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Uncertainty, attentional capacity and chromatic mechanisms in visual search

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Abstract

Two general questions were investigated using a visual search task. First, we asked whether effects of target uncertainty on reaction time varied with the discriminability of the target and distractors. Second, a higher order chromatic mechanism model was tested against a flexible model in which the signals in cardinal color-opponent mechanisms are combined through an attentional process. The models were tested by measuring the effects of target uncertainty on search time. A regression analysis indicated that the magnitude of the uncertainty effect was approximately constant in logarithmic units as a function of the chromatic difference between the target and distractors. The constant magnitude of the uncertainty effect suggested that an attentional capacity limit was exceeded when observers were required to monitor several chromatic mechanisms at several locations. The results of experiments 3 and 4 suggested that search for chromatic targets among distractors was mediated by diagonally tuned higher order chromatic mechanisms, rather than by signals in cardinal color-opponent mechanisms that were combined through an attentional mechanism. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Chromatic mechanisms; Color; Search; Uncertainty

1. Introduction

Stimulus uncertainty has been shown to raise detection thresholds for several visual stimulus characteristics. For example, detection performance for a spatial frequency grating intermixed with gratings of different spatial frequencies is worse compared with performance for the detection of the grating alone (Davis & Graham, 1980). Similarly, Ball and Sekuler (1980, 1981) found motion detection to be worse when the direction of a pattern of moving dots was uncertain. In the color domain, Greenhouse and Cohn (1977) demonstrated that the detection of a temporal chromatic shift was worse when the chromatic direction of the shift was uncertain. Kurylo, Reeves, and Scharf (1997) have found uncertainty effects using an orientation detection task. Effects of stimulus characteristic uncertainty have also been reported using visual search tasks. Using a visual search task, Olds, Cowan, and Jolicœur (1999) found uncertainty effects, albeit small, for conditions in which observers were presented with intermixed target and distractor colors. Treisman (1986) had her observers detect targets that could differ from the distractors either in color, orientation, or size. When the target characteristic was uncertain, observers took longer to find the target compared with conditions in which the target characteristic was certain. Müller, Heller, and Ziegler (1995) also report similar results in a series of experiments where the task was to detect a target that differed unpredictably from the distractors in either size, color, or orientation. When the target characteristic was unpredictable, response times were slower compared with conditions where the target characteristic was certain. Bravo and Nakayama (1992) also found stimulus characteristic uncertainty effects for three different types of tasks. In their experiments, a target was either red or green while the distractors were green for red targets and red for green targets. When the target and distractor colors were unpredictable, response times to detect a target were slower compared with conditions where the distractor and target colors were

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known a priori. In the same study, uncertainty effects were also found when the color of the target was to be judged or when the task was to indicate the shape of the target (Bravo & Nakayama, 1992). For all three tasks, reaction times were slower when the target and distractor colors were uncertain.

Spatial uncertainty effects, or the lack of a priori knowledge about the location of a stimulus, have also been demonstrated in both detection and search tasks. Davis, Kramer, and Graham (1983) found that detection of a grating was poorer when its spatial position was uncertain. Pelli (1985) reported similar effects of spatial position uncertainty for detection tasks. Using a search task, Yeshurun and Carrasco (1999) found that spatial cuing resulted in better search performance for spatial resolution tasks. Palmer, Ames, and Lindsey (1993) found that observers were able to restrict their attention to cued spatial locations by demonstrating performance to be unaffected by the appearance of stimulus elements outside the attended locations. Spatial uncertainty effects were also demonstrated using Gabor patches varying in contrast (Foley & Schwarz, 1998) and using stimulus elements differing in orientation (Morgan, Ward, & Castet, 1998). In both cases, detecting the interval that contained a target among a varying number of non-target elements was worse for uncertain conditions.

To account for stimulus characteristic and spatial uncertainty effects, two general models of attention have been proposed and tested (e.g. Greenhouse & Cohn, 1977; Ball & Sekuler, 1980; Yager, Kramer, Shaw, & Graham, 1984; Palmer et al., 1993; Palmer, Verghese, & Pavel, 2000). Generally, capacity unlimited models of attention postulate that multiple channels can be monitored simultaneously and that attention can be deployed without limit. Capacity limited models, on the other hand, postulate that attention is a resource with limited capacity (e.g. Davis & Graham, 1980; Ball & Sekuler, 1981; Graham, 1989; Palmer et al.; Pashler, 1997). Capacity limited models are often conceptualized in terms of a limited sampling process sometimes referred to as a spotlight of attention. The two classes of attentional models have been tested by either varying the number of stimulus elements (set-size) presented to an observer (e.g. Palmer et al.), or by introducing stimulus characteristic uncertainty (e.g. Greenhouse & Cohn; Davis et al., 1983). When gratings of different spatial frequencies are intermixed, detection performance is best described by a capacity unlimited model indicating that multiple spatial frequency channels can be monitored simultaneously without attentional limit (Davis et al.; Yager et al.; Kramer et al., 1985). Similarly, the uncertainty effects found by Greenhouse and Cohn in the chromatic domain fit a multi-band model. However, uncertainty effects for motion detection seem best described by a single-band model where observers appeared to monitor a single channel sensitive to both possible motion directions (Ball & Sekuler).

The two models of attention have also been tested with spatial uncertainty effects in search tasks. Palmer et al. (1993) (see also Palmer, 1994, 1995, 1998) measured the effect on detection threshold of increasing the number of stimulus elements within a search display (set-size). For simple conditions where the target differed from the distractors along a single dimension, the results supported a capacity unlimited model of attention. Support for a capacity unlimited model has also been provided elsewhere (Verghese & Nakayama, 1994; Solomon, Lavie, & Morgan, 1997; Foley & Schwarz, 1998), however, not all spatial uncertainty effects support a capacity unlimited model. For example, using a visual search paradigm where the task was to detect a line element differing from the distractors in orientation, Verghese and Nakayama found set-size effects best supporting a capacity limited model. Similarly, Morgan et al. (1998) found evidence in support of a capacity limited model with a search task. Morgan et al.'s stimuli were composed of oval Gabor patches differing in orientation. The task was to detect which of the two intervals contained a target element oriented differently from the other elements. A capacity limited model best described the set-size effects obtained.

Finally, there are some findings that are inconsistent with both a capacity limited and unlimited models. Rosenholtz (1997) and Morgan et al. (1998) found orientation thresholds to rise when some of the distractor elements were tilted away from the target orientation, increasing the orientation difference between the target and distractors. Neither attentional model can account for this effect since increasing the orientation difference between the target and distractors should have improved and not degraded performance. A possible explanation for these findings is that detection was mediated by some sort of texture or grouping mechanism sensitive to homogeneity or heterogeneity in the display (Duncan & Humphreys, 1989; Poirson & Wandell, 1990; Palmer, 1994; Morgan et al.; Rosenholtz, 1999). Such a grouping mechanism might compute an overall orientation difference for all the elements in the display. For a two interval forced-choice paradigm, the interval with the largest output would then be selected as the target interval. For such a grouping mechanism, heterogeneity in the distractor orientation would introduce noise in the averaging process and would degrade performance.

In the first two experiments in the present study, the two models of attention were tested by measuring the effects of chromatic uncertainty on response time. To optimally detect a target of an uncertain chromaticity, multiple chromatic mechanisms are likely to be monitored. Because a capacity unlimited model postulates multiple channels can be monitored simultaneously, the effects of chromatic uncertainty were predicted to occur only when the chromatic difference between the target and distractors was small. According to a capacity unlimited model, uncertainty has an effect on performance only because the representations of the stimulus elements are noisy and signals from the target and distractors are confusing at small chromatic differences (see Pelli, 1985; Graham, 1989; Palmer et al., 1993). As the chromatic difference between the target and distractors increases, a distractor is less likely to be mistaken for a target, even when multiple chromatic mechanisms are monitored. As a result, a capacity unlimited model predicts an interaction between the effect of chromatic uncertainty and chromatic difference. The effect of chromatic uncertainty should be largest when the chromatic difference between the target and distractors is small and should decrease as the chromatic difference is increased. When the chromatic difference between the target and distractors is large, there should be no effect of chromatic uncertainty.

