Detection of between-eye differences in color: Interactions with luminance

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Between-eye differences in color or luminance result in the appearance of luster, which provides a cue for detecting between-eye differences. We measured thresholds for detecting between-eye differences in both hue and chromatic contrast (saturation) in dichoptically superimposed color patches. Sensitivity was found to be highest at isoluminance and decreased with the addition of task-irrelevant, spatially coextensive, binocular (i.e., same in both eyes) luminance contrast. However, when the members of each dichoptic pair were presented side by side on the screen and viewed with the same eye, the added luminance contrast had no effect on the detection of their differences. If the effect of the luminance contrast was simply to dilute or desaturate the chromatic signals, we would expect thresholds to increase for the within-eye and not just the between-eye (dichoptic) conditions. We suggest that the presence of binocular luminance contrast reduces the interocular suppression between the dichoptic colors, causing the dichoptic color pairs to blend, thus rendering their differences harder to detect.

Introduction

Humans and animals are said to have binocular vision if they possess two spatially separated eyes that together provide a coherent image of the external world. Two eyes offer a range of advantages over one—for example, a wider field of view, stereopsis, and binocular summation. To achieve stereopsis, the visual system detects disparities in the positions of objects in the two eyes. However, we are also sensitive to between-eye differences in dimensions other than position—for example, in contrast or hue. We refer to such differences as dichoptic differences. Understanding how dichoptic differences are detected is an important part of understanding binocular vision.

The threshold for detecting a dichoptic difference can be measured using a conventional forced-choice Type 1 task—that is, one with a correct/incorrect response on each trial (Formankiewicz & Mollon, 2009; Malkoc & Kingdom, 2012; Yoonessi & Kingdom, 2009). This is a different task from that conventionally used to measure the effects of binocular differences, such as adjusting the difference until rivalry is perceived or recording the rate of perceptual alternation (for reviews of binocular rivalry, see Alais & Blake, 2005; Blake, 2001). Threshold dichoptic differences are typically lower than those for binocular rivalry. For example, Malkoc and Kingdom (2012), using isoluminant colored (chromatic) patches found that the threshold for detecting a dichoptic difference in hue was about 3 times lower than the threshold for perceiving hue rivalry.

In this communication we report measurements of dichoptic difference thresholds for the hue (e.g., red or green) and saturation (i.e., chromatic contrast) of colored patches on a gray background. The main purpose of the study, however, is to explore the effect of adding binocular luminance contrast to the patches—that is, luminance contrast presented equally to both eyes. Why this manipulation? Previous studies have shown that when there are matched features in the two eyes, the interocular suppression between unmatched features that manifests itself as dichoptic masking or rivalry is reduced (Blake & Boothroyd, 1985; Buckthought & Wilson, 2007; Meese & Hess, 2005; O'Shea, 1987). If binocularly matched luminance contrast reduces the interocular suppression between disparate hues or saturations, those disparities will presumably become harder to detect.

Recent findings from two other dichoptic vision paradigms support this possibility. Kingdom and Wang (2015) conducted a dichoptic *masking* experiment with colored patches, measuring the threshold color satura-

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tion for detecting a target in one eye in the context of a highly saturated mask in the other. They found that whereas at isoluminance target thresholds were dramatically elevated by the mask, threshold elevation was reduced when task-irrelevant binocular luminance contrast was added to both target and mask. Kingdom and Libenson (2015) conducted a dichoptic *matching* experiment with colored patches in which observers adjusted the saturation of one member of a dichoptic pair to match that of a binocular reference stimulus. They found that whereas at isoluminance the perceived saturation of the dichoptic mixture was dictated by the higher of the two saturations, perceived saturation shifted toward the average of the two saturations when binocular luminance contrast was added. The likely cause of these effects is that the added binocular luminance contrast reduced the interocular suppression between the disparate saturations: in the case of the masking experiment, this reduced the effectiveness of the mask; in the case of the matching experiment, this reduced the dominance of the higher saturation. The present study tests a prediction from this idea in relation to the dichoptic differencing paradigm. If the detection of dichoptic differences in saturation or hue is mediated by mechanisms that involve interocular suppression, then the addition of binocular luminance contrast should make those dichoptic differences harder to detect. Note that the prediction here is the opposite of Kingdom and Wang's (2015) dichoptic masking result. In their experiment, the addition of binocular luminance contrast reduced thresholds, whereas for the dichoptic difference experiment here, adding binocular luminance contrast is predicted to increase thresholds.

To test this prediction we have compared dichoptic difference detection thresholds (DTs) for hue and saturation at isoluminance with thresholds obtained in the context of added, binocularly matched luminance contrast.

General methods

Observers

Five observers took part in the experiments. The senior author (BJ) participated in both hue and saturation experiments. The remaining four observers were naive to the purpose of the experiment. AB and GS only participated in the hue experiments, and JP and KW only participated in the saturation experiments. All except JP were practiced psychophysical observers. All observers had 6/6 visual acuity, four with their correction, and all tested normal on the Ishihara color deficiency test (24 plates edition). Prior to experimental testing, informed consent was obtained from each observer; all experiments were conducted in accordance with the Declaration of Helsinki.

Equipment

All experiments were conducted using a Dell Precision T1650 PC with a VISaGe graphics card (Cambridge Research Systems, Rochester, Kent, UK). The visual stimuli were displayed on a Sony Trinitron Multiscan G500 CRT monitor, gamma corrected and color calibrated with a ColorCAL colorimeter and spectroCAL spectroradiometer (Cambridge Research Systems), respectively. The display was driven at 160 Hz and had a resolution of 800×600 pixels, giving a pixel size of $\sim 0.47 \times 0.47$ mm. Stimulus generation and experimental control used C software. Participants viewed the display through a modified eight-mirror Wheatstone stereoscope, which employed four front-surfaced mirrors per eye. Viewing distance along the light path was 100 cm. The stereoscope allowed approximately $9.8° \times 12.4°$ of the display to be visible to each eye. Prior to the start of any data collection, the monitor was warmed up for at least 20 min in order to ensure a stable luminance output. During the experiments, observers were seated in a darkened room and their responses were recorded via a Targus AKP10CA keypad (Targus Group International, Inc., Mississauga, Ontario, Canada).

The CIE 1931 xyY chromaticity coordinates, with maximum luminance outputs, of the phosphors were; Red xyY: [0.63, 0.34, 16.1], green xyY: [0.283, 0.613, 67.3], and Blue xyY: [0.151, 0.073, 7.64], where Y is given in Candelas per meter squared.

