Searching for variegated elements

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Visual search performance was investigated for variegated elements that differed from each other either in space-average chromaticity (identical chromatic contrast; Experiment 1) or in the chromatic contrast of the variegation (identical space-average chromaticity; Experiment 2). Specifically, search performance was measured as a function of noise contrast articulated either along the same color direction or orthogonally from the signal (target) variegation. Target-to-distractor difference thresholds were estimated in a two-alternative forced-choice task with briefly presented displays. First, when the signal and noise variegations were articulated along the same direction in color space, elements that differed from each other in space-average chromaticity were less susceptible to noise compared to elements that differed in the contrast of the variegation. Second, orthogonal noise had little effect on threshold supporting independence between the mechanisms mediating these searches. Third, the effect of the noise was similar across the different chromatic directions as well as between observers (but still differed for the two types of variegation) when differences in sensitivity between the various color directions and between observers were taken into account. This last statement only holds because the color space was normalized for each participant.

Keywords: color, visual search, variegation


Introduction

The visual system’s ability to process wavelength not only contributes aesthetically to everyday life, it also provides us with important and unique information about our environment. Color vision is believed to have evolved to facilitate foraging for fruit in foliage (Mollon, 1989; Regan et al., 2001), but wavelength discrimination provides other, perhaps more subtle, advantages. For example, absolute sensitivity to chromatic information is superior to achromatic information (Chaparro, Stromeyer, Huang, Kronauer, & Eskew, 1993). Color can help in breaking camouflaged objects (Mollon, 2000) and color information can interact with achromatic contrast to facilitate differentiating changes in the surface properties of objects from changes caused by the illuminant (Kingdom, 2003).

Despite over a hundred years of research, questions about fundamental issues in color science remain unanswered, and as a result, a comprehensive theory of color vision is missing. On a more positive note, the processing of small color differences and homogeneous chromatic stimuli presented on neutral backgrounds is relatively well understood and has resulted in several contemporary principles and theories of color vision. Unfortunately, relatively little is known about how more complex surfaces composed of multiple chromaticities are processed and these contemporary theories often are ill-suited to predict visual performance with these more complex scenes as well as in natural viewing (e.g., Shevell & Kingdom, 2008).

Most objects in the natural world are not chromatically homogeneous but vary spatially. Variegation within an object can either be caused by a non-homogeneous chromatic surface and/or by a non-uniform illuminant (or multiple illuminants). Perceptually differentiating between these two causes is critical so as to successfully segment a scene, specifically in segregating an object from its background. Not surprisingly, the visual system is sensitive to chromatic as well as achromatic variegation within a surface (e.g., D’Zmura & Knoblauch, 1998; Gegenfurtner & Kiper, 1991; Li & Lennie, 1997, 2001).

In this report, we used a visual search task to investigate search performance for variegated elements that differed from each other either in the space-average chromaticity of the variegation (identical chromatic contrast) or that differed in the chromatic contrast of the variegation (identical space-average chromaticity). Specifically, we used a noise-masking approach to compare the effectiveness of the noise to raise threshold (e.g., D’Zmura & Knoblauch, 1998; Gegenfurtner & Kiper, 1991; Hansen & Gegenfurtner, 2006; Lindsey & Brown, 2004).

Although color is an unequivocally effective guiding attribute (e.g., Wolfe & Horowitz, 2004), and a large number of visual search studies have investigated color with chromatically homogeneous search elements (e.g., Bauer, Jolicœur, & Cowan, 1996a, 1996b; Carter & Carter, 1981; D’Zmura, 1991; Nagy & Sanchez, 1990; Smith,
In this study, we established three general properties of the mechanisms mediating the processing of variegated elements: (1) search performance was much less affected by noise when elements differed from each other in the space-average chromaticity of the variegation compared to elements that differed in the chromatic contrast of the variegation; (2) the introduction of orthogonal noise affected threshold little supporting independence between the chromatic mechanisms mediating these searches; (3) search performance, in a normalized color space, was similar across chromaticities and observers (but still differed for the two types of variegation).

