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TEXTURE SEGREGATION IN CHROMATIC ELEMENT-ARRANGEMENT PATTERNS

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Abstract

We compare the perceived segregation of element-arrangement patterns, which are composed of two types of squares arranged in vertical stripes in the top and bottom regions and in a checkerboard in the middle region. The squares in a pattern are either equal in luminance and differing in hue or equal in hue and differing in luminance. Perceived segregation of squares differing in hue is not predicted by their rated similarity, but rather by the square-root of the sum of the squares of the differences in the outputs of the L-M and L+M-S opponent channels. Adaptation to the background luminance affects judgments of perceived segregation but does not affect judgments of perceived similarity. For a given background luminance, perceived segregation is a linear function of cone contrasts. Perceived hue similarity is instead a linear function of cone excitations across the background luminances. High and low luminance backgrounds decrease the perceived segregation of patterns differing in luminance. A high luminance achromatic background decreases the perceived segregation of patterns differing in hue but a low luminance achromatic background does not. The results indicate that the adaptation luminance affects the contribution of luminance differences between the two types of squares to perceived segregation but not the contribution of hue differences. For element-arrangement patterns composed of squares of equal luminance that differ in hue, perceived segregation is associated with differences in the perceived brightness of the hues. The results are consistent with the findings that the perceived segregation in element-arrangement patterns is primarily a function of the early visual mechanisms that encode pattern differences prior to the specification of the forms of the squares and their properties.

Key words: Texture segregation, Spatial-frequency channels, filtering, grouping, chromatic cortical mechanisms

Running head: Texture segregation in chromatic patterns
INTRODUCTION

An element-arrangement pattern is composed of two types of elements arranged in alternating vertical stripes in the top and bottom regions and in a checkerboard pattern in the middle region (Figure 1). Perceived segregation of an element-arrangement pattern is defined as the immediate perception of three regions. Texture segregation may be mediated either by a contour-detection system, which responds preferentially to the pattern of stimulation at the abutting edge of two texture regions, or by preattentive grouping processes, which lump coherent texture patterns into regions. The contour system thus segregates regions by means of boundaries, even though the features composing the regions may be similar and might not by themselves cause the regions to segregate (Beck, 1983). Preattentive grouping processes, on the other hand, segregate regions because similar features are grouped into uniform regions of texture; where elements with dissimilar features are juxtaposed, texture boundaries result. The present experiments are part of a programatic investigation of how the variables of luminance, brightness, hue, and saturation affect the contour system and preattentive grouping processes in producing texture segregation in chromatic patterns. Specifically, they are designed to discover to what extent mechanisms that control texture segregation for achromatic patterns also operate for chromatic patterns, and to what extent additional mechanisms are implicated. We report experiments on the perceived segregation of element arrangement patterns composed of squares that are either equal in luminance and differing in hue or equal in hue and differing in luminance. A brief review of past research is presented to provide context for the experiments reported.

Achromatic Element-Arrangement Patterns

Research with achromatic element-arrangement patterns indicates that the information for texture segregation takes place at a level of representation preceding the specification of individual squares and their perceptual qualities. First, texture segregation in element-arrangement patterns is not a direct function of the lightness differences of the squares (Beck, Graham, & Sutter, 1991). Perceived segregation is strong even with a small lightness difference between the squares when the luminances of the squares are close to the background luminance. On the other hand, perceived segregation is weak or fails to occur even with a large lightness difference between the squares when the luminances of the squares are far from the background luminance. Second, texture segregation is not impaired by contour misalignment (spatial phase). Judgments of perceived segregation are the same when the elements composing an element-arrangement pattern were aligned squares, misaligned squares, circles or blobs (Beck, 1993). Third, texture segregation in an element-arrangement pattern fails to scale. Proportionally reducing the overall size of a pattern increases perceived segregation up to the point where the fundamental spatial-frequency of a pattern is at
Figure 1: An illustration of an element-arrangement pattern. The squares in a pattern were either equal in luminance and differed in hue or equal in hue and differed in luminance.

the peak of the contrast sensitivity function – approximately 4 cycles per degree. Patterns with higher or lower spatial frequencies are perceived to segregate less strongly (Sutter, Beck, & Graham, 1989).

A prevalent view is that much of texture segregation can be explained by differences in the spatial-frequency content of texture regions (Bergen & Landy, 1991; Graham, Beck, & Sutter, 1992; Malik & Perona, 1990; Nothdurft, 1990; Sutter et al., 1989). For achromatic element-arrangement patterns, Sutter et al. (1989) showed that texture segregation is primarily mediated by the outputs of the large receptive fields that are sensitive to the fundamental spatial-frequency of a texture pattern (the distance between two columns of the same type of squares). These receptive fields match the period of the pattern and signal the differences in the overall pattern of luminance in the striped and checkerboard regions. In the striped region changes of overall luminance occur in the horizontal direction, strongly stimulating vertically oriented receptive fields and in the checkerboard region changes of overall luminance occur in a direction 45 degrees from horizontal strongly stimulating obliquely oriented receptive fields (see Figure 2). Sutter et al. (1989) proposed that the differences in the outputs of these receptive fields are used by the visual system to establish boundaries separating the regions of the pattern.
Figure 2: An illustration of how responses of cells with oriented receptive fields may account for element-arrangement segregation. *Top:* excitatory and inhibitory lobes of an even symmetric operator. *Bottom left:* large vertical receptive fields respond strongly to the vertical columns of squares in the striped region. *Bottom right:* large oblique receptive fields respond strongly to the diagonal columns of squares in the checkerboard region. (Adapted from Pessoa et al., 1996, with permission.)

The large receptive fields that are primarily responsible for perceived segregation do not have the right properties to signal the lightness of the squares, because they average lightness over several squares. Thus perceived segregation would not be expected to be a simple function of the lightness differences of the squares. Similarly, large receptive fields would also not be expected to be sensitive to edge alignment. Perceived segregation would therefore not be impaired by the misalignment of the squares. Perceived segregation would also not be expected to scale, since perceived segregation is a function of the visual system's sensitivity to the fundamental spatial frequency. Proportionally reducing the overall size of a pattern would increase perceived segregation up to the point where the fundamental spatial-frequency of a pattern is at the peak of the contrast sensitivity function.

