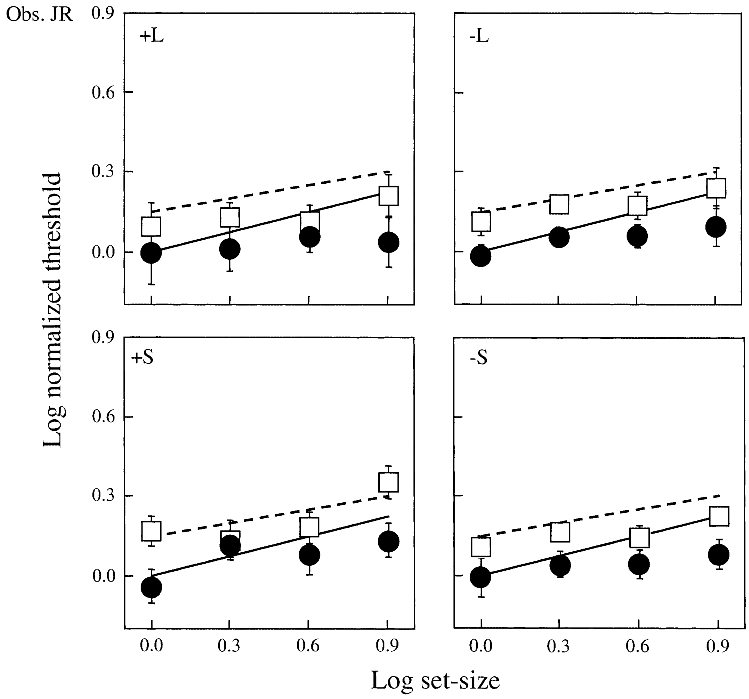

Fig. 4. Set-size thresholds are plotted as a function of log set-size for each chromatic direction for observer J.R. The solid symbols represent the cued thresholds and the open symbols represent the uncued thresholds. Error bars represent one standard error of the mean. The solid and dashed lines are the capacity unlimited model predictions for the cued and uncued thresholds, respectively.

predict no effect of spatial separation. The obtained slopes never exceeded 0.43 (observer P.M. in the 0.11 deg separation condition) and were therefore generally closer to the unlimited capacity prediction. Moreover, although the slopes were somewhat noisy, a decrease in the set-size slope with an increase in the spatial separation can be observed for all three observers. This, most likely, indicates that the assumption of a one-to-one mapping between the number of elements and internal representations or the assumption of independence between signals from different elements did not hold at smaller stimulus-to-stimulus separations. Potential interpretations are offered in Section 5.

4.3. Experiment 2: chromatic uncertainty

Because the largest stimulus-to-stimulus separation was most consistent with the assumptions of a one-to-one mapping between stimuli and internal representation and independence of internal representations, it was selected for Experiment 2.

Chromatic uncertainty was introduced by intermixing multiple target chromaticities within a block of trials. Chromatic uncertainty was introduced because it increased the attentional demands in our search task beyond that achieved by set-size alone. Furthermore, the hypothesis that signals within one chromatic mechanism from different spatial locations and signals from different chromatic mechanisms at one spatial location can be traded off without any effect on search performance could be tested (Pelli, 1985). As discussed above, if the hypothesis is correct, the uncued thresholds can be estimated from cued thresholds by simply multiplying set-size and the number of monitored chromatic mechanisms. Note that because of the normalization of the chromatic axes, the predictions for the three models of attention are obtained with no free parameters.

Figs. 4–6 represent the set-size thresholds plotted as a function of set-size for the three observers. Each plot represents thresholds for one chromatic direction (i.e. + L, − L, + S, and − S) in log normalized threshold by log set-size units. The solid and open symbols represent the cued and uncued thresholds, respectively. The error bars represent one standard error of the threshold estimate. The solid and dashed lines represent the predictions for cued and uncued conditions, respectively, for the unlimited capacity model (Fig. 4, obs. J.R.), the limited capacity model (Fig. 5, obs. L.R.), and the hybrid model (Fig. 6, obs. P.M.).