According to the capacity limited model, there are limitations in attentional capacity that are exceeded when multiple chromatic channels must be monitored simultaneously at several locations within the visual field. One possibility is that an observer cannot monitor more than one chromatic mechanism simultaneously at several locations, resulting in the sequential monitoring of the chromatic mechanisms (see Treisman & Sato, 1990; Wolfe, 1994). An alternative possibility is that multiple chromatic mechanisms can be monitored simultaneously but the information within each chromatic mechanism is degraded as a result of simultaneously monitoring multiple channels (see Palmer et al., 1993). As a result it takes longer to accumulate enough information to make an accurate decision about the presence or absence of a target. In this view the uncertainty effects occur because a capacity limit is exceeded when uncertainty is introduced. In Section 4, we describe a simple capacity limited model as an example to show that at least some versions of such models predict that the magnitude of the chromatic uncertainty effect should be approximately independent of the chromatic difference between target and distractors.

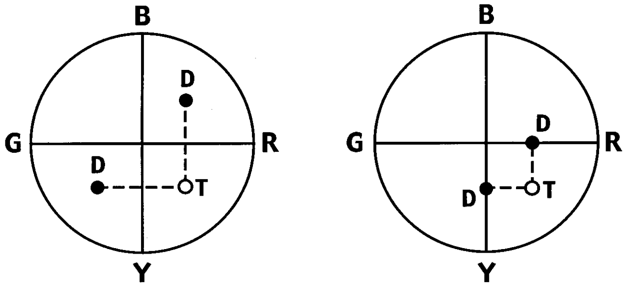

Fig. 1. Two of the conditions tested by D’Zmura. In the condition on the left, half of the distractors were yellow–green, the other half were blue–red and the target was orange. In the condition on the right, half of the distractors were red and the other half were yellow while the target was orange. If the search process were mediated by color-opponent mechanisms, the target detection in both conditions ought to be difficult since the distractors provide matched levels of excitation along these two channels as demonstrated by the dashed lines.

While several of the studies described above have investigated the effects of stimulus uncertainty on search times, the purpose of the present study was to measure uncertainty effects over a large range of target–distractor discriminability, so that the interaction between the uncertainty effects and chromatic difference, or difficulty of the search, could be investigated. Uncertainty effects will be defined here as the difference in response time between conditions in which the target and distractor chromaticities are known a priori compared with conditions where the target and distractor chromaticities are uncertain. Uncertainty will be introduced by intermixing and randomly presenting target and distractor chromaticities within a block of trials.

The second question addressed in this study had to do with mounting evidence for the existence of cortical higher order chromatic mechanisms. In the last 10 years, both psychophysical and physiological evidence has emerged suggesting the existence of mechanisms tuned to colors intermediate from the classical color-opponent directions (Lennie, Krauskopf, & Sclar, 1990; D’Zmura, 1991; D’Zmura & Knoblauch, 1998; D’Zmura, Lennie, & Tiana, 1997; Webster & Mollon, 1991; Gegenfurtner & Kiper, 1992; Krauskopf & Gegenfurtner, 1992; Krauskopf, Williams, Mandler, & Brown, 1986; Kiper, Fenstemaker, & Gegenfurtner, 1996; Nagy, 1999). One source of evidence most pertinent to this study came from the visual search experiment conducted by D’Zmura (see also Bauer, Jolicœur, & Cowan, 1996; D’Zmura et al.). The conditions used by D’Zmura critically tested the higher order chromatic mechanism model because some of the searches could not easily be mediated by the two cardinal color-opponent channels. Fig. 1 represents two of the conditions tested by D’Zmura. On the left of Fig. 1, half of the distractors are yellow–green, the other half are blue–red, and the target is orange. On the right of Fig. 1, half of the distractors are red, the other half are yellow and the target is orange. In both cases, if the underlying mechanisms mediating the search were the two cardinal color-opponent mechanisms, the target should be difficult to detect. This prediction follows from the fact that the target cannot be easily detected by either the red-sensitive or yellow-sensitive channel since the distractors provided matched levels of excitation in these channels. If the underlying mechanisms mediating the search were the cardinal color-opponent mechanisms, performance should be slow for both conditions. This is not what D’Zmura found. Although the condition on

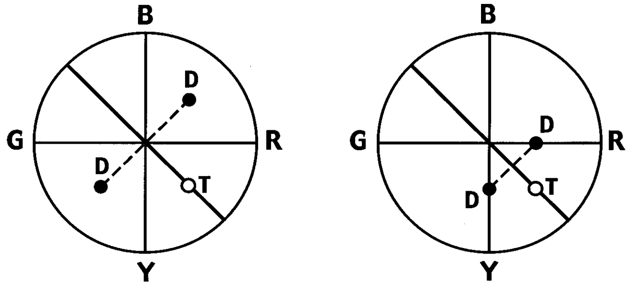

Fig. 2. If the search were mediated by higher order chromatic mechanisms, the condition on the left ought to result in better performance compared with the condition on the right. For the condition on the left, distractors do not produce any excitation along the diagonal mechanism (as represented by the dashed line). For the condition on the right, distractors do produce some excitation along that diagonal mechanism and should interfere with the search for the orange target.

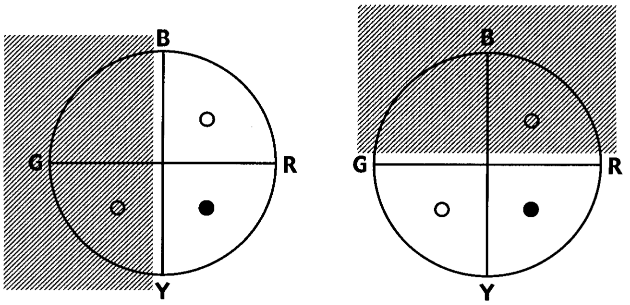

Fig. 3. Because the conditions were blocked, it is possible that D'Zmura's observers used a segregation strategy. For example, green elements might be segregated and inhibited from the others (left). Similarly, blue elements might be segregated and inhibited (right).

the right of Fig. 1 resulted in slow search times, the condition on the left of Fig. 1 resulted in fast search times.

A possible interpretation of the results suggested by D'Zmura (1991) was that targets were detected by diagonally tuned higher order chromatic mechanisms. Such color-opponent higher order chromatic mechanisms would combine signals from the color-opponent cardinal mechanisms (Fig. 2). As the dashed line on the left of Fig. 2 demonstrates, the yellow–green and blue–red distractors produce little or no excitation in a diagonal mechanism sensitive to orange stimuli. The target detection should, therefore, be performed rapidly by such a diagonal higher order chromatic mechanism in the condition on the left. For the condition on the right in Fig. 2, the distractors generate excitation in this hypothetical higher order mechanism and ought to interfere with the detection of the target resulting in a slow search, as D'Zmura found. The condition on the left in Fig. 2 resulted in significantly faster response times than the condition on the right, supporting the existence of higher order chromatic mechanisms. Similar results in support of higher order chromatic mechanisms mediating the search for colored targets have been obtained by Bauer et al. (1996), Bauer, Jolicœur, and Cowan (1998) as well as by D'Zmura et al. (1997).