The data of Sutter et al. (1989) also indicate that the perceived segregation in an element-arrangement pattern is minimal when the area × contrast of large and small squares were equal. The area × contrast of the large and small squares is the same when the greater area of the large square is compensated for by the higher contrast of the small square. Squares that have the same area × contrast produce the same output at the fundamental frequency of the pattern, i.e., the frequency which the excitatory
region of a receptive field falls on one column of squares (e.g., the high luminance ones), the inhibitory region of the receptive field falls on the adjacent column of (low luminance) squares. Although the contrast ratio — the ratio of the contrasts of the two square types with the background — at which the minimum perceived segregation occurs is correctly predicted by the outputs of simple cell-like mechanisms, the amount of segregation at this minimum is incorrectly predicted. The amount of perceived segregation depends also on the difference in the sizes of the squares. When the area contrast of the large and small squares is equated, perceived segregation is greater as the size difference between the large and small squares increased. One way of accounting for this discrepancy is by a more complicated spatial frequency model in which the initial linear filtering is followed by a rectification and a second filtering at a lower spatial frequency (Sutter et al., 1989).

Graham et al. (1992) showed that texture segregation in element-arrangement patterns can not be explained in terms of solely linear operations, and the application of spatial frequency analysis to texture segregation involves at least two nonlinearities. One nonlinearity is an intensity dependent nonlinearity which can be accounted for by either sensory adaptation occurring before the channels or by a compressive intracortical interaction among neuronal responses which normalizes the responses (Graham, 1994; Grossberg & Mingolla, 1985). The second nonlinearity is a rectification-like nonlinearity that is like that presumed to occur in complex cells (Graham, 1994; Grossberg & Mingolla, 1985; Prazdny, 1983; Shapley & Gordon, 1985; Spitzer & Hochstein, 1985).

Chromatic Element-Arrangement Patterns

Beck (1994) and Pessoa, Beck, and Mingolla (1996) investigated the perceived segregation of equal-luminance element-arrangement patterns composed of squares differing in hue. The perceived segregation of chromatic element-arrangement patterns differing in the hues of the squares differed in two important respects from the perceived segregation of achromatic element-arrangement patterns differing in the luminances of the squares. For element-arrangement patterns composed of squares differing in luminance, perceived segregation was greatest when the background luminance was between the luminances of the squares. When the squares composing an element-arrangement pattern differed in their sign of contrast, perceived segregation was strong and decreased only when the background luminance was very close to the luminances of the squares (Beck, Sutter, & Ivry, 1987). Perceived segregation decreased as the background luminance was raised above the luminance of the higher luminance square or lowered below the luminance of the lower luminance square.²

Element-arrangement patterns composed of squares differing in hue differed in both respects. First, the effect of background luminance is asymmetric. Unlike with achromatic element-arrangement patterns, perceived segregation was strong with low luminance backgrounds. A high luminance background decreases perceived segregation
but a low luminance background does not decrease perceived segregation. Second, perceived segregation was also not greatest when the luminance of the background was between the luminances of the squares. Perceived segregation was a negatively decreasing function of the background luminance. It is important to note that the squares composing an element-arrangement pattern do not have to be of equal luminance for perceived segregation to be diminished by a high intensity background. Pessoa et al. (1996) found that perceived segregation tended to decrease with increasing luminance of the interspaces when the squares composing an element-arrangement pattern were not of equal luminance. Perceived segregation varied approximately inversely with the ratio of the background luminance to the higher luminance square. Pessoa et al. (1996) also found that perceived segregation was approximately constant for constant ratios of interspace luminance to square luminance. Stereoscopic cues that caused the squares composing the element-arrangement pattern to be seen in front of the interspaces did not appreciably improve perceived segregation with high luminance interspaces. As in the case of achromatic element-arrangement patterns, these results suggest that the explanation of the perceived segregation of chromatic element-arrangement patterns should be in terms of early visual processes, such as mechanisms sensitive to cone contrasts.

EXPERIMENTS

Four experiments investigate the perceived segregation of element-arrangement patterns differing in hue. Experiments 1 and 2 show that perceived segregation of chromatic element-arrangement patterns is not a function of hue similarity, but rather of cone contrasts and the outputs of the opponent processes. Experiment 3 compared the perceived segregation for element-arrangement patterns differing in luminance with the perceived segregation of element-arrangement patterns differing in hue. As mentioned above, the perceived segregation of element-arrangement patterns differing in luminance is decreased by both a high and low luminance backgrounds. In contrast, the perceived segregation of element-arrangement patterns differing in hue is decreased by a high luminance background but not by a low luminance background. The experiment suggests that adaptation to the background luminance does not affect hue discrimination. Experiment 4 examined perceived segregation in element-arrangement patterns composed of equal luminance purple and gray squares of increasing luminance. The results suggest that perceived segregation was associated with differences in the perceived brightness of the hues.

Experiment 1

Experiment 1 was designed to investigate how the perceived segregation of chromatic element-arrangement patterns depends on hue similarity.
Stimuli

The stimuli were presented on the CRT screen of a Silicon Graphics workstation. An element-arrangement pattern was composed of 15 rows and 15 columns of equal-size squares. In the top and bottom 5 rows, the two types of squares composing a pattern were arranged to form alternating columns. In the center 5 rows the types of squares were arranged in a checkerboard pattern. A head rest was used at a viewing distance of .57 meters. The squares were 10 pixels (.29 deg) on a side. The horizontal and vertical interspaces were 7 pixels (.20 deg). The patterns' fundamental frequency was 1 cycle per degree. The overall patterns subtended 7.1 deg.

Each pattern was composed of a red square (x=.607, y=.340) and of a second square that differed in hue. The other hues varied in their similarity to red and were red-orange (RO) (x=.556, y=.377), orange (O) (x=.504, y=.413), yellow (Y) (x=.454, y=.451), green (G) (x=.293, y=.569), blue-purple (BP) (x=.242, y=.118), and purple (P) (x=.321, y=.166). The luminances of the squares were 5 ft.-L. The backgrounds were achromatic (x=.300, y=.320) with luminances of .1, 2.5, 10.0, and 20.0 ft.-L.