Hue experiment

Stimuli

The stimulus for the hue experiment comprised patches as shown in Figure 1. Figure 1a shows the patches in the right eye (RE) and left eye (LE), and Figure 1b shows the patches as the observer would see them when fused using the stereoscope. In Figure 1a and b, the top patch is the test (the dichoptic pair with unequal hues) and the bottom is the comparison (the pair with equal hues). Each patch had a radius of 0.8°. The distance from the fixation point to the center of each patch was 1.9°. The patches were presented on a midgray background of luminance 45.5 cd m^{-2}, one above and one below the fixation point. The patches were randomly spatially jittered on each trial within the angular range $\pm 25°$ relative to vertical, such that they always formed a straight line that ran through the fixation point. This minimized the build up of afterimages while keeping constant their separation. The entire stimulus was surrounded by a dark gray

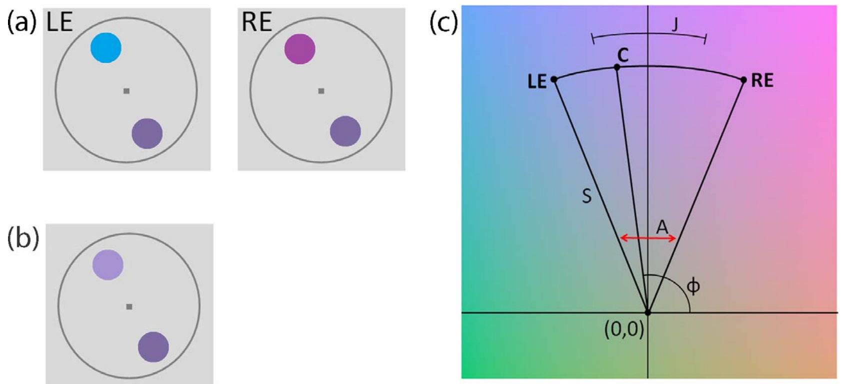

Figure 1. Panel (a) shows the LE and RE views of the dichoptic stimulus. Once fused, the observer perceived the stimuli as shown in panel (b). Note the top patch contains the hue difference to be detected. Panel (c) illustrates how the hue of each patch was defined; S is chromatic contrast, or saturation; C is the hue of the comparison patch; RE and LE are the hues of the target patch in the right and left eyes; ϕ is the mean hue direction of the target and comparison hues and J the applied hue jitter. The measured threshold is expressed in terms of the difference in hue direction, given by angle A.

circle with a diameter of 8.0°, which helped achieve binocular fusion.

Figure 1c indicates how the chromaticity of each patch was specified. The mean target and comparison color directions were defined by the DKL color space (Derrington, Krauskopf, & Lennie, 1984) as the angle ϕ. The target was composed of hue directions located at points LE and RE as shown in Figure 1c. Chromatic saturation was defined by the length of the vector S from the midgray background located at [0, 0] to the point C. The length of S was determined for each observer, and equalled 8 times the hue detection threshold (see the contrast detection threshold section). On each trial the mean color directions of the target and comparison were independently jittered within the range $\pm 10°$ (hue angle). This minimized the possibility that the judgment of hue difference was based on the learned mean hue direction rather than the between-eye difference in hue direction. On some trials, for example, C could fall outside the range defined by LE and RE. On a given trial the LE and RE hues of the target were randomly swapped to eliminate any possible eye dominance effects. Target versus comparison positions were also randomized on each trial. Hue directions were generated around a mean hue of violet, corresponding to a hue angle of 90°.

Luminance contrast was added equally to all color patches. The chromatic and luminance components of the stimulus were drawn on separate pages of video memory and presented alternately on the monitor at the 160-Hz frame rate using lookup table cycling. This minimized the possibility of any display device-based color-luminance interactions. No color or luminance flicker was perceived, as the 160-Hz frame rate was sufficiently above the temporal resolution of both the chromatic and luminance systems (Lee, Pokorny, Smith, Martin, & Valberg, 1990). For the isoluminant conditions, the colored patches were interleaved with the midgray background on alternate frames. Luminance contrast was defined using a particular RGB triplet (where R = G = B, in the range [0–1]) relative to the RGB value of the employed midgray background (where R = G = B = 0.5). In practice, the luminance contrast was half this value due to the lookup table cycling method employed. The stimuli (both chromatic and luminance components) were additionally ramped on and off according to a cosine temporal envelope to remove sharp transients. The envelope, and hence stimulus, duration was 750 ms.

Procedure

Observers were instructed to identify the patch with the between-eye hue difference, via its lustrous appearance. If the observer was unable to identify the target patch, s/he was instructed to guess. On each trial a brief tone followed stimulus presentation indicating the end of the trial and prompting the observer to make his/her response (two alternate forced choice [2AFC]: top or bottom). The response initiated the next trial. Feedback was provided in the form of a longer and lower pitched tone for an incorrect response. The method of constant stimuli controlled the size of the dependant variable on each trial (angle A; Figure 1c). In total six stimulus levels (i.e., color separation angles) were tested per block at a rate of 35 trials per stimulus level. The fixed stimulus levels were different between some viewing conditions as pilot data indicated thresholds varied significantly with viewing condition.

Control conditions

Three control conditions were employed to test if the results from the main experiment could be explained in

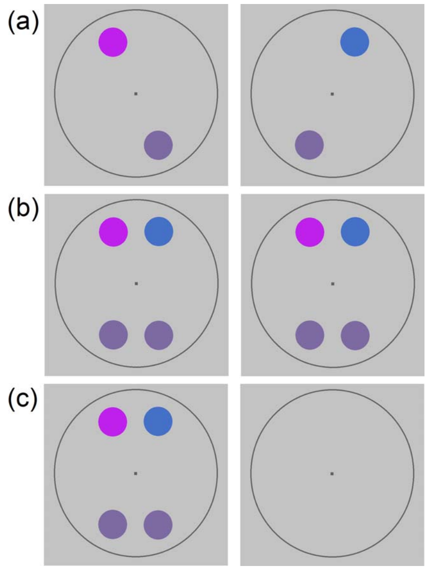

Figure 2. LE and RE views are illustrated for each of the additional viewing conditions. (a) Dichoptic spatially separated condition, (b) binocular condition in which the image to each eye is identical, and (c) the monocular condition in which one eye receives the stimulus and the other eye receives the mean gray background.

terms of the effects of luminance contrast on overall saturation. These are illustrated in Figure 2a through c. The first (Figure 2a) was a dichoptic, but nonsuperimposed stimulus, in which the color patches were spatially separated so as to project them to noncorresponding retinal locations. Where one eye saw a patch, the other saw the blank background. The task was to identify the pair (top or bottom) with the different hue. The second (Figure 2b) was a binocular condition in which the stimulus was identical in both eyes. Observers were presented with two pairs of color patches, and the task was to identify whether the hue difference was in the top or bottom pair. The third (Figure 2c) was a monocular condition that was similar to the binocular condition except that the stimulus was presented to only one eye, with the other eye viewing the blank midgray background. On each trial the monocular stimulus was randomly presented to either the LE or RE with a 50% probability.