Methods

Apparatus and calibration

Search displays were presented on a 22” calibrated color monitor (LaCie Electron Blue IV, 1360 by 1024 pixels, 75 Hz non-interlaced) controlled by a Macintosh G3 computer with an ATI Radeon 7500 auxiliary video board (10 bits per gun). The spectral output of the three guns was measured between 400 and 750 nm (4-nm increments) at maximum gun output using a spectrophotometer (Photo Research PR-650). The output of each gun was measured over the full range (1,024 levels) using a radiometer (International Light, Model IL 1700) and stored in lookup tables. The calibration was checked regularly throughout the duration of the study and did not differ significantly.

Chromaticities were selected from an isoluminant cone-based color space (MacLeod & Boynton, 1979). The two dimensions of the color space are the two color-opponent axes. The x-axis represents the difference between L- and M-cone signals, normalized by luminance \[ l = \frac{L}{L + M} \]. The y-axis represents the difference between S-cone signals and the sum of L- and M-cone signals normalized by luminance \[ s = \frac{S}{L + M} \]. The center represents a color metameric to equal-energy white (EEW).

Procedure and stimuli

An accuracy visual search task was used in which an array of 16 search elements each composed of 64 tiles (see Figure 1a for a sample variegated search display) were presented as brief flashes (200 ms). Thresholds were estimated in a two-temporal interval forced-choice task using two interleaved 3-up/1-down staircases. In each trial, one interval selected randomly contained one target and 15 distractors and the other interval contained 16 distractors and no target. The observer’s task was to indicate whether the target appeared in interval one or two. Each staircase ran until 10 reversals occurred; only the last 8 reversals in both staircases were averaged and represented a threshold. Each condition was repeated two to three times, typically on different days (each measurement therefore was a mean of 32–48 staircase reversals).

The search elements were equal in luminance (30 cd/m²) and were presented on a uniform achromatic background \((l, s, Y): 0.666, 1.0, 15 \text{ cd/m}^2\)). Every block of trials began with a 2-min adaptation period to the achromatic uniform background. Each search element consisted of 64 tiles that were assigned one of 8 chromaticities (each chromaticity was therefore represented by 8 small tiles in each element, Figure 1b). The eight chromaticities were selected from a uniform distribution in color space (equal-spaced intervals) from a vector of particular direction and length.

In Experiment 1, the variegated target and distractors differed from each other in space-average chromaticity (identical contrast) and were therefore defined by vectors equal in length but shifted away from equal-energy white toward either the +l, −l, +s, or −s direction. The distractor variegation was always centered at white and the distractor vector direction matched that of the target (e.g., a +l-target vector with an l-distractor vector or a −s-target with s-distractor vector). Thresholds were estimated by adjusting in the staircases the mean target vector holding contrast constant. Figure 2a shows vectors in color space defining the variegation of a target and distractors that differ from each other in space-average chromaticity. That is, the target and distractor vectors were of equal length (equal contrast) and the target vector was shifted toward higher \(L/(L + M)\) chromaticity resulting in elements that appeared roughly red–green and a target that was redder than the distractors.

In Experiment 2, the variegated target and distractors differed in the contrast of the variegation (identical space-average chromaticity) and were therefore defined by vectors that were different in length (the target vector was always larger than the distractor vector) but centered at white (Figure 2b). As in Experiment 1, the target and distractor vectors’ direction matched. Thresholds were estimated by adjusting in the staircases the contrast of the target.

Figure 2b shows a condition with target and distractor vectors that were equal in space-average chromaticity and a target vector that was larger than the distractor vector (higher contrast). This particular condition resulted in elements that appeared roughly red–green and a target that was more saturated than the distractors. The spatial assignment of the chromaticities within each search element was randomly determined so that spatial structure could not be used to discriminate the target. In some conditions, orthogonal noise was added to both the target and distractor elements (gray vectors in Figures 2a and 2b). Orthogonal noise was articulated in half of the tiles (32) while the other 32 tiles carried the signal variegation.
Since orthogonal noise was identical for both the target and distractors, it provided no information about the target identity and could therefore only impair search performance. Two levels of orthogonal noise contrast were tested.