Procedure

Seven subjects rated the perceived segregation of the patterns and the similarities of the hues on a scale from 0 to 4 in separate sessions. A subject was presented with 6 blocks of trials. The first block of trials served as a practice block and was discarded. Individual subject means were based on five ratings of each stimulus. A block of trials consisted of one presentation of each of the 24 stimulus patterns (6 hue pairs × 4 background luminances) in a random order. A subject initiated a trial by pressing the space bar. A trial consisted of a fixation “X” presented for 1 second in the center of a blank screen, whose luminance was the luminance of the background in the upcoming trial. This was followed immediately by a stimulus display presented for 1 second. At the offset of a stimulus, a slider was presented on a background of the same luminance as the immediately preceding trial.

A subject rated perceived segregation by using a mouse to move a slider in a rectangle. As a subject moved the slider from the left to the right edge of the rectangle, the numbers from 0 to 4 appeared below the slider in .1 increments. A subject’s rating was recorded by hitting the space bar. The subjects were instructed to report their immediate impression of segregation and told that a rating of 0 meant that there was no segregation between the two regions. A rating of 4 meant that the two regions were very distinct and segregation was “immediate”. The intermediate ratings indicated intermediate perceptions of segregation from “barely perceptible” to “weak” to “moderate”. In a separate session subjects used the slider to rate the similarity of the hues. A rating of 0 meant that the two squares were very dissimilar. A rating of 4 meant the two squares were very similar. The subject was presented with the
same 6 blocks of trials as in the segregation ratings. The stimuli in this experiment were presented for 4 seconds instead of 1 second. The subjects were only presented the checkerboard section (the middle section) of the element-arrangement pattern. This was done to prevent the subjects’ similarity ratings from being influenced by the segregation of the pattern. The similarity ratings were always made after the segregation ratings.

**Subjects**

Seven subjects served in the experiment. Three of the subjects were the authors. Four of the subjects were graduate students who were naive about the purpose of the experiment. All had normal or corrected to normal vision.

**Results and Discussion**

![Graph](image)

Figure 3: Mean segregation ratings plotted as a function of mean similarity ratings in Experiment 1. The hues of the squares were red and green (G), red and yellow (Y), red and blue-purple (BP), red and orange (O), red and purple (P), and red and red-orange (RO).

Figure 3 plots the mean of subjects’ mean rated segregation as a function of the mean of subjects’ mean rated similarity. Background luminance \( F(3, 18) = 24.02, p < .01 \) and hues of the squares \( F(5, 30) = 77.22, p < .01 \) significantly affected perceived segregation. The interaction of the background luminance and the hues of the squares
was also significant \( F(15, 90) = 6.23, p < .01 \). The interaction reflects the greater effect of background luminance on the perceived segregation of dissimilar hues than of similar hues.

Two questions need to be considered. First, how does perceived segregation vary as a function of the hues of the squares? As would be expected there is an overall inverse relationship between perceived similarity and perceived segregation. Perceived segregation, however, is not a simple function of hue similarity. Perceived segregation, as in earlier experiments, varied inversely with the luminance of the background (Beck, 1994; Pessoa et al., 1996). Figure 6, however, shows that the judgments of hue similarity were very similar for the different luminance backgrounds. Also, the blue-purple and yellow hues were judged equally similar to the red hue, but the red and blue-purple element-arrangement patterns segregated more strongly than the red and yellow element-arrangement patterns. Similarly, the purple and orange hues were judged equally similar to the red hue, but the red and purple element-arrangement patterns segregated more strongly than the red and orange element-arrangement patterns. Tukey tests of the differences in perceived segregation of the red and yellow and red and blue-purple element-arrangement patterns for the black, dark gray, and white backgrounds were significant \( (p < .05) \). Tukey tests of the differences in perceived segregation of the red and purple and red and orange element-arrangement patterns for the black, and dark gray backgrounds were significant \( (p < .05) \). Perceived segregation is not a function only of the judged similarity of the hues.

Perceived segregation of the different hue pairs can not be a function of the differences in cone responses, since perceived segregation is greatly affected by the background luminances. The cone responses are the same for the different background luminances. The decrease in perceived segregation with increasing background luminance suggests that the relevant variable is cone contrast. Increasing the luminance of the background would decrease the difference between the cone contrasts of the two hues in an element-arrangement pattern. We examined whether perceived segregation of the different hue pairs can be explained by cone contrasts. The long (L-cone), middle (M-cone), and short-wavelength (S-cone) responses were estimated from the measured luminances and chromaticity coordinates of the hues (Cole & Hine, 1992). For the L-cone, the cone contrast is:

\[
L_c = (L_s - L_b)/L_b. \tag{1}
\]

The L-cone contrast \( (L_c) \) is the difference between the L-cone responses to the squares \( (L_s) \) and to the background \( (L_b) \) divided by the L-cone response to the background \( (L_b) \). Cone contrasts for the M and S-cones are calculated analogously.

We explored a number of equations and found that perceived segregation of the hue pairs is predicted best by the square-root of the sum of the squares of the differences
in the outputs of the L-M opponent channel and of the L+M-S opponent channel.

\[
\sqrt{[(L_{cr} - M_{cr}) - (L_{cw} - M_{cw})]^2 + [(L_{cr} + M_{cr} - kS_{cr}) - (L_{cw} + M_{cw} - kS_{cw})]^2}
\]

(2)

\(L_{cr}, M_{cr}, \text{ and } S_{cr}\) are the cone contrasts of the L, M, and S-cones to the red hue. \(L_{cw}, M_{cw}, \text{ and } S_{cw}\) are the cone contrasts for L, M, and S-cones to the variable second hue. The first term in the equation squares the difference in the outputs of the L-M opponent channel of the two hues. The second term is an analogous calculation for the L+M-S opponent channel. The S-cone is usually weighted less than the L and M-cones in modeling pattern vision (Tansley & Boynton, 1978). We examined values of \(k\) from 0.1 to 1 and found that a value of \(k = 0.25\) gave the best fit to our data.