Contrast detection thresholds

Chromatic contrast (saturation) DTs were obtained using a modified version of the stimulus illustrated in Figure 1b. Only one color patch was displayed per trial, either above or below the fixation point; the observers' task was to indicate the position of the patch via keypad press. For a fixed hue direction, the chromatic contrast (length S in Figure 1c) was varied via an adaptive staircase procedure (Watson & Pelli, 1983), and the 75% threshold was obtained by fitting a Weibull function to the proportion correct data using a maximum likelihood criterion, using the Palamedes Toolbox (Prins & Kingdom, 2009). In subsequent experiments the contrast of the color patches was set to $8 \times$ DT for each observer.

Saturation experiment

Stimuli and procedure

The stimulus arrangement was similar to that used by Formankiewicz and Mollon (2009) in their study of dichoptic difference thresholds for luminance contrast. The stimulus is illustrated in Figure 3b. It consisted of eight colored patches (radius = 0.8°), arranged into two subgroups, four above and four below the fixation point. Each color patch, in both eyes, contained an identical hue (a bluish-purple hue was used, corresponding to a hue angle of 120°), but the saturation (chromatic contrast) of the hue differed, as indicated in Figure 3a. On each trial each dichoptic pair could potentially have

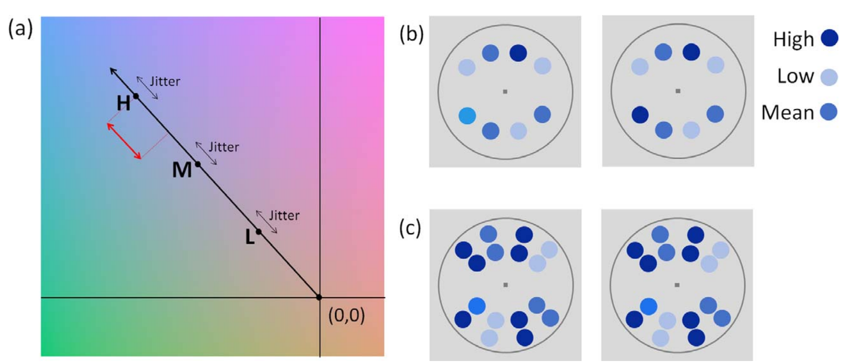

Figure 3. Panel (a) shows a vector of constant hue originating radially from the location of the midgray background hue, confined to the isoluminant plane. Along this vector the positions of the L, H, and M saturations are labeled. The red double-ended arrow indicates a target pair saturation difference. Panel (b) shows the LE and RE dichoptic stimuli. Panel shows the LE and RE binocular stimuli. In (b) and (c) the target pair is located on the left-hand side of the bottom row.

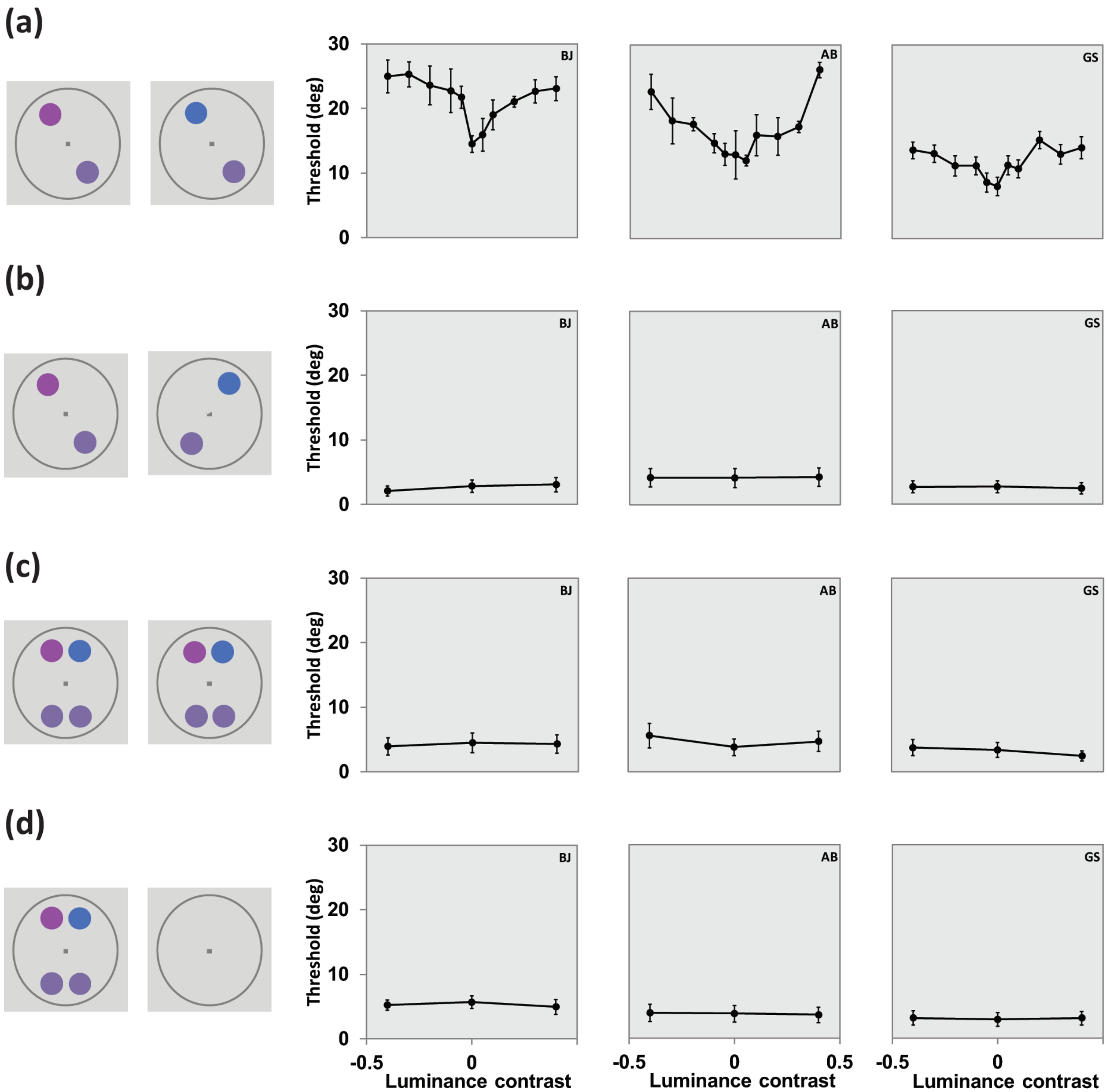

Figure 4. Threshold data for each observer (BJ, AB, and GS) in different columns, for each stimulus type: (a) dichoptic superimposed, (b) dichoptic but spatially separated, (c) binocular, and (d) monocular. Each of the 12 plots has an identical abscissa, with zero in the middle of the range, and an ordinate that represents the threshold (i.e., the hue difference, in degrees).