Generally, as in Experiment 1, thresholds were observed to increase with set-size. Furthermore, uncued thresholds were generally elevated relative to the cued thresholds. These trends were similar for all three observers. Of the three models, the unlimited capacity model was superior to the other two and predicted the cued and uncued thresholds well. The limited capacity model grossly overpredicted both the cued and uncued thresholds. The hybrid model predicted the cued thresholds well. This might be expected since the hybrid model simplifies to the unlimited capacity model for cued conditions. The hybrid model somewhat overpredicted the uncued thresholds. RMS errors for cued and uncued conditions, for each model and each observer were computed and are reported in Table 1. The mean standard error of the threshold estimates for each observer for cued and uncued conditions is reported as well for comparison. The RMS errors for the unlimited capacity model were at least two times smaller and as large as 14 times smaller than for the other two models. The superiority of the unlimited capacity model is

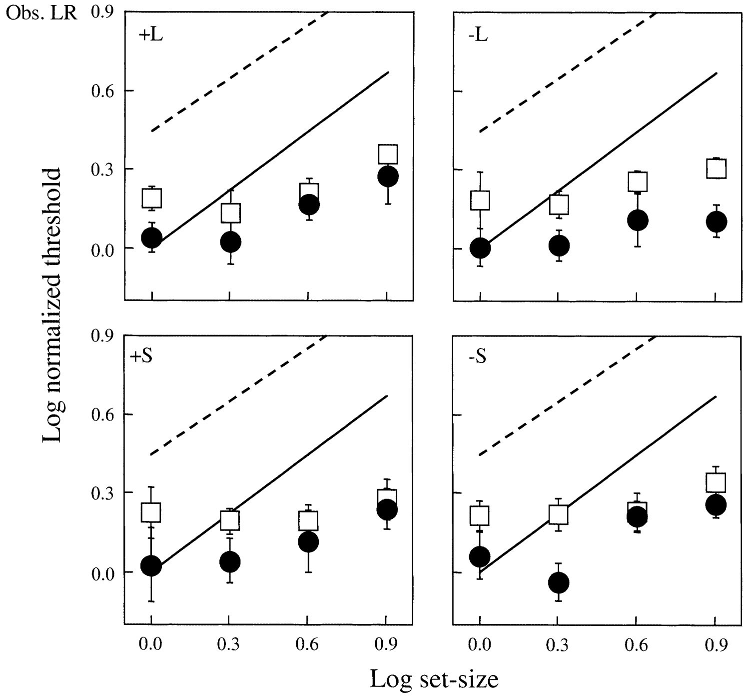

Fig. 5. Same as Fig. 4 for observer L.R. with the capacity limited model predictions.

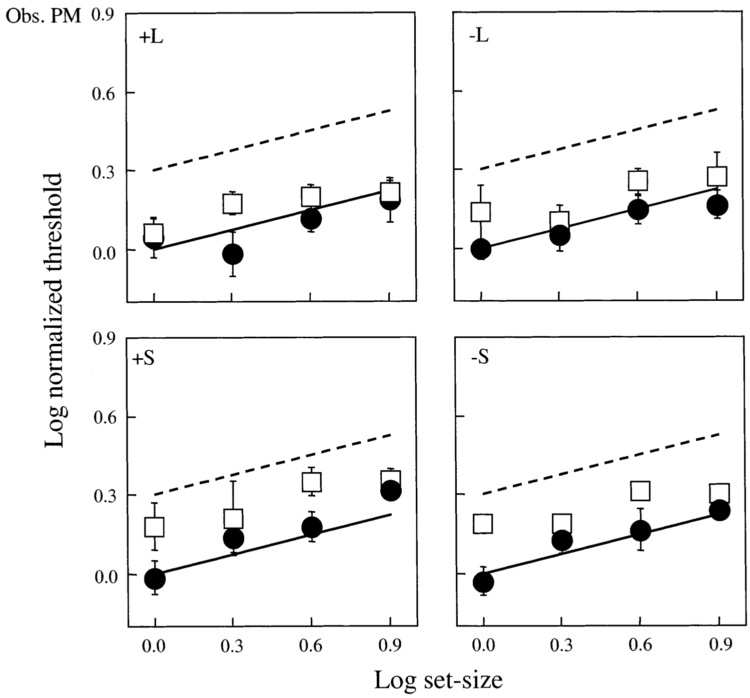

Fig. 6. Same as Fig. 4 for observer P.M. with the hybrid model predictions.