![Graph showing mean and predicted segregation ratings as a function of the background luminance and the hues of the squares for \(k = 0.25\) in Experiment 1. The backgrounds were black (.1 ft.-L.), dark gray (2.5 ft.-L.), light gray (10 ft.-L.), and white (20 ft.-L.). The hues of the squares were red and green (G), red and yellow (Y), red and blue-purple (BP), red and orange (O), red and purple (P), and red and red-orange (RO). A value of \(k = 0.25\) produced the best fit to the data in Experiment 1 (see text).]

Light adaptation affects chromatic discriminability in complex ways which Equations 1 and 2 do not take into account (Kaiser & Boynton, 1996). We, therefore,
Figure 5: Mean and predicted segregation ratings as a function of the background luminance and the hues of the squares for \( k = .13 \) in Experiment 1. The backgrounds were black (.1 ft.-L.), dark gray (2.5 ft.-L.), light gray (10.0 ft.-L.), and white (20.0 ft.-L.). The hues of the squares were red and green (G), red and yellow (Y), red and blue-purple (BP), red and orange (O), red and purple (P), and red and red-orange (RO). A value of \( k = .13 \) produced the best fit to the data in both Experiments 1 and 2 (see text).

correlated the predicted segregation values from Equation 2 with the mean rated segregation values separately for each of the backgrounds. The proportion of the variance accounted for by linear correlation \((r^2)\) is .89, .94, .88, and .96 for the black, dark gray, light gray, and white backgrounds respectively. Linear transformations were applied to bring the predicted segregations into the same range as our rated segregations. Figure 4 shows the mean and predicted segregation ratings for the four backgrounds for \( k = .25 \). A value of \( k = .13 \) gave the best fits to the data in both Experiments 1 and 2. For a value of \( k = .13 \), the \( r^2 \) values are .71, .74, .89, and .78 for the black, dark gray, light gray, and white backgrounds respectively. Figure 5 shows the mean and predicted segregation ratings for the four background luminances for \( K = .13 \). It is of interest to note that the square-root of the sum of the squares of the differences in the L-, M-,
and S- cone contrasts fails to account for the perceived segregation. The proportion of the variance accounted for by linear correlation is .40, .41, .26, and .46 for the black, dark gray, light gray, and white backgrounds respectively. Changing the weights of the S-cone difference did not strikingly alter the proportion of the variance accounted for. It should also be noted that the predicted segregation of the purple and blue-purple element-arrangement patterns tended to underestimate the perceived segregation (see Figures 4 and 5). A possible explanation is the greater perceived brightness of the purple and blue-purple hue. Purple and blue-purple hues generally tend to be seen as brighter than other equiluminant hues. We investigate this possibility in Experiment 4.

Second, why does perceived segregation decrease with increased background luminance? The decrease in perceived segregation is qualitatively in accord with the differences in cone contrast. The differences in the L-, M-, and S- cone contrasts of the two hues in an element-arrangement pattern decrease as the background luminance increases. However, Equation 2 fails to quantitatively describe the decrease in perceived segregation with increased background luminance. The proportion of the variance accounted for by linear correlation of the predicted segregations from Equation 2 with the mean segregation judgments for the 24 stimuli across the four background luminances was .26 for \( k = .25 \) and .23 for \( k = .13 \). The correlation can be improved by taking into account that the .17 ft.-L background luminance probably does not fall within the range in which Weber’s law holds. A constant is often added to the denominator of the Weber fraction to account for the detection of luminance increments at low luminance levels (Helmholtz, 1962). The correlation between the mean rated segregations and the predictions from Equation 2 is improved by adding a constant of .4 to the denominator in calculating the cone contrasts for the .17 luminance background. The proportion of variance accounted for by a linear correlation between the predicted and mean segregation ratings is .53 for a \( k = .25 \) and .47 for a \( k = .13 \).

The mean similarity ratings of the hues are shown in Figure 6. (The spacing on the x-axis is arbitrary.) As expected, the hues of the squares significantly affected the judgments of perceived similarity \([F(5, 30) = 107.58, p < .01]\). As mentioned earlier, the similarity ratings of the hues were not affected by the background luminance and were similar \([F(3, 18) = .25, p > .85]\). We examined whether perceived similarity is predicted by the square-root of the differences in the outputs of the L-M and the L+M-S opponent channels. The relevant variable for predicting hue similarities from Equation 2 is the cone response and not the cone contrast, since the background luminance did not affect the judgments of hue similarity. For the hues in the experiment, the S-cone response is very small and the predictions did not vary appreciably with the value of \( k \). Small calculated values in Equation 2 represent high hue similarity, while large calculated values represent low hue similarity. The \( r^2 \) value of the predicted similarity and the judged similarity ratings is .94 for the 24 stimuli across the four background luminances.
Figure 6: Mean similarity ratings as a function of background luminance and the hues of the squares in Experiment 1. The hues of the squares were red and green (G), red and yellow (Y), red and blue-purple (BP), red and orange (O), red and purple (P), and red and red-orange (RO).

luminances. Linear transformations were used to bring the predicted similarities into the same range as the rated similarities. Figure 7 shows the mean similarity ratings and the predicted similarities for the four background luminances for $k = .13$. The results indicate that perceived segregation is a function of cone contrasts whereas hue similarity is a function of cone responses.

**Experiment 2**

Experiment 2 also investigated how hue similarity affects the perceived segregation of chromatic element-arrangement patterns. Blue was not included in the hues presented in Experiment 1 because a luminance of 5 ft.-L. could not be achieved with blue. In Experiment 2 one set of squares in a pattern was always blue. The hue of the second set of squares varied in their similarity to blue.
Figure 7: Mean and predicted similarity ratings as a function of the background luminance and the hues of the squares for $k = .13$ in Experiment 1. The backgrounds were black (.1 ft.-L.), dark gray (2.5 ft.-L.), light gray (10.0 ft.-L.), and white (20.0 ft.-L.). The hues of the squares were red and green (G), red and yellow (Y), red and blue-purple (BP), red and orange (O), red and purple (P), and red and red-orange (RO) (see text).