Although the higher order chromatic mechanism model is a viable explanation for D'Zmura's results, an alternative explanation involving a segregation or inhibition process under attentional control was tested in the present study (Treisman & Sato, 1990; Wolfe, 1994). Because D'Zmura's conditions were run in blocks of identical trials, observers always were aware of the target and distractor colors. It is, therefore, possible that this information was used to attentionally segregate some of the stimulus elements and make the search more efficient. For example, using a visual search task Treisman and Sato demonstrated the ability of observers to ignore or inhibit distractor stimuli based on signals irrelevant to the target. This inhibition scheme, they argue, might be used to make the target more detectable and could explain fast conjunction searches. Yielding support for this idea, Kaptein, Theeuwes, and van der Heijden (1995) have obtained results suggesting it is possible for observers to attentionally 'select' stimuli of a specific color and inhibit or ignore stimuli of a different color using a visual search task. The nature of the attentional selection mechanism in Kaptein et al.'s experiments is not clear. For example, observers could have inhibited the irrelevant elements or activated the relevant ones (Wolfe). Friedman-Hill and Wolfe (1995) found evidence of feature activation using search displays containing red and green line elements varying in orientation (experiment 4). It, therefore, appears that both feature inhibition (Treisman & Sato, 1990) and feature activation (Wolfe; Friedman-Hill & Wolfe, 1995) might occur. Based on this evidence of attentional feature inhibition/activation, it is possible that in D'Zmura's (1991) conditions observers used some sort of segregation strategy to make the search process more efficient. Using the conditions presented in Fig. 1 as an example, segregating and inhibiting green stimuli would eliminate the yellow–green distractors (Fig. 3, left). If the cardinal mechanism excited by the yellowish elements were monitored for the remaining stimuli, the target could then be detected rapidly since it was the only remaining yellowish element. Similarly, if stimuli exciting the cardinal mechanism responsive to bluish stimuli could be inhibited, the target could then rapidly be detected by the cardinal mechanism sensitive to the reddish stimuli (Fig. 3, right). If the target color is uncertain, the segregation scheme will not be as efficient since the stimulus elements to be inhibited would be uncertain. For example, if the target were randomly selected from one of the four diagonal directions on each trial, the observer would not know which elements to segregate and inhibit. If the segregation scheme were used to detect targets on diagonals (Fig. 1, left), search performance in uncertain conditions should be degraded relative to conditions without uncertainty. On the other hand, if the search is mediated by diagonal 'hard-wired' higher order color-opponent mechanisms, the uncertainty effects ought to be similar in magnitude for targets selected on the diagonal axes and targets selected from the cardinal axes. In order to test the higher order chromatic mechanism and segregation models, uncertainty effects were introduced in conditions where the two models made different predictions; conditions similar to those depicted in Fig. 1.

Two questions were addressed. First effects of chromatic uncertainty on response time were tested using a visual search paradigm. To test the interaction predicted by a capacity unlimited model of attention, the uncertainty effects were measured over a wide range of chromatic difference between the target and distractors. Second, two models of search for color elements on diagonals (e.g. D'Zmura, 1991) were tested. A higher order chromatic mechanism model postulating four mechanisms combining signals from the cardinal color-opponent mechanisms tuned to diagonal directions in color space was tested against a segregation model under attentional control. To differentiate between the two models, the uncertainty effects were measured in conditions where distinctly different predictions were made by the two models.

2. Methods

2.1. Subjects

Three participants between the ages of 24 and 28 took part in the study. Two participants were paid for their participation. The third observer was the first author. All observers had normal color vision and normal or corrected to normal acuity. Participants were highly trained and practiced observers familiar with similar psychophysical experiments. One of the three observers (JB) was naive as to the purpose of the study.

2.2. 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 presented on a 17 in. Nanao T2-17 color monitor at a resolution of 832 by 624 pixels driven at a refresh rate of 74 Hz. Fifty-four elements were presented in a circular area subtending approximately 4.25° of visual angle in diameter. The target and distractors were disk elements of identical surface area with a diameter subtending approximately 0.14° in visual angle. The distractor and target stimuli were isoluminant (6 cd/m^2) and differed in chromaticity only. The elements were presented on a dark background of less than 0.3 cd/m^2. The background chromaticity could not be measured reliably because of the low luminance level. The elements were presented in pseudo-random locations following two restrictions: a disk had to be within the 4.25° field and had to be separated from another disk by at least half a degree of visual angle center-to-center. The edges of any two disk elements could, therefore, not be any closer than 0.36° of visual angle. The presentation of the elements on the monitor was done within one frame (at 74 Hz), which represents a 13.5 ms drawing time.

The cone-excitation space was used to represent all the chromaticities used in this study (MacLeod & Boynton, 1979). For experiments 1 and 3, target and distractor stimuli were selected from the cardinal axes ($+$L or reddish, $-$L or greenish, $+$S or bluish, and $-$S or yellowish) of the cone-excitation space while stimuli were selected from diagonal axes for experiments 2 and 4.

2.3. Procedure

Fifteen or more target colors were selected along each of the four chromatic directions (e.g. $+$L, $-$L, $+$S, and $-$S). The 15 levels represented different levels of chromatic differences between the target and the distractors in the cone-excitation space roughly corresponding to different levels of saturation. The large number of chromatic differences was tested to investigate the uncertainty effects over a large range of search performance. All four experiments were run in blocks of 60–66 trials (a maximum of six errors were permitted per block; see below for details). Within a block, four target chromaticities (e.g. one $+$L, one $-$L, one $+$S and one $-$S) of similar difficulty were selected based on a normalization procedure described below. A block of trials included ten target present repetitions for each of the four target colors for a total of 40 target-present trials. The remaining 20 trials in a block were target-absent trials and contained distractors only. All the trials within a block were intermixed and presented in random order. In cued trials, a pre-trial cue representing the target and distractor colors for the given trial was presented. In uncued trials, no such cue was presented. The order in which the blocks were completed was randomized although the cued/uncued blocks for a given chromatic difference level were always run back to back. The order in which the cued/uncued blocks were run was determined randomly. The room in which the study was conducted was dark and observers were dark adapted for at least 5 min before data collection was initiated. During data collection, the observer sat 125 cm away from the monitor and responses were collected using the computer mouse.

A typical block was initiated by having the observer enter the necessary information for the desired block into the computer. A warning display indicated that the block was about to begin and a dim desk light was turned off. The observer then placed him/herself on the chin rest and four target-present trials, each trial containing one of the four target chromaticities and two target-absent trials, were presented as a practice. During the four practice trials the target was always presented at the center of the 4.25° field for easy identification. The elements remained on the display until the observer pressed the mouse button. Response times for the practice trials were disregarded. After the practice trials, the observer was warned that the block was about to begin.

The typical sequence for both a cued and uncued trial is presented in Fig. 4. First, the fixation cross appeared at the center of the screen and in cued blocks, the pre-trial cue was presented as well. The cue consisted of a triangular arrangement of three elements with the target above two distractor stimuli. In experiments 1 and 2 the distractors were always white and therefore, the two distractor elements presented as a cue were white and of equal luminance. In experiments 3 and 4, distractors of two different colors were presented in each display and therefore, the two distractor elements of the cue differed in color but not in luminance. The cuing display was removed after 1.2 s and was followed by a fixation display which remained visible for another 1.5 s. A blank display was presented next for a random time period (0.4–1.6 s). The stimulus display was then presented and remained visible until the observer pressed the mouse button indicating that he or she had made a present/absent decision regarding the status of a target. The recorded response time consisted of the period of time between the display presentation and the observer's initial button press. Finally, the response display, which consisted of two fields each half the size of the monitor was presented. The left field was to be clicked for an 'absent' response and the right field for a 'present' response. Responses were collected in this fashion to avoid a potential bias between the two responses. Only correct trials were analyzed. After a response, a 1.5 s delay preceded the presentation of the next trial.

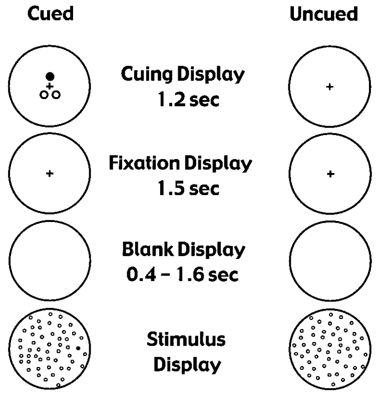

Fig. 4. A cued and uncued trial sequence is represented on the left and on the right, respectively. First, the cuing display was presented followed by a fixation display. A blank display was presented next for a random time interval, followed by the stimulus display. When the observer made his or her decision regarding the present or absence of a target, the mouse button was clicked. The stimulus display was followed by a response display. A click on the right side indicated a target present response while a click on the left side of the display indicated a target absent response.

To avoid a speed-accuracy trade-off, error rates were kept under 10%. Error rates were computed for each target color and therefore, only one error was permitted for each target color condition within a block. For target absent trials, two errors were permitted since a block contained 20 such trials. If the criterion was not maintained by the observer, the block was terminated and had to be restarted. When an error was committed, the observer was informed of it by an auditory signal and was presented with an error cue representing both the target and distractor colors for the condition in which the error was committed. Because some errors were permitted, a block of trials contained between 60 (no error) to 66 (six errors) trials. In order to avoid fatigue effects, observers were asked to take breaks any time they felt necessary by postponing their present/absent response to a given trial. Observers usually collected data for no more than 2 h a day.