a saturation equal to the highest (H), lowest (L), or mean (M, where $M = 0.5[H + L]$) saturation. These were randomly assigned to each pair, so that at least two pairs with the H, L, and M saturations were present on each trial. One pair was randomly chosen to be the target (left-most pair on the bottom row in Figure 3c). The target pair had one patch set to the highest saturation and the other patch set to some multiple of the distance between H and L. This multiple could take one of six possible predetermined values, presented according to the method of constant stimuli, allowing psychometric functions to be fitted to the detection data. Thresholds are presented as the length of the vector starting at H and pointing in the direction of the background hue (i.e., point [0, 0]); this is represented by the double-ended red arrow in Figure 3a. On each trial the saturation H and L (and hence M) were randomly jittered. Each trial, as with the hue experiment, lasted 750 ms. Binocular

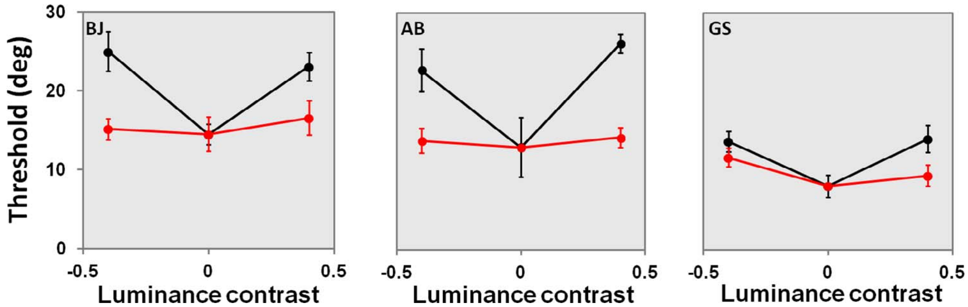

Figure 5. Data is plotted for each observer and illustrates the difference in measured thresholds for spatially and nonspatially correlated binocular luminance contrast. The black curves reproduce the data presented in Figure 4a; only the isoluminant and extreme luminance increment and decrement points are plotted for clarity. The red curves are the measured thresholds for the condition where the luminance increment/decrement is applied to the entire visible display. With the exception of one data point (GS's decrement) when the luminance is not superimposed with the chromatic information, thresholds are independent of binocular luminance contrast.

luminance contrast, in the form of increments or decrements, was added to the color patches. A binocular version of the stimuli was also employed (shown in Figure 3c), consisting of eight pairs of colored patches—four pairs presented above and four pairs below fixation. Also, as before, at least two pairs consisted of the H, L, and M saturations. In the target pair (left-most pair on the bottom row in Figure 3c), there was a within-eye difference in saturation defined in the same way as in the dichoptic condition (i.e., as in Figure 3a). Initial concerns regarding the cognitive demand of the task proved unjustified, as a pilot study indicated that only about five practice trials were required for each observer to become competent with the task.

Thresholds were also measured using an identical method for the between-eye detection of luminance contrast differences. Measures were obtained at the isochromatic point and also with the addition of bluish and yellowish irrelevant color information.

Heterochromatic flicker photometry

Heterochromatic flicker photometry (Walsh, 1958), was employed to measure the amount of luminance contrast needed to be added to the stimulus to achieve isoluminance for each observer, thus correcting for individual differences in the luminous efficiency function (Wyszecki & Stiles, 2000). Note this added luminance contrast is not the same as the independent variable of added binocular luminance, as plotted, for example, in Figure 4. The heterochromatic flicker photometry method exploits differences in the temporal resolution of the luminance and chromatic channels—the luminance channel has a higher frequency flicker resolution than the chromatic channel. Hence, if an observer adjusts the relative luminance levels of a chromatically flickering stimulus until the perception of flicker reaches a minimum (or disappears completely), the luminance difference will also be minimized. A testing and averaging procedure identical to Jennings and Martinovic (2014) was employed.

Results

Hue difference results

Individual data is presented in Figure 4a through d for each of the tested conditions. In all plots, hue

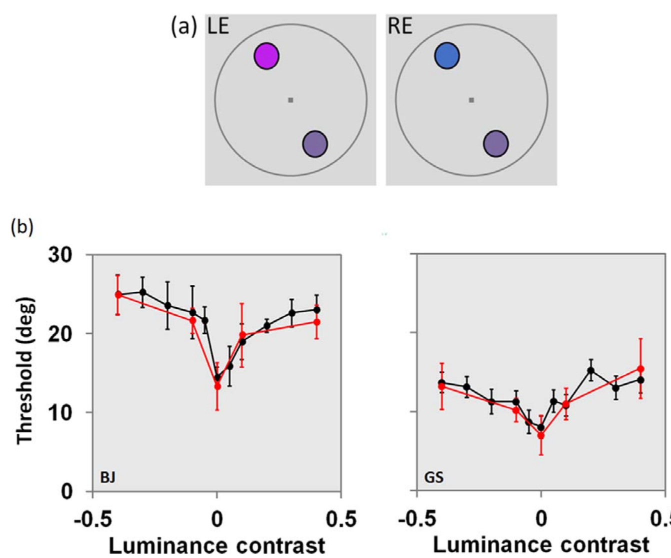

Figure 6. The modified stimulus design is illustrated in (a), with the addition of the black borders surrounding the color-defined patches. The plots presented in (b) shows the variation of measured thresholds (black points) for this modified stimulus as a function of added luminance contrast for two observers; the red points are the same data as presented in Figure 4a for comparison. No significant differences exist between the two.