Table 1
RMS errors for cued and uncued conditions, for each observer and each model. Average standard error of the means are also reported

Observer	SEM		Unlimited capacity RMS		Limited capacity RMS		Hybrid RMS	
	Cued	Uncued	Cued	Uncued	Cued	Uncued	Cued	Uncued
J.R.	0.0648	0.0557	0.0865	0.0707	0.3600	0.6092	0.0865	0.2492
L.R.	0.0810	0.0628	0.0564	0.0432	0.2920	0.5522	0.0564	0.1907
P.M.	0.0576	0.0593	0.0465	0.0548	0.2803	0.5597	0.0464	0.2028

reinforced by the RMS error results. The unlimited capacity model's RMS errors are comparable to the standard errors of the threshold estimates. In summary, the effects of set-size and chromatic uncertainty were well described by an unlimited capacity model and by assuming chromatic uncertainty increased the number of internal representations by a factor of four; the presumed number of monitored chromatic mechanisms.

5. Discussion

5.1. Stimulus-to-stimulus separation

The aims of Experiment 1 were twofold. First, thresholds were measured as a function of set-size in a simple feature visual search task in which the target differed from the distractors in chromaticity only. Second, the separation between stimulus elements was varied to test the assumptions of a one-to-one mapping between the number of elements and the number of internal representations and the independence of the internal representations. With respect to the first aim, the data tended to support an unlimited capacity model and provide further evidence suggesting no capacity limit for simple feature searches over the set-size range tested (e.g. Palmer, 1994). With respect to the second aim, varying stimulus-to-stimulus separation had a small but consistent effect on the set-size slopes. Set-size slopes at the smaller spatial separations were generally steeper compared to the slopes for larger spatial separations. One possible explanation for the steeper slopes at the smaller spatial separations is that a grouping mechanism was operative, implying that the one-to-one mapping assumption was violated. For example, a mechanism computing a mean signal from some or all the stimulus elements in the display would predict steeper slopes (e.g. Morgan et al., 1998). Quantitative predictions for such a model are difficult to make without adopting arbitrary assumptions regarding the details of the averaging process. Another possibility for the steeper set-size slopes at the smaller stimulus-to-stimulus spatial separations is that signals from different stimulus elements interacted with each other, but remained separate signals. Interaction between signals from different elements would be a violation of the signal detection assumption that signals from different stimuli are independent of each other. For example, it has been shown that the chromatic appearance of a region can be affected by the light distribution some distance away (e.g. Barnes, Wei, & Shevell, 1999).

Overall, the results of Experiment 1 provide several conclusions. First, an unlimited capacity model describes the data, as long as stimulus elements are widely separated. Second, slopes for elements close in proximity were generally steeper, suggesting either a grouping mechanism or interactions between signals from stimulus elements in close proximity. A major question that arises from the results is whether a grouping process or interactions between signals from stimulus elements is responsible for the steeper slopes. Further experimental work might be designed to test the grouping and interaction hypotheses. Although the signal detection approach goes a long way toward extending basic detection theory to visual search, the spatial configuration of elements are likely to have to be incorporated in future models of visual search.

5.2. Chromatic uncertainty

The second issue addressed in this study was how chromatic uncertainty would affect threshold versus set-size functions. Chromatic uncertainty was hypothesized to affect thresholds because intermixing chromatic targets from different cardinal directions would likely force observers to monitor multiple chromatic mechanisms (Ball & Sekuler, 1981; Davis & Graham, 1981; Greenhouse & Cohn, 1977). The results, consistent across the three observers, indeed showed that thresholds in uncertain conditions were generally elevated compared to thresholds in certain conditions. These results are in agreement with Monnier and Nagy (2001) who reported chromatic uncertainty effects in a visual search task employing a response time measure.

In the present study, three models of attention were used to predict the combined effects of set-size and chromatic uncertainty. Over the range of set-sizes tested, an unlimited capacity model accounted for the effects of set-size and chromatic uncertainty best. Furthermore, the effect of chromatic uncertainty was successfully modeled by assuming the number of internal representations equaled the number of elements multiplied by the number of monitored chromatic channels. The RMS errors for the unlimited capacity models were between 2.2 and 14 times smaller than the RMS errors for the other two models tested (Table 1). We therefore conclude that observers were able to monitor four chromatic mechanisms at 16 spatial locations without encountering limits in attention capacity.