2.4. Normalization of the chromatic axes

In uncertain conditions, four target chromaticities were intermixed and presented randomly within a block of trials. Chromatic uncertainty was hypothesized to force observers to monitor multiple chromatic mechanisms. If, within a block of trials, the target chromaticities varied greatly in their discriminability from distractors, it is possible the search strategy might be biased toward the easier or more conspicuous targets. To avoid such a bias, the four target chromaticities within a block were chosen to produce approximately equal response times. Prior to the main experiments, the four cardinal axes were normalized for each observer to allow for the selection of target chromaticities of roughly equal search difficulty. Four target excitation levels along each of the four cardinal axes ($+L$, $-L$, $+S$, and $-S$) of the cone-excitation space were selected. Response times were obtained for each of these target stimuli presented along with 53 equal energy white isoluminant distractors. A best fitting line was then calculated for the response times on each axis.

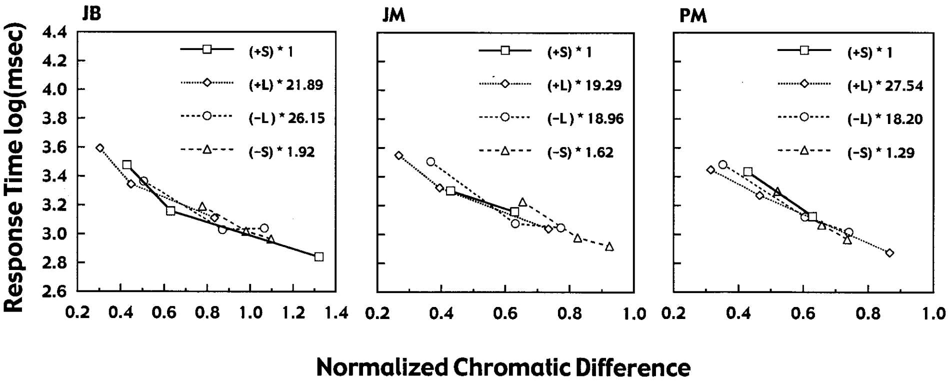

Fig. 5. To present targets of equal difficulty within a block, the color space was normalized for each observer. Response time data were collected for each of the four axes (+ L, − L, + S, − S) in separate blocks of trials. A best fitting line was then calculated for each axis and the axes were finally normalized. The normalization factors for each observer are reported on the graph.

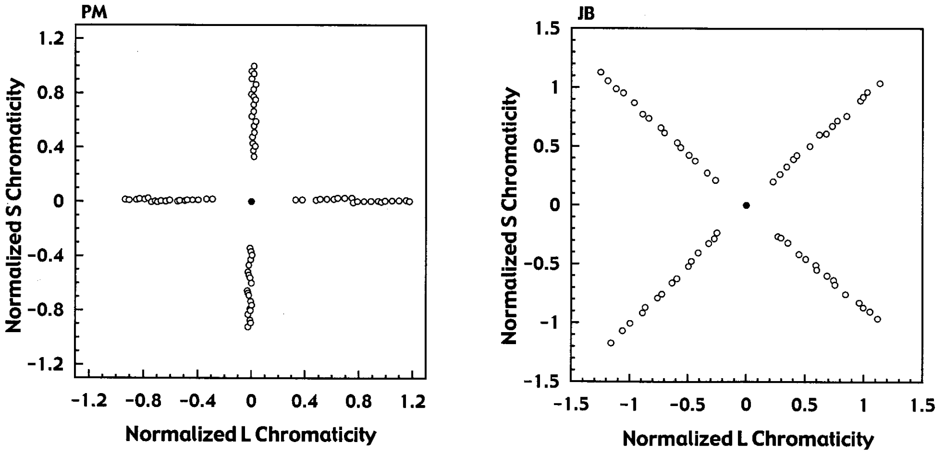

Fig. 6. Target and distractor chromaticities that were selected for experiment 1 for observer PM (left) and for observer JB for experiment 2 (right). For both experiments, the distractors were white (solid symbols) while the targets were selected from either the cardinal axes for experiment 1 or the diagonal axes for experiment 2 (open symbols). Because the normalization was performed for each observer, colors were slightly different across observers.

Finally, the four axes were normalized for each observer, by scaling the units along each axis so that the four best fitting lines fell approximately on top of each other as shown in Fig. 5. In each graph presented in Fig. 5, curves from all four axes are plotted as a function of the normalized chromatic difference. The normalizing factors for each observer were also reported on the graphs. These normalized units were then used to generate 15 or more blocks of trials of varying difficulty for each observer. Each block of trials contained four target chromaticities roughly equal in search difficulty. Normalizing the axes allowed for the selection of target chromaticities similar in their search difficulty.

To verify the validity of the normalization, response times for each cardinal direction were compared via one-way ANOVAs. For each observer and for each experiment, response times for the four cardinal directions were compared and out of 24 tests, only eight were significant. Pairwise comparisons revealed no systematic differences across experiments. We, therefore, felt confident that the normalization was successful.

2.5. Chromaticities for experiments 1, 2, 3 and 4

Fig. 6 shows the target and distractor chromaticities selected for experiments 1 and 2 in cone-excitation space for two observers. In both experiments 1 and 2, distractors were white and the targets were either selected from the cardinal axes (experiment 1; Fig. 6, left, observer PM) or from the diagonal axes (experiment 2; Fig. 6, right, observer JB). Experiments 3 and 4 were composed of distractors of two chromaticities. In these experiments, a target was presented among a pair of distractor colors falling on a line perpendicular to the target line in the normalized cone-excitation space. Within a trial, the target, if present, was presented with distractors selected from a direction orthogonal to the target. For example, a + L (reddish) target was presented with − S (yellowish) and + S (bluish) distractors. The distractor colors were chosen roughly halfway between the largest and smallest chromatic difference tested along each chromatic axis. Experiment 3 (Fig. 7, left observer JB) was composed of target and distractor colors falling on the cardinal axes while experiment 4 (Fig. 7, right observer JM) was composed of target and distractor colors falling on diagonals. The chromatic difference in both experiments was expressed in terms of the distance along the normalized L and S cardinal axes between the target and the origin of the cone-excitation diagram. The origin of the cone-excitation diagram represented an equal-energy white.

2.6. Data analysis

A multiple hierarchical regression analysis (Cohen & Cohen, 1983) was conducted for each of the four experiments and for each observer separately. Although the regression analysis is atheoretical, we feel it was appropriate given the main goal was not to model the search process per se but to (a) determine whether the uncued conditions were slower than the cued ones, (b) determine whether the cuing effects interacted with the chromatic difference between the target and distractors, and (c) determine whether cuing effects were larger for diagonal conditions compared with cardinal conditions. The regression analysis was used to derive equations describing response time as a function of the normalized chromatic difference for both the cued and uncued conditions. Before conducting the analysis, the raw response times were transformed to logarithmic units to normalize the skewed linear response time distribution. Using the logarithmic response times and the normalized chromatic difference units, a basic expression containing a linear chromatic difference term and a cuing term was tested first. Subsequently, a squared chromatic difference term and an interaction term were sequentially added and the contribution of each of these terms to the amount of explained variance was tested. The inclusion of the interaction term allowed the model predictions for the cued and uncued conditions to converge to similar values at large chromatic differences as predicted by the unlimited capacity model. Because the addition of a term to an expression will almost always result in an increment in the amount of variance explained, the appropriateness of the new fit cannot be determined by simply assessing the squared multiple R. Instead, the increment in the squared multiple R due to the added term must be tested for significance (Cohen & Cohen). The increment in the variance explained with the addition of each term was, therefore, tested using Cohen and Cohen's recommended technique. The final fits, therefore, only contained terms that significantly added to the amount of explained variance.

The full model is given below:

$$\log(\mathrm{RT}) = a(\mathrm{CD}) + b(\mathrm{CUE}) + c(\mathrm{CD}^2) + d(\mathrm{INTER}) + e$$

where log(RT) represents the logarithm of response time, CD represents the linear chromatic difference term, CUE represents a dummy variable coding the cued or uncued condition, CD^2 represents a squared chromatic difference term, and finally INTER represents the interaction between the cuing effects and the chromatic difference.