**Stimuli and Procedure**

The stimuli were presented on the CRT screen of a Silicon Graphics workstation. The pattern dimensions were the same as in Experiment 1. Each pattern was composed of a blue square ($x=.145, y=.060$) and of a second square that differed in hue. The hues of the second square varied in their similarity to blue and were blue-purple (BP) ($x=.191, y=.189$), purple (P) ($x=.307, y=.161$), red (R) ($x=.592, y=.337$), orange (O) ($x=.499, y=.402$), green (G) ($x=.292, y=.550$), and blue-green (BG) ($x=.216, y=.299$). The luminances of the squares were 2.1 ft.-L. The backgrounds were achromatic ($x=.300, y=.320$) with luminances of .2, 1.1, 4.4 and 10.4 ft.-L. A subject was presented with 24 stimulus patterns (6 hue pairs $\times$ 4 background luminances). The procedure for rating segregation and similarity was the same as in Experiment 1.
Subjects

Seven subjects served in the experiment. One of the authors (S.O.) served as a subject. Six subjects were graduate students who were naive about the purpose of the experiment. Five of the subjects were the same as in Experiment 1. All had normal or corrected to normal vision.

Results and Discussion

![Graph showing mean segregation ratings plotted as a function of mean similarity ratings for Experiment 2. The hues of the squares were blue and red (R), blue and orange (O), blue and purple (P), blue and green (G), blue and blue-green (BG), and blue and blue-purple (BP).]

Figure 8: Mean segregation ratings plotted as a function of mean similarity ratings for Experiment 2. The hues of the squares were blue and red (R), blue and orange (O), blue and purple (P), blue and green (G), blue and blue-green (BG), and blue and blue-purple (BP).

Figure 8 plots the mean of subjects’ mean ratings of segregation as a function of the mean of subjects’ mean ratings of similarity. Background luminance \( F(3, 18) = 38.65, p < .01 \) and hues of the squares \( F(5, 30) = 65.51, p < .01 \) significantly affected perceived segregation. The interaction of the background luminance and the hues of the squares was also significant \( F(15, 90) = 7.64, p < .01 \). The interaction reflects the greater effect of background luminance on the perceived segregation of dissimilar hues than of similar hues. For a given background luminance, there is an overall
Figure 9: Mean similarity ratings as a function of background luminance and the hues of the squares in Experiment 2. The hues of the squares were blue and red (R), blue and orange (O), blue and purple (P), blue and green (G), blue and blue-green (BG), and blue and blue-purple (BP).

inverse relationship between perceived similarity and perceived segregation. Perceived segregation, however, is not a simple function of hue similarity. Figure 8 shows that perceived segregation, as in earlier experiments, varied inversely with the luminance of the background. However, the judgments of hue similarity as shown in Figure 9 were similar for the different luminance backgrounds. Adaptation to the background luminance affected perceived segregation but did not affect perceived similarity.

We examined whether perceived segregation is a function of the differences in opponent-channel outputs. As in Experiment 1, the long- (L-cone), middle- (M-cone), and short-wavelength (S-cone) responses were estimated from the measured luminances and chromaticity coordinates of the hues (Cole & Hinc, 1992). Equations 1 and 2 were used to calculate the cone contrasts and the predicted segregations. We examined values of $k$ from .1 to 1 and found that a value of $k = .08$ gave the best fit to our data. The proportion of the variance accounted for by linear correlation is .93, .91, .97, and .97 for the black, dark gray, light gray, and white backgrounds respectively.
Figure 10: Mean and predicted segregation ratings as a function of the background luminance and the hues of the squares for $k = .08$ in Experiment 2. The backgrounds were black (.2 ft.-L.), dark gray (1.1 ft.-L.), light gray (4.4 ft.-L.), and white (10.4 ft.-L.). The hues of the squares were blue and red (R), blue and orange (O), blue and purple (P), blue and green (G), blue and blue-green (BG), and blue and blue-purple (BP). A value of $k = .08$ produced the best fit to the data in Experiment 2 (see text).

Linear transformations were applied to bring the predicted segregations into the same range as the rated segregations. Figure 10 shows the mean and predicted segregation ratings for the four background luminances for $k = .08$. As mentioned earlier, a value of $k = .13$ gave the best fits to the data in both Experiments 1 and 2. For a value of $k = .13$, the $r^2$ values were .77, .71, .89, and .83 for the black, dark gray, light gray, and white backgrounds respectively. Figure 11 shows the mean and predicted segregation ratings for the four background luminances for $k = .13$. As in Experiment 1, the square-root of the squares of the differences in the L-, M-, and S-cone contrast fails to account for the perceived segregation. The $r^2$ value for $k = .08$ is .40, .43, .75, and .69 for the black, dark gray, light gray, and white backgrounds respectively. Equation 2 also again fails to quantitatively describe the perceived segregation across the four background luminances. The $r^2$ value for the predicted and mean segregation
ratings across the four background luminances is .34 for \( k = .08 \) and .30 for \( k = .13 \). When a constant of .4 is added to the denominator in calculating the cone contrast for the .17 ft.-L. background, the \( r^2 \) value between the predicted and mean segregation ratings is .69 for \( k = .08 \) and .61 for \( k = .13 \).^5

![Figure 11](image)

**Figure 11:** Mean and predicted segregation ratings as a function of the background luminance and the hues of the squares for \( k = .13 \) in Experiment 2. The backgrounds were black (.2 ft.-L.), dark gray (1.1 ft.-L.), light gray (4.4 ft.-L.), and white (10.4 ft.-L.). The hues of the squares were blue and red (R), blue and orange (O), blue and purple (P), blue and green (G), blue and blue-green (BG), and blue and blue-purple (BP). A value of \( k = .13 \) produced the best fit to the data in Experiments 1 and 2 (see text).

We examined whether perceived similarity is predicted by the square-root of the differences in the outputs of the L-M and the L+M-S opponent channels. Since the background luminance did not affect the judgments of hue similarity, the relevant variable for predicting hue similarities in Equation 2 is cone response and not cone contrast. The predictions did not vary appreciably with the value of \( k \). Small calculated values represent high hue similarity. Large calculated values represent low hue similarity. The proportion of the variance accounted for by a linear correlation
of the predicted similarities with the hue differences calculated from the formula was .92 for the 24 stimuli across the four background luminances. Linear transformations were used to bring the predicted similarities into the same range as the rated similarities. Figure 12 shows the mean similarity ratings and the predicted similarities for the four background luminances for \( k = .13 \). Perceived segregation is a function of cone contrasts whereas hue similarity is a function of cone responses.