Each stimulus element measured 0.95 by 0.95 degree of visual angle representing a spatial frequency of approximately 4.2 cycles/degree. The 16 search elements were spatially presented on a 4 by 4 grid that measured 5.7 by 5.7 degrees. Each element was randomly jittered by

Figure 1. (a) A typical search display was composed of 16 variegated elements. The target (second row, third column) in this case differs from the distractors in space-average chromaticity (redder overall). (b) Each variegated element was composed of 64 tiles. In the “Noise” condition, all 64 tiles were assigned one of 8 chromaticities selected from a uniform chromatic distribution. “Control” elements were composed of 32 tiles articulating the variegation and the other 32 tiles were set to gray. “Orthogonal noise” elements consisted of 32 signal tiles (signal variegation) and 32 orthogonal noise tiles (noise variegation). The noise was applied to both the target and distractor elements and therefore conveyed no information regarding the identity of the target. Within a search display, the spatial composition of the variegation was determined randomly for each element.

Figure 2. Search elements differed from each other either in (a) the space-average chromaticity or (b) in the chromatic contrast of the variegation. Variegation was expressed by selecting chromaticities from vectors in color space. Eight chromaticities were selected from vector defining a uniform distribution. These eight chromaticities were applied to either 64 tiles (noise) or 32 tiles (“Control” and “Orthogonal noise” conditions). Orthogonal noise (gray vectors) was used to test mechanism independence.
±0.4 degree resulting in a minimum and maximum element spacing of 0.23 and 1.03 degrees, respectively.

Normalization of the color space

The units of the axes of the color space used to select chromaticities are arbitrary and the color space is not a uniform color appearance space. Additionally, because of individual differences in spectral sensitivity and visual search performance, the color space was normalized for each observer. The normalization procedure went as follows. Thresholds were measured for chromatically uniform homogeneous target and distractor elements (non-variegated), with the distractors set at gray (EEW; \( l, s, Y \): 0.666, 1.0, 30 cd/m\(^2\)). In separate blocks of trials using the same adaptive two-alternative forced-choice procedure, thresholds were estimated for the discrimination of a target with a chromaticity in the \(+l\) (reddish), \(-l\) (greenish), \(+s\) (bluish), and \(-s\) (yellowish) directions. Although small asymmetries were observed along opposite chromatic poles, the \(+l\) and \(-l\) and \(+s\) and \(-s\) normalizing thresholds were averaged so that the space-average chromaticity of the distractors was set at equal-energy white. This normalizing procedure is time-consuming but important as individual differences can make the measurements difficult to compare (e.g., Monnier, 2010).

Observers

A total of six observers participated in the study (three different ones in each experiment). All had normal or corrected acuity (20/20) and had normal color vision (Ishihara plates). Observers completed extensive practice sessions (approximately 10 h) before data collection was initiated. Observers gave written consent and the research was approved by an Institutional Review Board at Colorado State University.

Results

Experiment 1: Space-average chromaticity-defined variegation

In this experiment, a target, when present, differed from the distractors in space-average chromaticity of the variegation. Target and distractor variegation was articulated along four chromatic directions (+\(l\) (reddish), \(-l\) (greenish), +\(s\) (bluish), \(-s\) (yellowish)). The distractor variegation was always centered at the origin of the color space and articulated in the same chromatic direction as the target vector (Figure 2a). Thresholds were estimated at four different levels of variegation noise contrast to determine the effectiveness of the noise to raise threshold.

Figure 3 shows squared threshold contrast as a function of squared noise contrast for elements that differed from each other in space-average chromaticity of the variegation. Each panel is for a different observer. As expected, threshold rose with noise contrast. Squared threshold contrast has been shown to rise approximately linearly with the square of noise contrast for achromatic patterns (Legge, Kersten, & Burgess, 1987) as well as for chromatic patterns (e.g., D’Zmura & Knoblauch, 1998; Gegenfurtner & Kiper, 1991; Hansen & Gegenfurtner, 2006; Lindsey & Brown, 2004). Legge et al. (1987) and...
Pelli (1981) show that such relationship can be captured by a linear function relating squared threshold contrast and squared noise contrast with the intercept and slope of the function capturing the intrinsic noise of the underlying mechanism and the effect of external noise, respectively. Since the slope of the function represents the effectiveness of the noise to raise threshold, it can be used to infer the efficiency of the mechanism to process, in this case, multiple variegated elements. Lines in Figure 3 are such fits with the slopes ($k$) for each function indicated in the figure. Although thresholds for variegated elements that were articulated along the $S/(L + M)$ direction were elevated compared to $L/(L + M)$ direction, the slopes of the functions were similarly shallow (mean slope: 0.0338) for the various conditions and across observers.