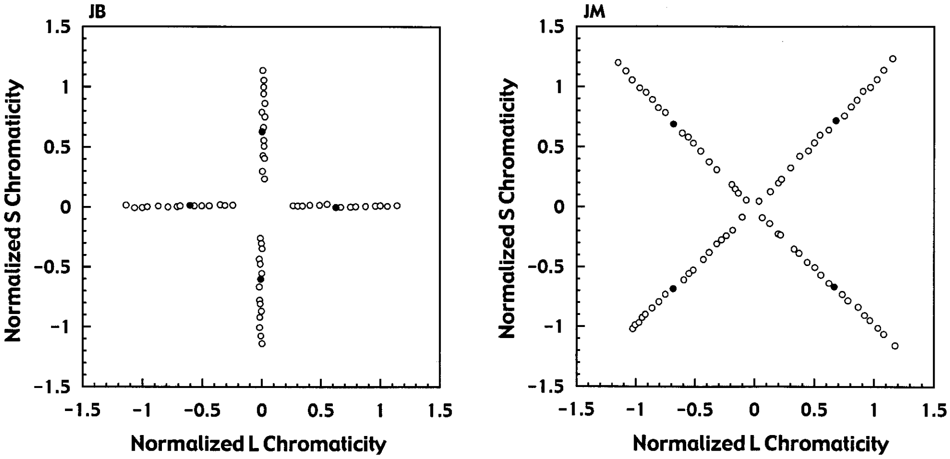

Fig. 7. Target and distractor chromaticities that were selected for experiment 3 for observer JB (left) and for experiment 4 (right) for observer JM. In both experiments, two sets of distractor colors were used (solid symbols). For experiment 3, the target (open symbols) and distractor colors were selected from the cardinal axes. A target was paired with a set of distractor colors from the orthogonal axis. Target and distractors colors were similarly paired in experiment 4 except that the colors fell on diagonal directions.

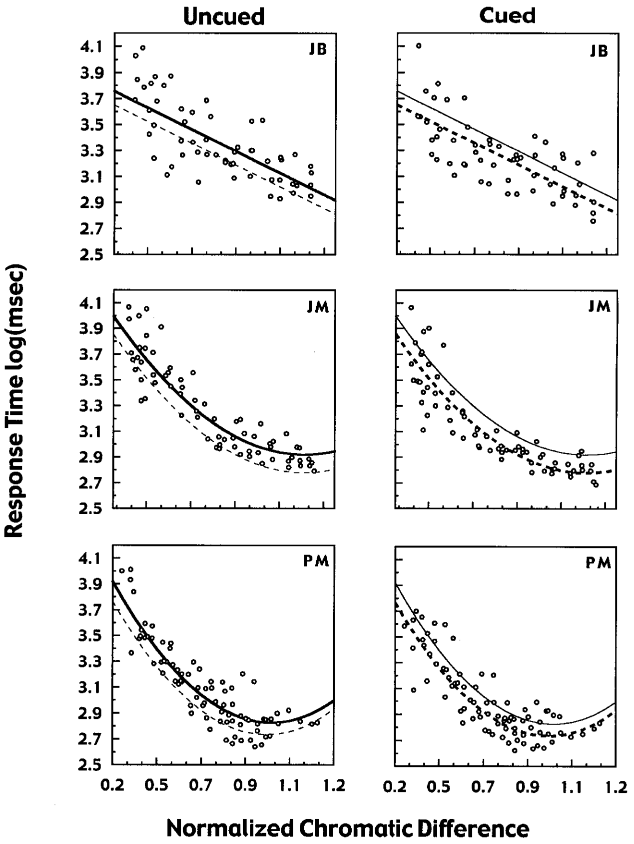

Fig. 8. Results of experiment 1. Log response time data are plotted as a function of the normalized chromatic difference between the target and distractor colors. The solid lines represent the fit according to the regression analysis for the uncued data while the dashed lines represent the fit for the cued data. The uncued and cued fits are presented on both uncued and cued graphs for comparison purposes.

3. Results

3.1. Experiment 1 and 2 — white distractors with target colors on cardinal and diagonal axes

In experiments 1 and 2, targets were presented among white distractors of equal luminance. The target chromaticities for experiment 1 were selected from cardinal directions while target chromaticities in experiment 2 were selected from diagonal directions (Fig. 6). Fig. 8 shows pooled data for the four chromatic axes from experiment 1 for each observer. The logarithmic uncued and cued response time data are plotted on the left and right, respectively, as a function of the normalized chromatic difference. At least 15 chromatic difference levels were measured for each chromatic axis and each data point represents the mean of ten trials. The most adequate fit as determined by the hierarchical regression procedure is also represented on both uncued and cued graphs. The solid lines represent the fit of the model for the uncued data while the dashed lines represent the fit for the cued data. The uncued and cued fits are presented on both uncued and cued graphs for comparison purposes. An α level of 0.05 was used for all tests in the regression analysis. For all three observers in experiment 1 both the linear chromatic difference term and the cuing effect term were significant. For observers JM and PM, the squared chromatic difference term was significant as well. The interaction between the cuing effect and the normalized chromatic difference was not significant for any of the observers (Table 1 shows the results of the interaction term analysis for each observer). The fits in Fig. 8 only comprise terms that significantly added to the amount of explained variance and therefore, none contained an interaction term.

Fig. 9 shows the data for experiment 2 for each observer. The graphs follow the same format as in Fig. 8. Data from each observer for the uncued and cued conditions are plotted in logarithmic units on the left and right, respectively. Response times for 15 or more levels of chromatic difference are plotted as a function of the normalized chromatic difference. An analysis identical to the one used for experiment 1 was conducted. For all three observers, the linear chromatic difference term, the squared chromatic difference term, and the cuing effect term were significant. The interaction was not significant for any of the observers (Table 1) and was not included in the fits in Fig. 9. In summary, in both experiments 1 and 2 and for all three observers, the uncertainty effects were significant and approximately constant in logarithmic units across the

Table 1
Results of the regression analysis for the interaction term for each observer and for the four experiments[a]

JB		JM		PM	
$R^2_{\mathrm{Y.A}}$	$R^2_{\mathrm{Y.AB}}$	$R^2_{\mathrm{Y.A}}$	$R^2_{\mathrm{Y.AB}}$	$R^2_{\mathrm{Y.A}}$	$R^2_{\mathrm{Y.AB}}$
Experiment 1					
0.617	0.619	0.934	0.936	0.797	0.801
$F(3,114)=0.20$		$F(4,128)=0.39$		$F(4,152)=0.76$	
Experiment 2					
0.874	0.880	0.916	0.922	0.750	0.755
$F(4,112)=1.40$		$F(4,128)=2.46$		$F(4,136)=0.69$	
Experiment 3					
0.587	0.590	0.779	0.784	0.527	0.530
$F(3,114)=0.28$		$F(4,112)=0.65$		$F(3,154)=0.33$	
Experiment 4					
0.706	0.707	0.799	0.799	0.721	0.723
$F(3,138)=0.16$		$F(4,144)=0.00$		$F(4,112)=0.20$	

[a] $R^2_{\mathrm{Y.A}}$ is the squared multiple R before the interaction term was added and $R^2_{\mathrm{Y.AB}}$ is the squared multiple R after the interaction terms was added. The significance of the increment in the squared multiple R was assessed using Cohen and Cohen (1983) method. None of the tests were significant ($P<0.05$) indicating that the contribution by the interaction term in the amount of explained variance was negligible.