**Experiment 3**

The perceived segregation of achromatic element-arrangement patterns differing in luminance is decreased as the background luminance is decreased below the lower luminance square or increased above the higher luminance square (Beck et al., 1987;
Sutter et al., 1989). The decrease in the perceived segregation is consistent with a compressive intensity nonlinearity that abolishes the differences in the neural responses to the high and low luminance squares differing from the adaptation level set by the background luminance (Graham et al., 1992). The failure of a low luminance background to decrease the perceived segregation of element-arrangement patterns differing in hue suggests that adaptation to the background luminance does not affect the discrimination of hue differences. However, as shown in Experiments 1 and 2, a high luminance background which strongly stimulates the L, M, and S cones decreases the differences in the cone contrasts to the hues of the two squares and decreases perceived segregation. Experiment 3 directly compared the perceived segregation of element-arrangement patterns differing in luminance with element-arrangement patterns differing in hue as a function of the background luminance.

Stimuli and Procedure

The experiment compared the perceived segregation of element-arrangement patterns composed of red (x=.601, y=.337) and purple (x=.580, y=.330) squares and of brighter and darker red squares. The backgrounds were achromatic (x=.300,y=.320) with luminances of .17, 1.2, 2.4, 9.2 and 16.0 ft.-L. The luminances of the red and purple squares were 3.8 ft.-L. The luminance of the brighter red square in the luminance element-arrangement pattern was also 3.8 ft.-L. Prior to making their segregation judgments, the chromatic and achromatic element-arrangement patterns were presented on the monitor side by side. A subject lowered the luminance of the second red square on the luminance element-arrangement pattern until its perceived segregation was equal to the perceived segregation of the red and purple element-arrangement pattern. The background luminances for these judgments was 2.4 ft.-L. Each subject made 5 judgments and the mean of a subject's judgments was used in the presentations of the achromatic element-arrangement patterns for that subject. The luminance of the darker red squares ranged between 1.6 and 2.4 ft.-L. The element-arrangement patterns subtended 1.66 cycles per degree and were viewed from a distance of .94 m. The squares were 10 pixels on a side (.17 deg) and the horizontal and vertical inter-spaces were 7 pixels (.12 deg). The overall patterns subtended 4.2 deg. A subject was presented with 10 stimulus patterns (2 hue pairs X 5 background luminances). The apparatus, pattern dimensions, and the procedure for rating segregation were the same as in Experiment 1.

Subjects

Six subjects served in the experiment. One of the authors (S.O.) and five graduate students who were naive about the purposes of the experiment served as subjects. The subjects were the same as in Experiment 2. All had normal or corrected to normal vision.
Results and Discussion

Figure 13: Mean segregation ratings plotted as a function of background luminance in Experiment 3. The background luminances were .17 ft.-L., 1.2 ft.-L., 2.4 ft.-L., 9.2 ft.-L., and 16.0 ft.-L.

Figure 13 presents the mean segregation judgments as a function of background luminance. The perceived segregation of the red and purple element-arrangement patterns decreased with increasing luminance of the background. In contrast, the perceived segregation of the red and dark red element-arrangement pattern was maximal with a background luminance of 2.4 ft.-L. and decreased with lower and higher background luminances. The interaction between the type of element-arrangement pattern and the background luminance was significant \( F(4, 20) = 8.22, p < .01 \). There was also a significant quadratic trend for the red and dark-red element-arrangement patterns \( F(1, 20) = 19.77, p < .01 \). Equation 2 predicts that perceived segregation should decrease with increasing background luminance and fails to predict the quadratic trend.

The proportion of the variance accounted for by a linear correlation of the predicted segregations from Equation 2 and the mean segregations of the red and purple element-arrangement pattern across backgrounds is .37. The correlation between the mean rated segregations and the predictions from Equation 2 is improved by adding a constant of .4 to the denominator in calculating the cone contrasts for the .17 lu-
The $r^2$ value is then .81. Figure 14 shows the mean rated segregations and the predicted segregations for a value of $k = .13$ in Equation 2. A linear transformation was applied to bring the predicted segregations into the same range as the rated segregations.

![Figure 14: Mean and predicted segregation ratings of the red and purple element-arrangement patterns as a function of background luminance for $k = .13$ in Experiment 3. The background luminances were .17 ft.-L., 1.2 ft.-L., 2.4 ft.-L., 9.2 ft.-L., and 16.0 ft.-L. A constant of .4 was added to the denominator for the .17 ft.-L. luminance background (see text).](image)

As in the experiments with achromatic element-arrangement patterns, perceived segregation for the element-arrangement patterns composed of brighter and darker red squares was greatest when the background luminance was in between the luminances of the squares and decreased as the background luminance both increased above and decreased below that of the squares. When the luminance of the background is between that of the squares two distinct populations of cells are stimulated by the brighter and darker squares. The squares above the luminance of the background stimulate on cells while the squares below the luminance of the background stimulate off cells. The decrease in perceived segregation with the increase and decrease of the background luminance is consistent with the well established finding that luminance discriminations

23
are best when the luminances being discriminated are close to the adapting luminance level and become worse when the luminances are further away from the adapting luminance level (Craik, 1938).

The background luminance controls the adapting luminance and one would expect perceived segregation to become worse when the background luminance is far from that of the squares. The contrast ratio of the squares is one way of quantitatively expressing that texture segregation becomes worse when the background luminance is raised above or lowered below the luminances of the squares. The contrast ratio (Equation 3) is equal to the luminance of the high contrast square ($L_{s1}$) minus the luminance of the background ($L_b$) divided by the luminance of the low contrast square ($L_{s2}$) minus the luminance of the background.

$$\frac{L_{s1} - L_b}{L_{s2} - L_b}$$

The contrast ratio approaches a value of 1 as the background luminance increases above the high luminance square and approaches the ratio of the luminances of the squares as the background luminance tends to zero. In experiments with achromatic squares differing in luminance, we found that the contrast ratio of the squares yields a first-order approximation to the perceived segregation if the cases when the background luminance was in between the luminances of the squares were excluded (Beck et al., 1991). The $r^2$ value between the mean rated segregations and predicted segregations, excluding the instance in which the background luminance was in between, is .90. The mean rated segregations and the segregations predicted by the contrast ratio are shown in Figure 15. A linear transformation was applied to bring the predicted segregations into the same range as the rated segregations.