Another interesting point is that the results support the notion that monitoring a single chromatic signal at several spatial locations and several different chromatic signals at fewer spatial locations are equivalent in their attentional demands, if the total number of signals monitored is held constant. Pelli (1985) first postulated the signal equivalence hypothesis for detection thresholds, although we believe this study to be the first systematic test of such a hypothesis for a search task. The findings support Pelli's (1985) hypothesis of signal equivalence, at least for spatial and chromatic signals, and may not support models, such as Feature Integration Theory (FIT) (Treisman & Gormican, 1988; Treisman & Sato, 1990), which suggest that monitoring different spatial locations and different feature coding channels may involve different attentional demands. According to FIT, objects in a visual scene are analyzed and represented by a number of feature maps. Elements within a feature map can be searched in parallel but combining information across feature maps requires attention; a resource with limited capacity. The model treats signals from different spatial locations and signals from different feature channels somewhat differently. When an object cannot be identified within a single feature map, information between feature maps must be combined. According to FIT, this process requires attention; a limited capacity process. The hybrid attentional model was intended to capture this architectural aspect of FIT. The data did not support the hybrid model since the attentional cost for monitoring multiple chromatic channels was much less than predicted by the hybrid model. Although the signal equivalence hypothesis was supported for chromatic and spatial channels, it needs to be tested with other dimensions such as spatial frequency, orientation, luminance, etc.

Experiment 2 of this study was motivated in large part by the results of Monnier and Nagy (2001). Using a latency visual search task, the effects of chromatic uncertainty were observed over a large range of chromatic differences between the target and distractors. Based on the signal detection theory, we had expected that uncertainty effects would become small as the difference between target and distractors increased and the search became easier. However, results showed that the magnitude of the uncertainty effect was approximately constant in log units regardless of the difficulty of the search. We concluded that a potential explanation for this result was that attention capacity limits were exceeded when the observers were required to monitor multiple chromatic signals from multiple spatial locations. We described a crude model showing the results were consistent with a sequential monitoring of chromatic mechanisms and that such a model could explain the constant magnitude of the uncertainty effect in logarithmic units. To test this hypothesis further, the present accuracy search task was designed and yielded evidence against a limited capacity process. One difference between the two studies, which might account for the difference in conclusions, is that a fixed set-size of 54 was used in the latency study whereas the largest set-size tested in the present study was 16. Thus the maximum number of signals that had to be monitored differed in the two studies. Because of the relatively large number of elements in the latency study, the spatial separation between elements was also much smaller. This factor might have had some influence on the results due to the grouping of elements, or inhibition between elements, as indicated in Experiment 1. It would be interesting to determine what effect uncertainty has on thresholds in more crowded displays. If indeed a capacity limit is encountered with larger set-sizes and more crowded displays, the uncertainty effects ought to be larger than those observed here. It would also be interesting to increase the number of monitored signals further using the uncertainty technique to test attention capacity further. For example, a task requiring observers to search for chromatic as well as differently shaped target elements would increase the number and type of monitored signals. Introducing shape in addition to chromatic uncertainty would increase the number of monitored signals while minimizing proximity effects. It would also test the channel equivalence hypothesis further.

Overall, several points can be made about the results. First, the spatial arrangement between stimulus elements is a critical variable. Experiment 1 showed that thresholds for a target among elements in close proximity are higher than thresholds for a target among elements widely separated. Second, an unlimited capacity model was shown to adequately describe detection thresholds for set-sizes larger than usually tested. Third, the chromatic uncertainty effect observed suggests observers were able to select a color channel to attend and ignore irrelevant color channels. This selective monitoring is likely to be effective since it can reduce the amount of noise in cued conditions. Fourth, the results of experiment 2 suggest observers could monitor four chromatic channels at 16 spatial locations without encountering limits in attention capacity. Fifth, chromatic uncertainty appears to be a viable technique to increase the attentional demand without having to increase set-size. Finally, the results support the signal equivalence hypothesis in search tasks, at least for signals from different chromatic mechanisms and different spatial locations.

References

Ball, K., & Sekuler, R. (1981). Cues reduce direction uncertainty and enhance motion detection. *Perception and Psychophysics*, *30*, 119–128.

Barnes, C. S., Wei, J., & Shevell, S. K. (1999). Chromatic induction with remote chromatic contrast varied in magnitude, spatial frequency, and chromaticity. *Vision Research*, *39*, 3561–3574.

Boynton, R. M., & Kambe, N. (1980). Chromatic difference steps of moderate size measured along theoretically critical axes. *Color Research and Application*, *5*, 13–23.

Davis, E. T., & Graham, N. V. S. (1981). Spatial frequency uncertainty effects in the detection of sinusoidal gratings. *Vision Research*, *21*, 705–712.