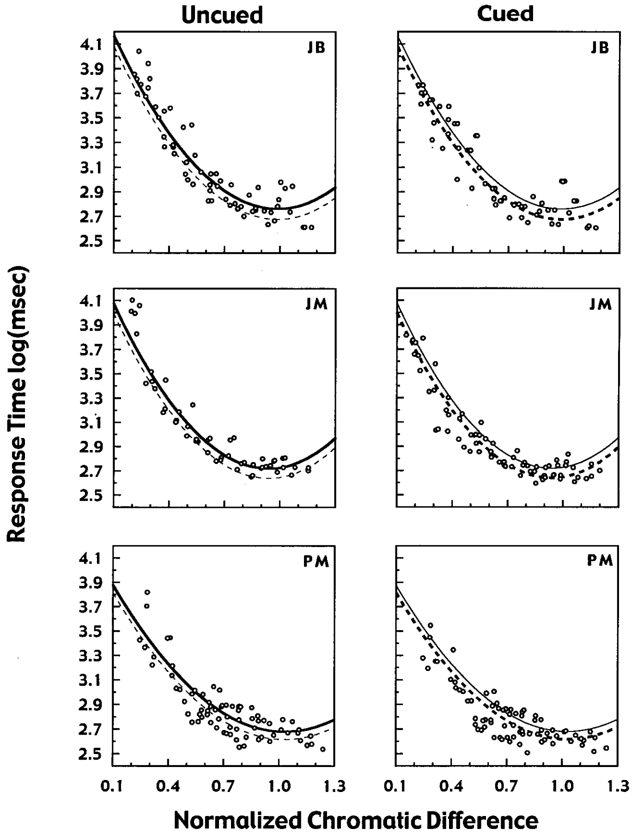

Fig. 9. Results of experiment 2. The format is similar to Fig. 8.

whole range of chromatic difference tested (the interaction was not significant). Possible interpretations for the absence of an interaction are provided in Section 4.

3.2. Experiments 3 and 4: two distractor color conditions with target colors on cardinal and diagonal axes

In experiments 3 and 4, targets were presented among two sets of distractor chromaticities selected from a line orthogonal to the target in the normalized cone-excitation space. In experiment 3, target and distractor chromaticities were selected from the cardinal directions while in experiment 4, target and distractor chromaticities were selected from diagonal directions (Fig. 7). Fig. 10 shows the data for experiment 3. The most adequate model is again represented on the graphs. The solid lines represent the model's fit to the uncued data while the dashed lines represent the fit to the cued data. For all observers, the linear chromatic difference term as well as the cuing effect term were significant. The squared chromatic difference term was significant for observer JM only. For all three observers, the interaction term was not significant (Table 1). Fig. 11 represents the pooled data for experiment 4. The solid lines represent the model's fits to the uncued data and the dashed lines represent the fit to the cued data. For all observers, the linear chromatic difference term, the squared chromatic difference term, and the cuing effect term were significant. The interaction term was not significant for any of the observers (Table 1).

Overall, two conclusions can be drawn. First, the cuing terms were significant in all 12 tests (all four experiments), indicating faster response times for cued conditions. Second, the interaction between the cuing effect and the chromatic difference was not significant in any of the 12 tests suggesting that the magnitude of the cuing effect, in logarithmic units, was independent of chromatic difference. As discussed in Section 1, if searches were mediated by a segregation process, the magnitude of the cuing effects was expected to be larger in experiment 4 than in experiment 3. On the other hand, if the searches were mediated by higher order chromatic mechanisms, the magnitude of the cuing effects in experiments 3 and 4 should be similar. A one-way ANOVA comparing the magnitude of the cuing effects across all four experiments was conducted for each observer. For JB and PM, the tests were not significant indicating that the cuing effects did not reliably differ across experiments. For observer JM, the test was significant ($F(2,231) = 4.678$; $P = 0.034$). Pairwise comparisons revealed significant differences be-

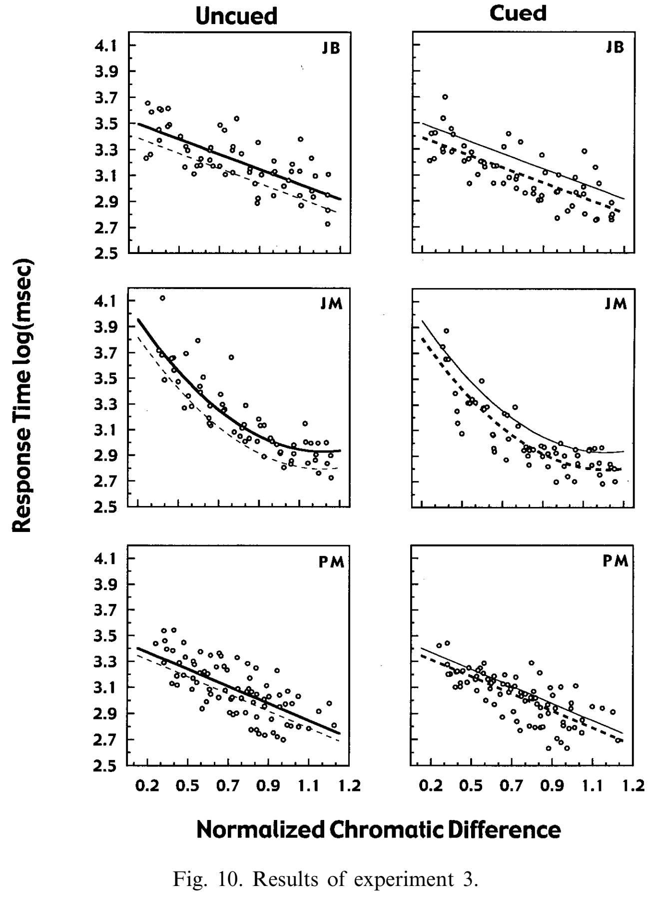

Fig. 10. Results of experiment 3.

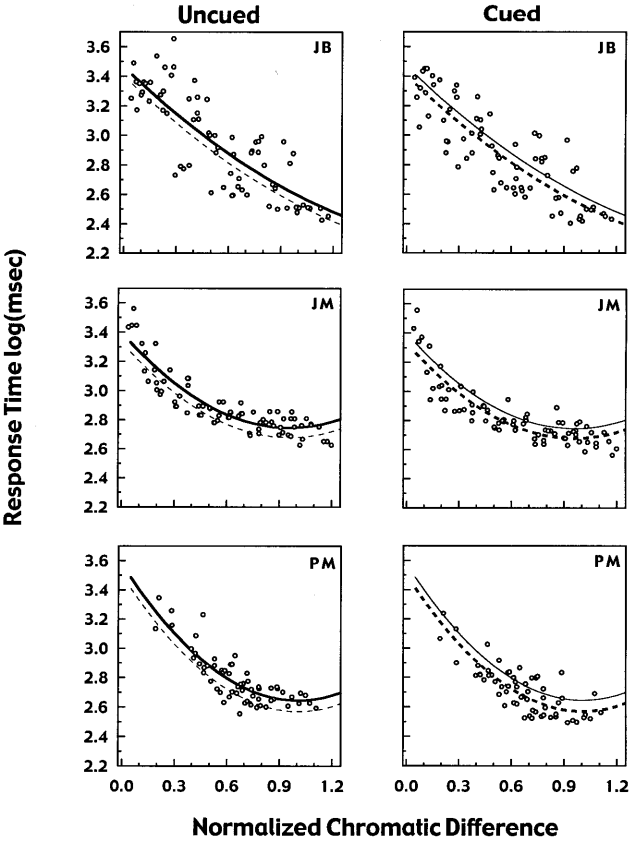

Fig. 11. Results of experiment 4.

tween experiments 1 and 4 ($t = 2.529$; $P = 0.015$) and between experiments 3 and 4 ($t = 3.164$; $P = 0.002$). However, since the segregation model predicted the uncertainty effects to be greatest in experiment 4, it can be ruled out for JM as well since the difference in the size of the cuing effect between experiments 3 (mean = 0.1350 log units) and 4 (mean = 0.0711 log units) was in the wrong direction.