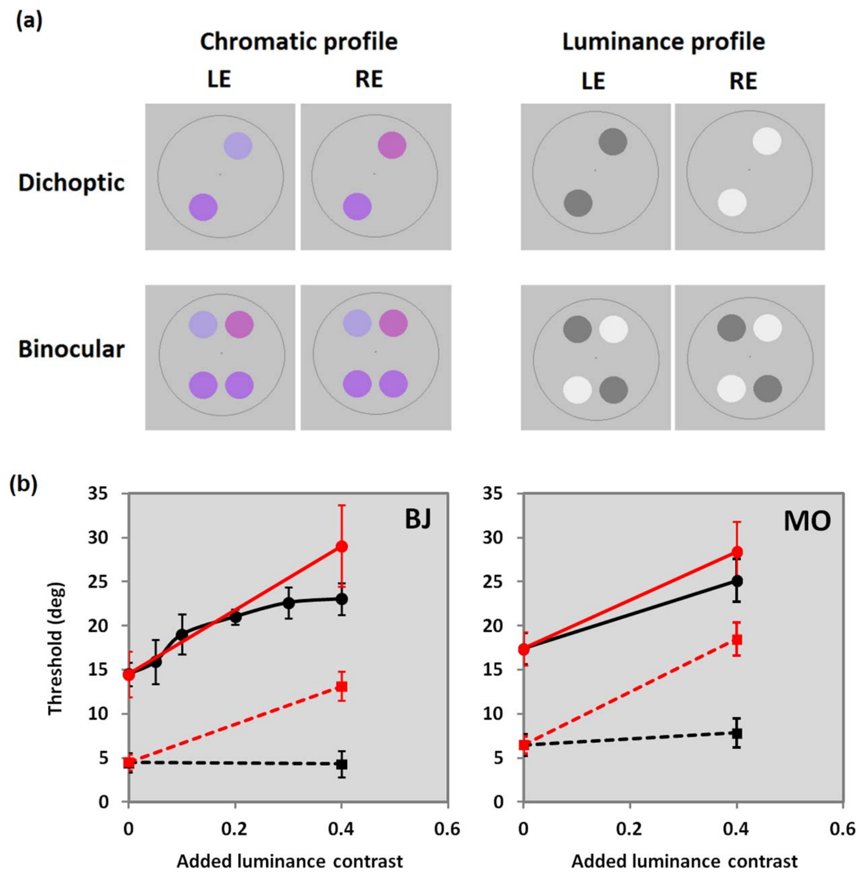

Figure 7. Unmatched luminance contrast experiment. Example stimulus profiles are illustrated in (a) for both the chromatic and luminance components of the dichoptic and binocular conditions. In the dichoptic condition the mismatched luminance is between-eye, in the binocular condition it is within-eye. Data for BJ and MO is shown in (b). The solid black and red lines represent the dichoptic matched and mismatched luminance contrast conditions. The dashed black and red lines represent the binocular matched and mismatched luminance conditions.

difference thresholds are plotted as a function of added luminance contrast. The hue difference thresholds are expressed as differences in hue angle (see Figure 1c). Error bars represent ±2 *SEM*s calculated via the bootstrap method using Palamedes. On the abscissa, the point zero (i.e., the isoluminant condition is at the center of the axis) with luminance contrast increments and decrements to the right and left, respectively.

As the figures show, thresholds (T) for the dichoptically separated (Figure 4b), binocular (Figure 4c), and monocular (Figure 4d) viewing conditions are relatively small and, importantly, very similar across the range of added luminance contrasts tested. For the dichoptic spatially separated condition, $T = 3.17° \pm 0.84°$ ($M \pm SD$), for the binocular condition $T = 4.05° \pm 0.89°$, and for the monocular condition $T = 2.10° \pm 0.99°$. In other words, for all these conditions, T falls within the relatively small range $2.10° \leq T \leq 5.65°$. For the dichoptically superimposed condition (Figure 4a), the data form V-shapes with minima at isoluminance. Thus, retinotopically corresponding luminance contrast reduces sensitivity to between-eye differences in hue.

Hue experiment: Spatially extended luminance contrast control

In order to determine if the loss in sensitivity caused by binocular luminance contrast in the dichoptically superimposed condition depends on whether or not the luminance and chromatic signals are spatially coextensive, we conducted an additional control experiment. The control condition is illustrated in Figure 4a, and consisted of the isoluminant condition and ±0.4 luminance contrast increments and decrements that were spatially extended to fill the entire aperture visible through the stereoscope (~9.8° × 12.4°). The red points in Figure 5 are the results for the previous three observers. The black points from Figure 4a are included for comparison. The isoluminant thresholds were unsurprisingly the same as those previously collected under identical conditions. Unlike the spatially coextensive luminance increments and decrements (black points), the full-aperture luminance increments and decrements (red points) had almost no effect on thresholds. One data point for one observer (GS)

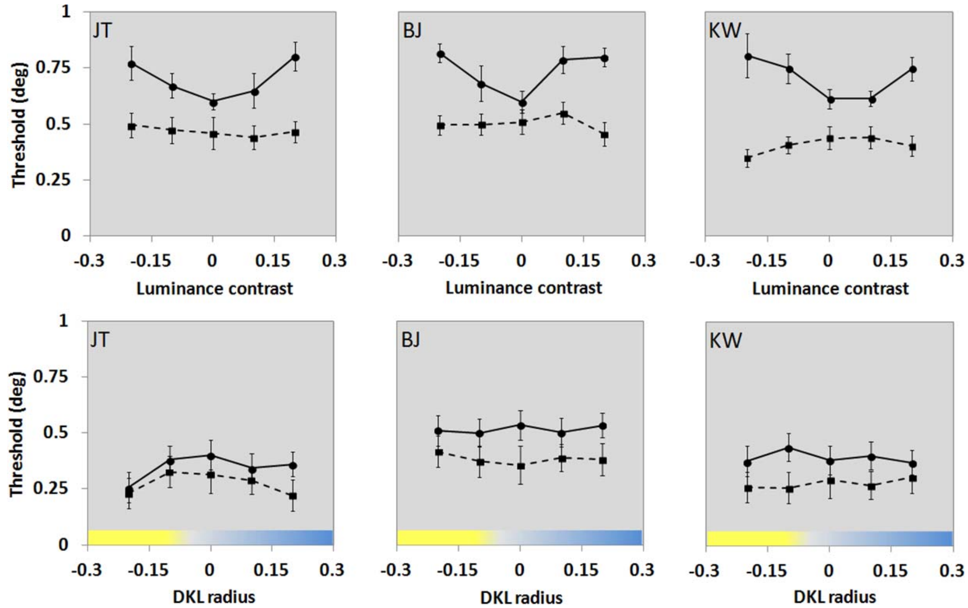

Figure 8. Top row: plots of saturation-difference thresholds as a function of binocular luminance contrast for dichoptic (circles connected with solid lines) and binocular (squares connected with dashed lines) stimuli for each observer. Bottom row: Plots luminance contrast–difference thresholds as a function of chromatic contrast for dichoptic (circles connected with solid lines) and binocular (squares connected with dashed lines) stimuli for each observer.

deviated from this lack of effect. Overall the results indicate that binocular luminance contrast only elevates between-eye hue difference DTs when the chromatic and luminance contrasts are spatially coextensive.