The results suggest an independence of hue and luminance discrimination consistent with the findings of Cole, Stromeyer, and Kromauer (1990), and Mullen and Losada (1994). For achromatic element-arrangement patterns, when the adapting luminance is distant from the luminances of the squares composing the pattern, the Weber threshold for discriminating luminance differences increases. Thus, black and white backgrounds decrease the perceived segregation of achromatic element-arrangement patterns. For chromatic element-arrangement patterns, adapting to an achromatic luminance distant from the squares does not increase the Weber threshold for discriminating a hue difference between the squares. Thus, a black background does not impair the perceived segregation of an achromatic element-arrangement pattern. A white background, however, decreases the perceived segregation of an element-arrangement pattern composed of squares differing in hue. This is because a high luminance background strongly stimulates the L-, M-, and S-cones. The cone contrasts with a high luminance white background are greatly decreased thereby decreasing perceived segregation.
Figure 15: Mean and predicted segregation ratings of the red and dark red element-arrangement patterns as a function of background luminance in Experiment 3. The contrast ratio of the squares was used to generate the predicted segregation ratings. The background luminances were .17 ft.-L., 1.2 ft.-L., 9.2 ft.-L., and 16.0 ft.-L. The 2.4 ft.-L. luminance background was excluded because it falls in between the luminances of the squares (see text).

**Experiment 4**

In Experiment 1 the patterns with purple squares tended to segregate more strongly than predicted by Equation 2. One possibility is that perceived segregation is affected by the difference in the perceived brightness of the hues. Chromatic stimuli of equal luminance need not be of equal brightness. The discrepancy between luminance and brightness is greatest for purple hues (Wyszecki & Stiles, 1982). Experiment 4 examined whether perceived brightness is associated with the perceived segregation of chromatic element-arrangement patterns.

**Stimuli and Procedure**

The element-arrangement patterns were composed of gray (x=.294, y=.302) and purple (x=.309, y=.164) squares. The luminances of the squares were .5, 1.0, 2.0, 4.0, and 8.0 ft.-L. The patterns were viewed from a distance of .94 meters and subtended
.83, 1.66 and 3.32 cycles per degree. The squares in the patterns measured 20, 10, and 5 pixels on a side (.34, .17, and .08 deg respectively). The horizontal and vertical edge-to-edge spacing of the squares were .75 of their sides. The background was achromatic with a luminance .2 ft.-L. (x=.255, y=.255). In a separate session, subjects also judged the relative brightness of the purple and gray squares. An orange square (x=.467, y=.436) with a luminance of 2.4 ft.-L. was assigned a value of 100. The square was 200 pixels on each side and subtended approximately 3.4 deg. The distance of the square from the stimulus patterns varied with the size of the stimulus pattern. The element-arrangement patterns subtended approximately 8.7, 1.2, and 2.1 deg. The smallest distance was for the largest stimulus pattern and was 3.35 deg. Subjects were instructed to rate the relative brightness of the purple and gray hues in a stimulus display using the method of magnitude estimation. When making the brightness estimates subjects were presented only the middle checkerboard region of a pattern. The magnitude estimations of brightness always followed the segregation judgments.

Results and Discussion

Figure 16 shows the mean segregation ratings as a function of pattern size (cycles per degree). The main effects of luminance \([F(4,20) = 4.66, p < .01]\), cycles per degree \([F(2,10) = 63.17, p < .01]\), and the interaction of luminance and cycles per degree \([F(8,40) = 3.29, p < .01]\) were significant. The interaction reflects the greater effect of luminance on perceived segregation at 3.32 cycles per degree than at .83 cycles per degree. Perceived segregation increased with decreasing pattern size or increasing cycles per degree. It is of interest to point out that a pattern subtending 3.32 cycles per degree is beyond the maximum of the chromatic contrast sensitivity function (Mullen, 1985). At .83 and 1.66 cycles per degree the luminances of the squares fail to significantly improve perceived segregation (Tukey test, \((p < .05))\). At 3.32 cycles per degree, perceived segregation significantly increased between .5 and 2 ft.-L (Tukey test, \((p < .05))\). Equation 2 does not take cycles per degree into account and does not predict the effect of this variable. The predicted segregation is the same for all three scales. One possible explanation of the increased perceived segregation with increased luminance of the squares at 3.32 cycles per degree is that at lower spatial frequencies there is inhibition from channels sensitive to the higher harmonics (Graham et al., 1992). At the higher spatial frequencies the visual system is not sensitive to the higher harmonics, thereby increasing perceived segregation.

At 3.32 cycles per degree, perceived segregation was similar for luminances of 2.0, 4.0, and 8.0 ft.-L. Since the background luminance was constant, increasing the luminances of the squares increased cone contrasts. Equation 2 is a function of cone contrasts and predicts that perceived segregation should increase with increasing luminance of the squares. The mean segregation ratings are not in accord with this prediction. The predicted segregations are shown by the dashed line in Figure 17. It
is possible that because of adaptation to the low luminance background the cones are responding approximately equally to the 2.0, 4.0, and 8.0 ft.-L. stimuli. The formula for calculating opponent channel differences does not take adaptation into account and would not reflect cone saturation limiting cone contrast. Figure 18 shows the mean magnitude estimations of brightness for the .83, 1.66, and 3.32 cycles per degree stimuli. The magnitude estimations of brightness are consistent with the mean segregation ratings in that the brightness judgments increase steeply up to 2.0 ft.-L. The brightnesses curves for the purple and gray squares can be approximated by two straight lines. A steep line from .5 to 2.0 ft.-L. and a second line of shallower slope from 2.0 ft.-L. to 8.0 ft.-L. The shallower slope from 2.0 to 8.0 ft.-L. is consistent with the suggestion that the cones at these higher luminances are approaching saturation and responding approximately equally. At equal luminance, the purple squares were judged brighter than the gray squares at all spatial scales $[F(1, 6) = 20.29, p < .01]$. The similarity of the brightness judgments at the three spatial scales $[F(2, 12) = .69, p > .52]$ indicates that brightness differences do not explain the effects of spatial scale.
Figure 17: Mean and predicted segregation ratings for element-arrangement patterns of 3.32 cycles per degree in Experiment 4. Since the background was always black (0.2 ft.-L.), as the luminance of the squares is increased (0.5, 1.0, 2.0, 4.0, 8.0 ft.-L.) the cone contrast and predicted segregation will increase. This is not in accord with the mean segregation ratings which increase up to 2.0 ft.-L. and then level off (see text).