4. Discussion

4.1. Uncertainty effects in experiments 1 and 2

Two hypotheses were formulated regarding the relationship between uncertainty effects and search difficulty. One hypothesis suggested that uncertainty effects should be inversely related to the chromatic difference between the target and distractors. The interaction hypothesis was based on a capacity unlimited model of attention (Davis & Graham, 1980; Davis et al., 1983; Kramer et al., 1985; Pelli, 1985; Palmer et al., 1993) as well as findings in the visual search literature. In general, a capacity unlimited model predicts uncertainty effects on discrimination to be present only when stimulus discriminability is low (i.e. near threshold). As target discriminability increases, uncertainty effects are predicted to decrease and eventually vanish since it is less likely that a signal confusable with the target signal would originate from the distractors. Supporting the interaction hypothesis are findings that search difficulty tends to vary greatly with the chromatic difference between the target and distractors. For example, using a visual search task, Nagy and Sanchez (1990) found that searching for targets similar in color to the distractors resulted in slow searches while searching for targets different in color resulted in fast searches. Nagy and Sanchez found that beyond what they called the critical color difference, response times remained constant with further increases in chromatic difference and were independent of the number of distractors presented with the target. When response time is independent of set-size, the search is often referred to as ‘pop-out’ since the target appears to capture attention. Because of this seemingly preattentive or automatic process and the results in support of a capacity unlimited model of attention described in Section 1, we expected an interaction between the cuing effects and the chromatic difference between the target and distractors.

The second hypothesis suggested that a priori knowledge of the target and distractor colors should have resulted in faster search times compared with conditions where target and distractor chromaticities were uncertain, regardless of the chromatic difference between the target and distractors. This hypothesis was based on a capacity limited model of attention suggesting that a capacity limit would be exceeded when observers were required to monitor several chromatic mechanisms at multiple locations simultaneously. Over the range of chromatic differences tested, we found no evidence of a significant decrease in the magnitude of the uncertainty effects (in logarithmic units) with increasing chromatic difference. Although we believe the results of experiments 1 and 2 support a capacity limited model, two alternative explanations for the constant cuing effects are presented next.

First, it might be that an interaction between the magnitude of the uncertainty effect and color difference was not revealed because the range of chromatic differences tested was too small. That is, with greater chromatic differences, the uncertainty effects might eventually decrease. Although this is a possibility, response times for the largest target-distractor differences approached an asymptotic level and we expected that the uncertainty effects would decrease significantly as asymptote was approached. One obvious solution to this question would be to run conditions with even greater chromatic difference levels. The largest color differences used in the experiments reported were the largest obtainable on our monitor. Thus we could not test this possibility but it seems unlikely that the uncertainty effects would disappear with larger color differences.

Second, the lack of an interaction might have been caused by differences in the pre-trial cue's effectiveness to indicate the target color and hence remove the uncertainty. For small chromatic differences, it is possible that the cue was not as effective in removing uncertainty since the cues themselves were less discriminable. In particular, it is possible that some colors used as cues were confused for one another. If this were the case, the cues for the difficult conditions might not have removed uncertainty entirely. This possibility was raised by the report of one subject that he sometimes found it difficult to distinguish the reddish and bluish cues. On the other hand, this confusion took place only at the smallest chromatic difference levels and was reported by only one subject. Such an explanation would not explain why uncertainty effects were still present at the largest color differences. Therefore, this explanation for the constant magnitude of the uncertainty effects seems unlikely. The capacity limited explanation is, therefore, favored over the other explanations offered above. Next, we present a simple capacity limited model as an example. We present this model only to show that at least some versions of capacity limited models are consistent with a cuing effect of constant magnitude in logarithmic units. There may be many other versions of capacity limited models that make different predictions.

First, suppose that observers monitored only one chromatic mechanism in the certain conditions and as many as four different chromatic mechanisms in the uncertain conditions on each trial of experiments 1 and 2. In experiment 1 the targets randomly intermixed within a block of trials were chosen from the cardinal axes in the cone excitation space. There is evidence supporting the notion that the cardinal axes represent independent chromatic mechanisms (e.g. Boynton & Kambe, 1980). Furthermore, there is evidence that in visual search tasks as well as in some detection and discrimination tasks, the four directions along these two axes are represented by four underlying neural mechanisms (DeValois & DeValois, 1993; Zaidi & Halevy, 1993; Monnier & Nagy, 1997). The magnitude of the uncertainty effect in experiments 1 and 2 was similar, suggesting that four different chromatic mechanisms also were used to detect the targets in experiment 2, where targets were chosen from diagonal axes.

Second, suppose that when the chromatic difference between the target and distractors was reduced, observers monitored fewer stimuli simultaneously and made multiple fixations in order to inspect all of the stimuli. Set-size effects have been found in simple feature tasks when the perceptual difference between target and distractors is small and have been attributed to sequential inspections of sub-groups of stimulus elements (e.g. Treisman & Gormican, 1988; Nagy & Sanchez, 1990). Some search models include explicit formulations of this multiple fixation process (e.g. Treisman & Gelade, 1980; Geisler & Chou, 1995). Since signals from targets and distractors are noisy, the possibility that a distractor will be confused with the target increases as the difference between the target and distractors is made smaller. This forces the observer to monitor fewer stimuli at a time and make multiple fixations to reduce the probability that a distractor will be confused with a target.

Finally, suppose that observers can monitor simultaneously several chromatic mechanisms at one spatial location or one chromatic mechanism at several stimulus locations, but that several chromatic mechanisms cannot be monitored at several stimulus locations simultaneously without encountering a capacity limit. This hypothesis is supported by threshold detection experiments, including those conducted by Greenhouse and Cohn (1977), Davis and Graham (1980) (see also Graham, 1989) suggesting that observers can monitor several detection mechanisms at one location without encountering capacity limits. Search accuracy experiments (Palmer et al., 1993) suggest that observers also can monitor a single detection mechanism at several locations without encountering capacity limits. However, search tasks that involve conjunction targets often show that performance is degraded when observers must monitor multiple feature coding mechanisms at multiple locations (e.g. Treisman & Sato, 1990). Performance on conjunction tasks varies considerably depending on the particular type of conjunction targets used, the discriminability of the stimuli, and the individual observer (Wolfe, 1994), but performance for such conditions is typically poorer than for single feature searches. The experiments conducted by Wolfe et al. (1990) are of particular relevance to the present study. The authors presented observers with color conjunction elements. An element was composed of two bipartite fields of different color. The authors found that the searches were difficult suggesting attentional mechanisms could not be used to make the search more efficient (in Wolfe's terminology, the top-down process cannot guide search when the conjunction target is composed of two instances of the same dimension such as two colors).

In our experiments, 54 stimuli were presented on each trial. In cued conditions where the target color was known, we assume observers were able to select the appropriate chromatic mechanism and monitor only signals in that mechanism. When the chromatic difference between the target and distractors was large, the nearly asymptotic response times suggested that signals from nearly all 54 stimuli could be monitored simultaneously to detect the target. When the chromatic difference between target and distractors was reduced, signals from distractors became more confusable with the target forcing the observer to make multiple fixations and monitor subsets of the 54 stimuli to maintain the high level of accuracy experimentally imposed. When the chromatic difference was reduced even further, the size of the subset of elements monitored on each fixation also had to be reduced, resulting in even longer search times. Since in uncertain conditions the observer does not know which of the four chromatic mechanisms may have contained the target signal, four chromatic mechanisms had to be monitored at each of the 54 stimulus locations for a total of 216 signals. Suppose that in this difficult condition a capacity limit is encountered. The effect of this capacity limit is that on each fixation it takes longer to make a decision about whether one of the monitored elements is a target. This increase in the decision latency may occur either because the observer cannot monitor all four chromatic mechanisms simultaneously, or because the information within each mechanism is degraded when four mechanisms are monitored simultaneously. If the information is degraded, it will take longer to collect enough information to make a decision. Below we describe an example to show that this simple model is consistent with the finding that the magnitude of the uncertainty effect varies little with chromatic difference or the difficulty of the search.