To test independence between the chromatic mechanisms mediating the searches for these variegated elements, measurements along the $l$ and $s$ directions were repeated at two levels of noise contrast (approximately $4\times$ and $16\times$ normalized threshold) with orthogonal noise added to both target and distractor elements. Since identical orthogonal noise was added to both the target and distractors, it provided no information about the target and could only impair search performance. Four levels of orthogonal noise contrast were tested ($0\times$, $4\times$, $8\times$, and $22\times$ normalized threshold). A noise vector of zero represents a control condition in which half of the small tiles (32) within each target and distractor element were set to gray (Figure 1, middle column) and the other half were used to articulate the target and distractor chromaticities.

![Figure 4](image.png)

Figure 4. Squared threshold contrast is plotted as a function of orthogonal squared noise contrast for targets that differed from the distractors along the $+l$ (reddish) and $+s$ (bluish) directions. Two levels of noise contrast were tested (labeled “low” and “high”). Each plot is for a different participant. Error bars are standard errors of the mean.

### Experiment 2: Contrast-defined variegation

In this experiment, a target, when present, differed from the distractors in the chromatic contrast of the variegation, with an identical space-average chromaticity (Figure 2b). Specifically, the target’s variegation contrast was higher than that of the distractors, and to estimate thresholds, staircases adjusted the contrast of the target vector, holding the space-average constant. Threshold was measured for variegations articulated along the $L/(L + M)$ and $S/(L + M)$ directions.

Figure 5 shows squared threshold contrast as a function of squared noise contrast. $S/(L + M)$ thresholds were again elevated compared to $L/(L + M)$ thresholds, and as observed with variegated elements that differed from each other in space average, thresholds rose with noise contrast. The effectiveness of the noise to mask threshold in this experiment was much higher as represented by much steeper slopes ($k$; average mean slope: 1.4452 vs. 0.0338 for space-average chromaticity-defined variegation). The slopes were similar for both target chromaticities and for the three observers.
Independence tests were again performed by adding orthogonal chromatic noise to both target and distractor elements (Figure 2b). Since orthogonal noise was identical in both target and distractor elements, it could only impair performance. Figure 6 shows squared threshold contrasts as a function of orthogonal squared noise contrast for two observers who participated in this experiment. Unsurprisingly, thresholds for the higher noise contrast (open symbols; \(0.5 \times \text{normalized threshold}\)) were elevated compared to the lower noise contrast condition (solid symbols; \(0.5 \times \text{normalized threshold}\)). Again, orthogonal noise had little influence on thresholds resulting in relatively flat functions.

**Discussion**

In this report, we measured visual search performance for variegated elements that differed from each other
either in the space-average chromaticity, keeping contrast constant (Experiment 1) or for elements that differed from each other in the contrast of the variegation, holding space average constant. Additional measurements tested the independence of the chromatic mechanisms mediating these searches.

The measurements suggested the following: (1) search performance was much less affected by noise for elements that differed from each other in the space average of the variegation compared to performance for elements that differed in the contrast of the variegation. (2) For both types of variegated elements, the addition of orthogonal noise had little effect on thresholds supporting independence between the mechanisms mediating the search for these variegated elements. This is consistent with literature on chromatic discrimination/detection (e.g., Krauskopf, Williams, & Heeley, 1982), texture segmentation (e.g., D’Zmura & Knoblauch, 1998; Gegenfurtner & Kiper, 1991; Hansen & Gegenfurtner, 2006; Lindsey & Brown, 2004), and visual search (e.g., D’Zmura, 1991; Nagy & Thomas, 2003).

The importance of a normalized color space

We previously noted the importance of normalizing the color space when attempting to make comparisons both across conditions and between individuals in visual search tasks (Monnier, 2010). The normalization is time-consuming but important for several reasons. First, there is no color space, including the one used in the present report, that adequately captures visual search performance or color appearance. Second, individual differences in sensitivity can contribute to differences in performance and hence mask general trends.