Derrington, A. M., Krauskopf, J., & Lennie, P. (1984). Chromatic mechanisms in lateral geniculate nucleus of Macaque. *Journal of Physiology*, *357*, 241–265.

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

Eckstein, M. P., Thomas, J. P., Palmer, J., & Shimozaki, S. S. (2000). A signal detection model predicts the effects of set size on visual search accuracy for feature, conjunction, triple conjunction, and disjunction displays. *Perception and Psychophysics*, *62*, 425–451.

Foley, J. M., & Schwarz, W. (1998). Spatial attention: effect of position uncertainty and number of distractor patterns on the threshold-versus-contrast function for contrast discrimination. *Journal of the Optical Society of America A*, *15*, 1036–1047.

Graham, N. V. S. (1989). *Visual pattern analyzers*. New York: Oxford University Press.

Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics*. New York: Krieger.

Greenhouse, D. S., & Cohn, T. E. (1977). Effect of chromatic uncertainty on detectability of a visual stimulus. *Journal of the Optical Society of America A*, *68*, 266–267.

Julesz, B. (1984). A brief outline of the textron theory of human vision. *Trends in NeuroSciences*, *7*, 41–45.

Kramer, P., Graham, N., & Yager, D. (1985). Simultaneous measurement of spatial-frequency summation and uncertainty effects. *Journal of the Optical Society of America A*, *9*, 1533–1542.

MacLeod, D. I. A., & Boynton, R. M. (1979). Cone excitation diagram showing cone excitation by stimuli of equal luminance. *Journal of the Optical Society of America A*, *69*, 1183–1186.

Monnier, P., & Nagy, A. L. (2001). Uncertainty, attentional capacity, and chromatic mechanisms. *Vision Research*, *41*, 313–328.

Morgan, M. J., Ward, R. M., & Castet, E. (1998). Visual search for a tilted target: Tests of spatial uncertainty models. *Quarterly Journal of Experimental Psychology A*, *Human Experimental Psychology*, *51A*, 347–370.

Nakayama, K., & Silverman, G. H. (1986). Serial and parallel processing of visual features. *Nature*, *320*, 264–265.

Nothdurft, H. C. (1991). Texture segmentation and pop-out from orientation contrast. *Vision Research*, *31*, 1073–1078.

Nothdurft, H. C. (1993). Saliency effects across dimensions in visual search. *Vision Research*, *33*, 839–844.

Palmer, J. (1994). Set-size effects in visual search: The effect of attention is independent of the stimulus tasks. *Vision Research*, *34*, 1703–1721.

Palmer, J. (1995). Attention in visual search: distinguishing four causes of set-size effects. *Current Directions in Psychological Science*, *4*, 118–123.

Palmer, J. (1998). Attention effects in visual search: relating visual search accuracy and search time. In R. D. Wright, *Visual attention*. New York: Oxford University Press.

Palmer, J., Ames, C. T., & Lindsey, D. T. (1993). Measuring the effect of attention on simple visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 108–130.

Palmer, J., Verghese, P., & Pavel, M. (2000). The psychophysics of visual search. *Vision Research*, *40*, 1227–1268.

Pelli, D. G. (1985). Uncertainty explains many effects of visual contrast detection and discrimination. *Journal of the Optical Society of America A*, *2*, 1508–1531.

Põder, E. (1999). Search for feature and for relative position: measurement of capacity limitations. *Vision Research*, *39*, 1321–1328.

Solomon, J. A., Lavie, N., & Morgan, M. J. (1997). Contrast discrimination function: spatial cuing effects. *Journal of the Optical Society of America A*, *14*, 2443–2448.

Townsend, J. T. (1990). Serial vs. parallel processing: sometimes they look like tweedledrum and tweedledee but they can (and should) be distinguished. *Psychological Science*, *1*, 46–54.

Treisman, A. (1988). Features and objects: The Fourteenth Bartlett Memorial Lecture. *The Quarterly Journal of Experimental Psychology*, *40A*, 201–237.

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

Treisman, A, & Gormican (1988). Feature analysis in early vision: evidence from search asymmetries. *Psychological Review*, *95*, 15–48.

Treisman, A., & Sato, S. (1990). Conjunction search revisited. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 459–478.

Verghese, P., & Nakayama, K. (1994). Stimulus discriminability in visual search. *Vision Research*, *34*, 2453–2467.

Wolfe, J. M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin and Review*, *1*, 202–238.