Suppose that in the certain condition, it takes 300 ms to monitor the signals in the appropriate color mechanism on a single fixation and decide whether a target signal is present. For simplicity we assume that for the cued conditions, the time for a single fixation is approximately constant regardless of the number of stimuli monitored. In addition it takes another 200 ms to complete the response. When the color difference is large and signals from all 54 stimuli are monitored on a single fixation the total response time would then be 500 ms (log ms = 2.70). When the color difference is decreased, suppose that the number of stimuli monitored on each fixation is reduced to about nine so that an accurate decision about the presence of a target can be made. On some trials it may take as many as six fixations (54/9 = 6) to find the target while on other trials the target may be found on the first fixation. Averaged across trials it should take approximately 3.5 fixations. If it takes 300 ms for each fixation and decision, the mean response time should be 1050 ms plus the 200 ms for generating the response for a total of 1250 ms (log ms = 3.10). Now, suppose that in the uncertain conditions when four chromatic channels must be monitored, it takes about 33% longer on each fixation to collect enough information and make a decision about the presence or absence of a target because of the capacity limitations described above. That is each fixation and decision now requires 400 rather than 300 ms because the observer must monitor four chromatic channels rather than one (if channels are monitored sequentially because of the capacity limitation and each of the three additional mechanisms is checked before a decision is made, this is equivalent to supposing that it takes on average 33 ms to monitor each of the additional chromatic channels on each fixation. If channels are monitored simultaneously but information in each channel is degraded because of the capacity limitation, this is equivalent to supposing that it takes 100 ms longer to collect enough information to make an accurate decision). We again assume that this time is approximately constant regardless of the number of stimuli monitored in each fixation for uncued conditions. When the chromatic difference is large and all 54 stimuli are monitored on one fixation, the total response time would be the sum of 400 and 200 or 600 ms (log ms = 2.78). When the chromatic difference is made smaller and the observer monitors approximately nine stimuli on each fixation, it should again take on average 3.5 fixations to find the target. Since each fixation now takes 400 ms the total response time will now be 3.5 times 400 ms plus 200 ms for the response for a total of 1600 ms (log ms = 3.20). In this simple example, uncertainty increased the response time by 0.08 log units in the easy condition and 0.10 log units in the difficult condition. The magnitude of the uncertainty effect does not vary much as a function of the chromatic difference. The values chosen for the decision and response components of the response time in this example were selected to approximate the results obtained in the experiments described above. We have not tried to fit a model of this type to the data, but it seems clear that such a model could be made to fit the results reasonably well with appropriate values for the decision and response components. Thus we conclude that a capacity limited model is consistent with the results obtained. The results suggest that observers are incapable of monitoring several chromatic channels at several locations without encountering a capacity limitation. Our results appear to be, at least qualitatively, consistent with Olds et al. (1999) findings. Olds et al. introduced chromatic uncertainty by intermixing distractors of different chromaticity and found a small but significant effect on reaction time. The authors also interpreted the small uncertainty effects as evidence for the inability to monitor multiple chromatic mechanisms simultaneously.

4.2. Higher order chromatic mechanisms

The second question addressed in this study was concerned with the underlying chromatic mechanisms mediating the search process for conditions with target and distractor stimuli on diagonals (D'Zmura, 1991). More specifically, a higher order chromatic mechanism model postulating four color-opponent mechanisms summing cardinal signals and tuned to the diagonals and an attentional segregation model with cardinal color-opponent mechanisms were tested. For the attentional segregation scheme to be effective in experiment 4, knowledge of the target color was essential. If the target and distractor colors were known, as in the cued conditions, observers might have segregated and inhibited some distractor stimuli based on their color (Fig. 2). On the other hand, under uncertain conditions, the efficiency of the segregation scheme should have been reduced since the chromatic signal(s) to inhibit was uncertain. In order to test this hypothesis, conditions similar to D'Zmura's were tested on the cardinal axes (experiment 3) and compared with the diagonal conditions (experiment 4). If the segregation scheme was adopted by our observers, randomly intermixing the target colors in the uncued conditions should have greatly reduced the efficiency of the scheme. As demonstrated by an ANOVA, the magnitude of the cuing effect in experiment 4 was different from the magnitude of the effect found in experiment 3 for only one observer (JM) and in the wrong direction; the cuing effects were larger in experiment 3 for this observer. The attentional segregation model was, therefore, not supported. Because the results obtained for such conditions are not easily explained by the cardinal color-opponent mechanisms nor by the segregation model, the results of experiment 4 are consistent with a model with at least four color-opponent higher order mechanisms combining signals from cardinal mechanisms. Although some evidence for segregation and inhibition processes in visual search exists (Treisman & Sato, 1990; Kaptein, Theeuwes, & van der Heijden, 1995), and has been incorporated in visual search models (Treisman & Sato; Wolfe, 1994), our results do not support such processes when the search is limited to stimuli that differ in chromaticity only. Treisman and Sato and Kaptein et al. did find evidence for segregation of stimuli based on color although in both cases, the experiments involved conjunction searches. It might be that segregation based on color is used only when other feature dimensions are involved.

In this study we set out to test one alternative to the HOCM model; an attentional model in which chromatic signals are combined in a certain way based on the pre-trial knowledge of the target chromaticity. However, our conclusions may extend to other models involving the combination of cardinal signals under voluntary attentional control. On certain trials with targets on diagonal axes, the observer can select the right combination of cardinal signals to monitor prior to the display presentation, so there may not be any apparent cost associated with combining the signals as compared with monitoring cardinal signals on certain trials. In uncertain trials with diagonal targets, the observer does not know what combination of signals to use and thus has to try various possibilities or, perhaps, (in experiment 4) determine what the likely possibilities are by inspecting the distractor chromaticities. It seems reasonable to expect that this would take some time and resources. Such a model would lead us to expect that uncertainty would have a larger effect for diagonal targets than for cardinal targets where the additional step of combining signals under attentional control is not needed. This kind of argument seems reasonable for any model involving voluntary combination of signals under attentional control, unless many different kinds of attentional combination can be done simultaneously without any cost to performance (for example, observers can voluntarily combine $+L$ and $+S$ signals while simultaneously combining $-L$ and $-S$ signals and monitor both combinations without any degradation in performance).

Finally, the uncertainty effects presented here might offer an effective way to investigate the often elusive higher order chromatic mechanisms. Detection and discrimination experiments give conflicting evidence. Using a texture segmentation task, Li and Lennie (1997) found some evidence for higher order chromatic mechanisms. D'Zmura and Knoblauch (1998) also found evidence for higher order chromatic mechanisms. Using a noise masking paradigm, D'Zmura and Knoblauch measured the effect of varying the spectral bandwidth of chromatic noise on the detection of a chromatic signal along diagonal directions in color space. The bandwidth of the noise had little effect on threshold suggesting chromatic signals along diagonal directions were detected by broadband higher order chromatic mechanisms that linearly summed signals from cardinal mechanisms (D'Zmura & Knoblauch). Using a noise masking detection task, Gegenfurtner and Kiper (1992) also found evidence for higher order mechanisms tuned to both chromaticity and luminance. Using noise masking and a detection task Sankeralli and Mullen (1997), Giulianini and Eskew (1998) found no evidence for higher order chromatic mechanisms. Results in support of higher order chromatic mechanisms have also been obtained using a habituation paradigm (Krauskopf & Gegenfurtner, 1992; Krauskopf, Williams, & Heeley, 1982; Krauskopf et al., 1986) and using a color matching paradigm (Webster & Mollon, 1991). Evidence from search experiments seems consistent with the existence of higher order chromatic mechanisms (D'Zmura, 1991; D'Zmura et al., 1997; Palmer et al., 1993; Bauer et al., 1996; Bauer et al., 1998; Nagy, 1999). It is possible, perhaps even likely, that different psychophysical tasks may reveal different stages of visual processing as others have suggested (Wolfe, 1994; Giulianini & Eskew). The difficulty lies in identifying the stage mediating a specific task. Previous work suggests that higher order mechanisms may be revealed more easily with suprathreshold stimuli. Suprathreshold chromatic signals might be necessary in order for these higher order mechanisms to be clearly observable since they might be less sensitive than the cardinal mechanisms.

5. Conclusions

Two general questions were posed. First, the effects of stimulus uncertainty on response time in a visual search task were investigated in experiments 1 and 2. The effect of uncertainty about the target chromaticity was tested over a large range of chromatic differences between the target and distractor colors and the results indicated that the uncertainty effects were present over the whole range of chromatic differences. Results are consistent with a capacity limited model of attention. Second, the chromatic mechanisms underlying the search process were investigated in experiments 3 and 4. In particular, a higher order chromatic mechanism model with four color-opponent mechanisms summing cardinal signals was tested against a model incorporating cardinal color opponent mechanisms and segregation under attentional control. The results suggest target chromaticities along diagonal axes were detected by at least four higher order color-opponent mechanisms roughly tuned to the diagonals.

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