Ring border experiment

Adding a luminance decrement to the stimuli introduces a common feature in the two eyes. Does this common feature have to be a coextensive luminance decrement? Here we test whether a surround decrement ring has a similar effect. A thin black border (2 pixels thick) was added to the stimulus bounding the patches, as indicated in Figure 6a. Figure 6b shows the results for observers BJ (nonnaive) and GS (naive). The black lines/symbols represents BJ's and GS's data from Figure 4a (i.e., using the spatially coextensive luminance contrast). The red lines/symbols show the black ring data. The two sets of data are nearly identical suggesting that the black ring has no effect.

Unmatched luminance contrast

Does the added luminance contrast need to be matched in the two eyes in order to elevate thresholds for between-eye detection? An experiment suggested by an anonymous reviewer was conducted in which the matched binocular luminance contrast was replaced by mismatched luminance contrast between the two eyes. To produce mismatched luminance, we added a luminance increment to one eye and a luminance decrement (of equal amplitude) to the other. Between-eye hue DTs were measured using an identical procedure as previously employed; the two conditions tested were otherwise the same as the dichoptic and binocular conditions illustrated in Figure 4a and c, respectively. Example color and luminance profiles for both dichoptic and binocular conditions are illustrated in Figure 7a. Figure 7b plots the results for two observers (BJ, an author, and MO, a naive observer). The circles connected with solid lines represent the dichoptic conditions, with black lines/symbols representing the matched luminance conditions, and red lines/symbols representing the unmatched luminance conditions. The square symbols connected with dashed lines represent the binocular data, with black lines/symbols representing the matched luminance conditions, and red lines/symbols representing the unmatched luminance conditions. As the figure shows, whereas with matched luminance contrast, observers' thresholds were elevated for dichoptic but not binocular conditions, with unmatched luminance contrast, thresholds were elevated equally for both dichoptic and binocular conditions. This demonstrates that adding matched luminance contrast has a uniquely dichoptic threshold elevation effect.

Saturation-difference results

Figure 8 shows dichoptic saturation-difference thresholds as a function of binocular luminance contrast for each observer. The dichoptically superimposed thresholds are the round points joined by solid lines, and the binocular thresholds are the square points joined by dashed lines. Error bars represent ±2 *SEM*s. The maximum and minimum luminance contrast levels for which measurable thresholds could be obtained, ±0.2, was less than those used with the hue experiment. As the figure shows, the pattern of data is similar to that of the hue experiments. Figure 8b deals with the reverse situation: the effect of added chromatic contrast on luminance-contrast-difference thresholds. The dichoptic data this time, however, does not have the V-shape of previous experiments, showing that irrelevant chromatic information does not raise thresholds for detecting between-eye luminance contrast differences.

Model: Binocular luminance contrast reduces the gain of interocular suppression between chromatic signals

How are these results best explained? Our working hypothesis is that the binocular luminance contrast reduces the gain on the interocular suppression among the disparate chromatic signals. To model this we have taken a conventional model of binocular interaction—the two-stage contrast gain control model employed by Meese, Georgeson, and Baker (2006)—and changed it in two fundamental ways. The first change is to enable it to model the detection of binocular differences. Models of binocular interaction typically sum the signals from the two eyes; in our model we take the difference between the two eyes' signals. Second, we incorporate a gain parameter on the interocular suppression with a magnitude that varies according to the strength of the signal from another dimension—in this case, the amount of added binocular luminance contrast.

In the first stage of the model, the signals generated by the left (L) and right (R) eyes are represented by Equations 1 and 2, respectively, where, $resp(L)$ and $resp(R)$ are the model responses of the LE and RE, respectively. The parameters L and R represent the chromatic signals in the LE and RE, respectively, and are represented in terms of hue angles. The constant s is a parameter that controls the shape of the transducer function. The numerators in these expressions represent the eyes' input signal, which is typically raised to a power greater than unity. However, we found that we were able to satisfactorily model our data with the exponent set to unity, and hence the exponent is omitted. The denominators represent the suppression acting on the signal. The total amount of suppression equals the sum of three components. The first is a suppressive signal from the same eye, in keeping with the results from conventional masking studies (e.g., Legge & Foley, 1980). The second is an inhibitory signal from the other eye to model interocular suppression, in keeping with dichoptic masking (Meese et al., 2006). The weighting function w controls the magnitude of this interocular suppression and is a function of the amount of added binocular luminance contrast (C_{lum}) as described by Equation 3. A fixed weighting on interocular suppression has been employed in other dichoptic interaction models (e.g., Kim, Gheiratmand, & Mullen, 2013; Zhou, Georgeson, & Hess, 2014), but here the weighting is a variable parameter controlled by the magnitude of another dimension. The final term is s, which is typically a free parameter.

$$resp(L) = \frac{L}{L + wR + s} \qquad (1)$$

$$resp(R) = \frac{R}{R + wL + s} \qquad (2)$$

Equation 3 indicates how w varies with the added binocular luminance contrast (C_{lum}).

$$w(C_{lum}) = \frac{1}{1 + 1.4\sqrt{|C_{lum}|}} \qquad (3)$$

The constants were obtained via a custom least squares–fitting algorithm. The modulus of the luminance contrast is taken to avoid a square rooting of a negative number when applied to the luminance decrements ($C_{lum} < 0$). The function described by Equation 3 is plotted in Figure 9a. The isoluminant condition is represented in the middle of the abscissa at $C_{lum} = 0$ (the vertical dashed line). As can be seen, as luminance contrast is added, the value of $w(C_{lum})$ systematically decreases.