GENERAL DISCUSSION

Experiments 1, 2, and 3 indicate that cone contrasts are the primary variable for determining perceived segregation of chromatic element-arrangement patterns. A high luminance background which strongly stimulates the L, M, and S cones decreases the differences in the cone responses to the hues of the two squares. Pessoa et al. (1996) found that perceived segregation for equiluminant squares was controlled by the ratio of the interspace luminance to the hue luminance. Equal ratios of interspace luminance to hue luminance yielded the same perceived segregation. Keeping the ratio of the interspace luminance to the hue luminance constant keeps the cone contrasts constant.

Experiments 1 and 2 indicate that hue similarity does not determine the perceived segregation of chromatic element-arrangement patterns. Perceived similarity is relatively unaffected by the background luminance, but a high luminance background decreases perceived segregation. Beck et al. (1991) found that population segregation is approximately a single-valued function of the lightness difference of the squares. In population displays a subject judges the extent to which two randomly interspersed
subpopulations of elements segregate. The reason for the difference between population segregation and region segregation may be that region segregation is mediated by detectors having large oriented receptive fields that are sensitive to the fundamental spatial frequency and orientation of the texture region, as defined by the arrangement of the squares (Sutter et al., 1989). These detectors may be conjectured to provide information to the contour system that constructs the boundaries that segregate the regions of an element-arrangement pattern. In the population displays there are no boundaries between regions. The segregation of a population display into light and dark squares is an example of pure similarity grouping. We would, therefore, expect population segregation to be predicted by hue similarity and not by cone contrasts or the output of opponent processes.

Pessoa et al. (1996) suggested that the modified Type II blob cells reported by Ts'o and Gilbert (1988) could provide an explanation of the asymmetric effect of background luminance. A modified Type II cell has a color-opponent center and a broad-band inhibitory surround. If the receptive field size of a cell coincided with the fundamental frequency of the element-arrangement pattern, then the center of

Figure 18: The mean magnitude estimations of brightness for the purple and gray squares of the .83, 1.66, and 3.32 cycles per degree stimuli in Experiment 4.
the receptive field, of an appropriately positioned cell, would receive input from one of the chromatic squares and the surround would receive input from the achromatic interspaces (see Figure 19). This would result in excitation in the center and inhibition in the surround. High luminance in the surround would inhibit the cells and lead to weak segregation. Low luminance in the surround would not inhibit the cells, leaving segregation strength to be determined by the responses of the color opponent centers. Modified Type II cells account for the background effect, but their outputs cannot lead directly to segregation perception, because the cells are unoriented and respond the same in all regions of the pattern. The outputs of the modified Type II cells must be fed into oriented cells for segregation to be determined. Pessoa et al. (1996) proposed that oriented complex cells pick up the differences between the vertical and oblique arrangements of squares and are used for determining segregation. We have begun to simulate center-surround filters with chromatic sensitivities that model the response of modified Type II cells. The outputs of the complex cell stage of processing agree well with the predictions of Equation 2. An alternative proposal by Grossberg and Pessoa (1996) uses the mechanisms of FACADE theory (Grossberg, 1994) to explain the asymmetric effect of background luminance on perceived segregation.

Figure 19: The center of the receptive field receives excitation from the chromatic square and the surround receives inhibition from the achromatic interspaces.

Sutter et al. (1989) showed that perceived segregation does not scale for achromatic element-arrangement patterns. Segregation improves as the fundamental frequency of
the element-arrangement pattern is increased (i.e. as the pattern gets smaller). The results from Experiment 4 show that this is also true for chromatic element-arrangement patterns. This is further evidence that the information for the perceived segregation of an element-arrangement pattern is prior to the specification of the squares and their properties. Perceptual grouping generally scales, i.e., remains the same if element separation to element size remains constant (Goldmeier, 1972). The equation for predicting segregation with cone contrast (Equation 2) needs to be modified to take scale into account. This might be done by implementing the equation for modified Type II cells of many different scales.

In summary, chromatic experiments show (a) hue similarity does not predict the perceived segregation of element-arrangement patterns; (b) For a given background luminance, opponent channel differences using cone contrasts approximately predict the perceived segregation of element-arrangement patterns differing in hue; (c) opponent channel differences using cone responses predict the perceived similarities of hues across the four background luminances; (d) the ratio of the contrasts of the squares approximately predict perceived segregation for element-arrangement patterns differing in luminance; (e) perceived segregation does not scale and improves as the image size of the pattern decreases to 3.32 cycles/deg; (f) differences in perceived brightness are associated with differences in perceived segregation. These results indicate that the early visual mechanisms that encode pattern differences primarily underlie perceived segregation in element-arrangement patterns.
References


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Footnotes

1. The critical variable is the luminance of the interspace between the squares. The luminance of the surround affects segregation minimally (Beck, 1994; Pessoa et al., 1996).

2. The method of minimally distinct borders was used to determine the isoluminance values of the squares comprising the element-arrangement stimuli in two preliminary experiments. The judged isoluminance values in these experiments were close to the equal luminance values determined by photometer. Pessoa et al. (1996) also showed that strict isoluminance of the squares was not necessary for the effects of background luminance. Photometer values were therefore used to equate the luminances of the squares in the experiments reported.

3. The chromaticity coordinates varied slightly with the luminance of the background. The mean chromaticity coordinates are given.

4. A forced-choice detection paradigm yielded similar results. The detection of a checkerboard odd tile in a display of striped tiles was easier on a black background than a white background (Pessoa et al., 1996, Experiments 4 and 5).

5. A constant of .4 yielded the maximum correlation in Experiment 3 and near maximum correlations in Experiments 1 and 2.

6. The chromaticity coordinates varied slightly with the luminance of the squares. The mean chromaticity coordinates are given.