The obtained measurements reflect such differences across chromatic directions and observers (Figures 3–6). In general and unsurprisingly, sensitivity was higher along

![Figure 7](https://example.com/figure7.jpg)

Figure 7. Measurements from Figures 3 (top row) and 5 (bottom row) are replotted in normalized units.
the L/(L + M) compared to the S/(L + M) direction. Figure 7 replots measurements from Figures 3 and 5 in normalized units. That is, the units were scaled by the normalizing thresholds obtained with homogeneous search elements (see Normalization of the color space section). Clearly, many differences in sensitivity caused either by arbitrary units of the color space or by individual differences have been eliminated.

**Space-average-defined vs. contrast-defined variegation**

The two types of variegation tested in the present report likely invoke different neural mechanisms as the two types of stimuli require different processing strategies. The optimal strategy for space-average differences is to integrate over the surface of an element while such a strategy will fail with elements that differ in the chromatic contrast of the variegation as space average in these elements is identical. Contrast-defined variegation differences require sensitivity to the chromatic distribution per se. Elements that differed in the chromatic contrast of the variegation were much more susceptible to noise compared to elements defined by the space-average chromaticity of the variegation. This difference suggests that space-average differences in the variegation of elements were processed more efficiently than differences in the contrast of the variegation for these particular stimuli.

Differences in the susceptibility of noise for the two types of stimuli are likely to be influenced by the following factors. First, the spatial frequency of the variegation is likely to play a role. High spatial frequency will favor the processing of space-average variegation since at the limit spatial integration of the chromatic signal will be done by the optics of the eye and not by neural mechanisms of the visual system. Second, search elements were presented as luminance increments on a uniform gray background. Luminance contrast could have been used to delineate the area of integration, which likely favored the processing of the space-average elements. An interesting condition would be one in which this luminance contrast between the search elements and the background is eliminated.

Last, the relative efficiency of processing the two types of stimuli also is likely to be influenced by the type of stimuli used in the normalizing procedure. In this study, performance was normalized using chromatically homogeneous search elements, which once again might have favored search performance with space-average-defined elements. Search performance could have been normalized using variegated elements. For example, chromatic threshold contrast for detecting the variegation in the target presented with spatially homogeneous element could have been used. While this choice makes sense as the overall goal was to assess visual search performance with variegated elements, it is likely that these stimuli also would have favored performance with space-average stimuli. Varying the spatial frequency of the variegation will establish whether susceptibility to noise will change with the spatial frequency for the two types of stimuli, work that we plan to pursue in the future. Last, we assumed that normalizing thresholds scaled linearly with the contrast of the variegation. Given the large chromatic contrast that had to be produced to estimate thresholds, this assumption might be invalid. Future work will also have to test this assumption by estimating the saliency of the variegation directly (e.g., Nothdurft, 1993).

**Future research**

The present measurements demonstrate clearly that individuals are able to search through variegated elements and find a target that differs from distractors either in space-average chromaticity or in the contrast of the variegation. This novel visual search task using variegated elements proved to be a viable paradigm to investigate the processing of large color differences. The main advantage of the paradigm is that it borrows well-established experimental methods that make clear and testable predictions. Additionally, the paradigm allows for questions related to how attention might interact with color vision.

Future work will have to explore several issues that were not addressed in the present study. For example, the role of the spatial frequency of the variegation will need to be investigated as it is likely to affect search performance differently. Additionally, it remains to be determined how effectively visual attention can be guided by variegation. Obvious manipulations will be to vary set size (total number of elements presented simultaneously), as well chromatic manipulations (e.g., intermediate or diagonal directions in color space) to probe specifically the number and properties of the chromatic mechanisms mediating this task. In addition, “top-down” manipulations such as introducing uncertainty with respect to the chromatic composition of the target will help determine how well visual attention can be guided by elements that are variegated.

Last, variegated stimuli offer a unique opportunity to dissociate color and object processing. Most visual search studies have used chromatically homogeneous search elements and therefore questions such as how color is processed within an object cannot be addressed. Future research will explore such a question; specifically, we will attempt to replicate classic findings in the literature to determine whether established principles in color hold with variegated elements (e.g., the linear separability effect; Bauer et al., 1996a, 1996b; D’Zmura, 1991; noise-masking manipulations to identify the number and
properties of the chromatic mechanisms mediating the task; e.g., D’Zmura & Knoblauch, 1998; Gegenfurtner & Kiper, 1991; Hansen & Gegenfurtner, 2006; Lindsey & Brown, 2004).

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