The outputs of the two eyes' signals are then differenced, taking the modulus of the difference to keep the result positive.

$$resp(L, R) = |respL - respR| \qquad (4)$$

As previously defined, the threshold in the hue difference experiment is defined as a difference in hue angle between the eyes. As expressed in Equation 5, we assume that at threshold there is a criterion level of difference between the internal binocular response to the stimulus with a between-eye difference, $resp(L, R)_{diff}$, and the internal binocular response to the stimulus with no between-eye difference, $resp(L, R)_{same}$. Hence:

$$resp(L, R)_{diff} = resp(L, R)_{same} + Threshold \qquad (5)$$

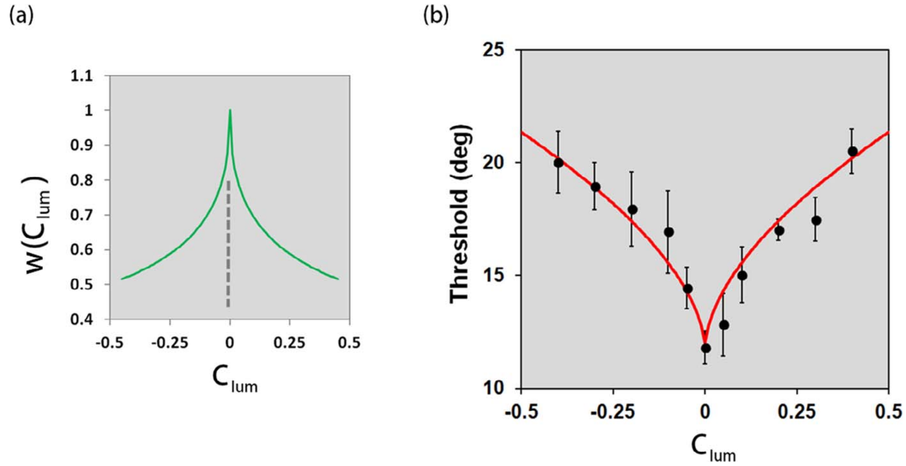

Figure 9. (a) Plot of the gain $w(C_{lum})$ on the interocular suppression as a function of added binocular luminance (C_{lum}). (b) Plots the average thresholds (black circles) for the between-eye hue detection task, again as a function of added binocular luminance (the ranges of abscissa in [a] and [b] are equal). The red curve is the model fit as calculated using Equation 3, coupled with Equation 4 driving the change in interocular suppression.

Figure 9b plots the mean threshold data for the between-eye hue difference task as a function of added binocular luminance contrast. The model output is obtained by substituting $w(C_{lum})$ into Equation 3; the red curve plots the model output in Figure 9b (the abscissas in Figure 9a and b are identical). The model is consistent with the data and the hypothesis that increasing the matched binocular luminance contrast signal reduces the gain on the interocular suppression, which in turn reduces sensitivity for luster detection.

How would $w(C_{lum})$ be assumed to vary for the other viewing conditions, that is where the color patches are not spatially superimposed between-eyes, as illustrated in Figure 2a through c? Since the thresholds in each of these conditions are independent of added binocular luminance contrast levels (see data in Figure 4b through d), the function $w(C_{lum})$ is simply modeled as a flat, horizontal line.

Discussion

Results for both the dichoptic hue difference and saturation difference experiments showed a similar pattern. In the dichoptically superimposed conditions, the addition of increments or decrements of binocular luminance contrast reduced sensitivity for the detection of the between-eye differences, provided the luminance and color contrasts were spatially coextensive. Yet both hue and saturation thresholds were unaffected by luminance contrast when the disks, rather than being superimposed, were presented side by side on the screen, and viewed either dichoptically (Figure 4b), binocularly (Figure 4c), or monocularly (Figure 4d). This second result is more consistent with previous psychophysical (Gegenfurtner & Kiper, 1992; Sankeralli & Mullen, 1997) and physiological (Lee, Sun, & Valberg, 2011) studies showing that the detection of chromatic contrast is largely unaffected by masking luminance contrast, and that therefore the mechanisms for color and luminance detection are largely independent.

Why then are thresholds for dichoptic chromatic differences not independent of task-irrelevant binocular luminance contrast signals? One possible candidate is desaturation. In a recent study Bimler, Paramei, and Izmailov (2009) showed how luminance contrast decreased the apparent saturation of chromatic signals. A desaturation of the colors in our dichoptic stimuli would likely bring them closer together in perceptual color space and as a result make them harder to discriminate. However, desaturation should equally affect the colors when presented side by side on the screen, yet in this condition there was no threshold elevation from the added binocular luminance contrast. Therefore, desaturation cannot be the cause.

Rather, our findings are consistent with the idea that binocularly matched luminance contrast reduces the interocular suppression between disparate color signals, resulting in reduced sensitivity to between-eye differences. That matched features reduce the interocular suppression between unmatched features is not a new finding. Blake and Boothroyd (1985) showed that perceptual alternation rates between gratings of opposite orientation in the two eyes were reduced when a third grating was added to one eye such that one eye viewed a plaid and the other a grating. It was concluded that the grating components that were matched in orientation in each eye were not binocularly suppressed and acted to promote fusion of the images. The Kingdom and Libenson (2015) and Kingdom and

Wang (2015) studies described in the Introduction attest directly to the idea that matched luminance signals reduce interocular suppression between unmatched chromatic signals.

Object commonality hypothesis

What purpose is served by reducing interocular suppression in this way? One idea is that matched features promote the interpretation that unmatched features nevertheless originate from a single object (Baker, Meese, & Summers, 2007; Kingdom & Libenson, 2015; Kingdom & Wang, 2015), which has been termed the "object commonality hypothesis" (Kingdom & Libenson, 2015; Kingdom & Wang, 2015). Luminance information has been shown to be dominant during the fast detection of edges (Gegenfurtner & Rieger, 2000), ultimately leading, via a series of mid- (e.g., contour integration) and high-level processes (e.g., memory access), to the recognition and classification of objects. It has been shown in a number of studies that edges in natural scenes have both luminance and chromatic contrast (Fine, MacLeod, & Boynton, 2003; Hansen & Gegenfurtner, 2009; Johnson, Kingdom, & Baker, 2005). If, as Hansen and Gegenfurtner (2009) suggest, the visual system evolved to take advantage of both information sources, then luminance and chromatic information originating from similar spatial arrangements and shapes, and projected onto corresponding retinal locations, are more likely to be interpreted as single objects in space.

Is the object commonality hypothesis however inconsistent with our findings with *mismatched* luminance contrasts? Thresholds in the dichoptic conditions were elevated by mismatched, not just matched luminance contrast, which at face value argues against a special role for matched luminance contrasts, and hence against the object commonality hypothesis. However, with mismatched luminance contrasts, subjects have to detect not luster in one alternative but a difference in luster between two alternatives. This would be analogous to the effect of a pedestal on contrast increment detection, where the pedestal has the effect of elevating thresholds. The object commonality idea posits a reduction in the between-eye difference between pairs of disparate hues/saturations, causing an increase in the threshold for detecting those differences. However, an increase in thresholds might also occur for other reasons, such as the presence of a pedestal level of between-eye difference, and we believe this to be the case. This is consistent with our finding that in the binocular mismatched luminance condition, in which the patches were spatially separated on the screen and in which there was a pedestal level of difference in both alternatives, thresholds were similarly elevated. Thus object commonality might still mediate the main effect of our study. The result with mismatched luminance contrast does, however, underscore the limitations of our model. As the model stands, the presence of matched luminance contrast reduces the interocular competition that normally facilitates the detection of between-eye differences, via a single parameter applied to both eyes' signals. The model therefore cannot handle the effects of mismatched luminance contrast, which doubtless produces the complex set of between-eye masking interactions that presumably underpins the results from this condition. Future research will hopefully provide the necessary data to enable the model to be refined, allowing it to describe luster DTs under conditions of between-eye mismatches in both luminance as well as chromatic contrast.

Keywords: between-eye color detection, hue, saturation, luminance contrast, binocular, dichoptic, interocular suppression

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References

Alais, D., & Blake, R. (2005). *Binocular rivalry*. Cambridge, MA: MIT Press.

Baker, D. H., Meese, T. S., & Summers, R. J. (2007). Psychophysical evidence for two routes to suppression before binocular summation of signals in human vision. *Neuroscience*, *146*, 435–448.

Bimler, D. L., Paramei, G. V., & Izmailov, C. A. (2009). Hue and saturation shifts from spatially induced blackness. *Journal of the Optical Society of America A*, *26*, 163–172.

Blake, R. (2001). A primer on binocular rivalry, including current controversies. *Brain and Mind, 2*(1), 5–38.

Blake, R., & Boothroyd, K. (1985). The precedence of binocular fusion over binocular rivalry. *Perception & Psychophysics*, *37*, 114–124.

Buckthought, A., & Wilson, H. R. (2007). Interaction between binocular rivalry and depth in plaid patterns. *Vision Research*, *47*, 2543–2556.

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

Fine, I., MacLeod, D. A., & Boynton, G. M. (2003). Surface segmentation based on the luminance and color statistics of natural scenes. *Journal of the Optical Society of America A*, *20*, 1283–1291.

Formankiewicz, M. A., & Mollon, J. D. (2009). The psychophysics of detecting binocular discrepancies of luminance. *Vision Research*, *49*(15), 1929–1938.

Gegenfurtner, K. R., & Kiper, D. C. (1992). Contrast detection in luminance and chromatic noise. *Journal of the Optical Society of America*, *A*, *9*(11), 1880–1888.

Gegenfurtner, K. R., & Rieger, J. (2000). Sensory and cognitive contributions of color to the recognition of natural scenes. *Current Biology*, *10*, 805–808.

Hansen, T., & Gegenfurtner, K. R. (2009). Independence of color and luminance edges in natural scenes. *Visual Neuroscience*, *26*, 35–49.

Jennings, B. J., & Martinovic, J. (2014). Luminance and color inputs to mid-level and high-level vision. *Journal of Vision*, *14*(2):9, 1–17, doi:10.1167/14.2.9. [PubMed] [Article]

Johnson, A. P., Kingdom, F. A. A., & Baker, C. L., Jr. (2005). Spatiochromatic statistics of natural scenes: First- and second-order information and their correlational structure. *Journal of the Optical Society of America A*, *22*, 2050–2059.

Kim, Y. J., Gheiratmand, M., & Mullen, K. T. (2013). Cross-orientation masking in human color vision: Application of a two-stage model to assess dichoptic and monocular sources of suppression. *Journal of Vision*, *13*(6):15, 1–14, doi:10.1167/13.6.15. [PubMed] [Article]

Kingdom, F. A. A., & Libenson, L. (2015). Dichoptic saturation mixture: Binocular luminance contrast promotes perceptual averaging. *Journal of Vision*, *15*(5):2, 1–15, doi:10.1167/15.5.2. [PubMed] [Article]

Kingdom, F. A. A., & Wang, D. (2015). Dichoptic colour-saturation masking is unmasked by binocular luminance contrast. *Vision Research, 116,* 45–52, doi:10.1016/j.visres.2015.08.016.

Lee, B. B., Pokorny, J., Smith, V. C., Martin, P. R., & Valberg, A. (1990). Luminance and chromatic modulation sensitivity of macaque ganglion cells and human observers. *Journal of the Optical Society of America A: Optics and Image Science*, *7*, 2223–2236.

Lee, B. B., Sun, H., & Valberg, A. (2011). Segregation of chromatic and luminance signals using a novel grating stimulus. *The Journal of Physiology*, *589*, 59–73.

Legge, G. E., & Foley, J. M. (1980). Contrast masking in human vision. *Journal of the Optical Society of America*, *70*, 1458–1471.

Malkoc, G., & Kingdom, F. A. A. (2012). Dichoptic difference thresholds for chromatic stimuli. *Vision Research*, *62*, 75–83.

Meese, T. S., Georgeson, M. A., & Baker, D. H. (2006). Binocular contrast vision at and above threshold. *Journal of Vision*, *6*(11):7, 1224–1243, doi:10.1167/6.11.7. [PubMed] [Article]

Meese, T., & Hess, R. (2005). Interocular suppression is gated by interocular feature matching. *Vision Research*, *45*, 9–15.

O'Shea, R. P. (1987). Chronometric analysis supports fusion rather than suppression theory of binocular vision. *Vision Research*, *27*(5), 781–791.

Prins, N., & Kingdom, F. A. A. (2009). Palamedes: Matlab routines for analyzing psychophysical data. Retrieved from http://www.palamedestoolbox.org

Sankeralli, M. J., & Mullen, K. T. (1997). Postreceptoral chromatic detection mechanisms revealed by noise masking in three-dimensional cone contrast space. *Journal of the Optical Society of America A*, *14*, 2633–2646.

Walsh, J. W. T. (1958). *Photometry* (3rd ed.). London: Constable & Co.

Watson, A. B., & Pelli, D. G. (1983). QUEST: A Bayesian adaptive psychometric method. *Perception & Psychophysics*, *33*, 113–120.

Wyszecki, G., & Stiles, W. S. (2000). *Color science: Concepts and methods, quantitative data and formulae* (2nd ed.). New York: Wiley.

Yoonessi, A., & Kingdom, F. A. A. (2009). Dichoptic difference thresholds for uniform color changes applied to natural scenes. *Journal of Vision*, *9*(2):3, 1–12, doi:10.1167/9.2.3. [PubMed] [Article]

Zhou, J., Georgeson, M., & Hess, R.F. (2014). Linear binocular combination of responses to second-order stimuli: Data and model. *Journal of Vision*, *14*(13):24, 1–19, doi:10.1167/14.13.24. [PubMed] [Article]