

Achromatic form perception is based on luminance, not brightness

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Two figures were examined, one a subjective disk and the other a cup whose shape was revealed by shadows. The figures were presented in a single color on a background of a different color, and the observers adjusted the radiance of one color until, in the first case, the vividness of the subjective contour reached a minimum (minimum subjective contour) or, in the second case, the impression of depth that is due to shadows disappeared (shadow disappearance). The results for these two tasks followed the data for minimum flicker matches (made with the same stimuli) much more closely than those for direct brightness matching. We therefore claim that achromatic form perception in general and subjective contour and shadow perception in particular are based on the intensity dimension measured by flicker photometry, not on that measured by brightness matching. Finally, in agreement with these findings, bleaching of short-wavelength sensitive cones did not affect settings for subjective contours, shadows, or flicker photometry but did affect brightness matching.

INTRODUCTION

The richness of visual experience provided by black-and-white photographs of natural scenes suggests that achromatic information is a major contributor to form perception. Certainly the interpretation of a scene is degraded if the same image is rendered only by its chromatic patterns with no variation in luminance. While there is little debate about the importance of achromatic information for form perception, there is some debate concerning which of two metrics—luminance or brightness—best characterizes the intensity dimension of the pathway or pathways involved. In this paper we shall show that luminance-type scale is the appropriate dimension for chromatic form perception.

Luminance¹ has been most closely linked with heterochromatic flicker photometry. In this task, two colored lights are alternated rapidly (approximately 15 Hz) and their relative radiances are adjusted until the observer reports that the sensation of flicker caused by their alternation has reached a minimum. The rationale for this task is that the chromatic pathways have a lower temporal frequency cutoff than the achromatic pathways²⁻⁴ and do not register the rapid color alternation; the setting is therefore based on equal response of the achromatic pathway to both colors. In fact, observers report that there is no sensation of chromatic flicker in these tests at the minimum flicker setting.

Several studies have suggested that luminance is the intensity dimension that characterizes achromatic form vision. For example, when the strength of the border defined by two fields is minimized (minimally distinct border) the relative radiances of the pair of lights is similar to the situation in which the same lights are evaluated

by minimum flicker.⁵ In addition, the relative radiances of lights that produce minimal visual acuity in a Snellen-type task show additivity properties similar to those of heterochromatic flicker photometry.⁶

Brightness is a second dimension that can be used to characterize the intensity of light. Equal intensity in terms of brightness is typically measured by the direct brightness matching method, in which the observers equate their subjective impression of brightness between two fields of different color. Studies have shown that settings of equal brightness and of equal luminance can differ substantially.^{5,7} In particular, direct heterochromatic brightness matches show higher sensitivity to short and long wavelengths than do minimum flicker matches.

The difference in results between brightness and luminance settings may be due to the differences in the stimuli used in the two techniques. Minimum flicker adjustments are based on high temporal frequencies. The stimuli used for brightness settings involve low temporal frequencies since they are presented as a static field or as pulses of relatively long duration. The minimally distinct borders studied by Boynton and his colleagues^{4,5} contain significant energy at high spatial frequencies. The settings in this task produce results similar to those for flicker judgments. It is not clear which, if any, of these judgments is appropriate for the typical conditions of viewing of colored objects in everyday scenes. It may be the case that the intensity dimension underlying achromatic form vision for ordinary figures in steady viewing is most similar to that measured by brightness settings. It may be that brightness and luminance measurements are mediated by the same mechanism and give different values only because of the differences in the stimuli used. In fact, the spectral sensitivity of brightness matches ap-

proaches that of flicker matches when either the stimulus duration⁹ or the stimulus size^{9,10} is decreased. On the other hand, two recent studies report little effect of stimulus properties. Lindsey and Teller¹¹ reported the spectral characteristics of minimally distinct border settings unchanged even when blurred edges [up to approximately 1 cycle/deg (cpd) of cutoff frequency] were used as stimuli; this suggests that high spatial frequencies may not be critical. Kaiser *et al.*¹² showed that brightness matching did not change the characteristics of the settings even for temporally modulating stimuli at high frequency.

In order to explore whether achromatic form vision is based on luminance or brightness, we introduced two form-based criteria for equating the achromatic intensity of two fields: the perception of subjective contours and the perception of shape from shadows. These two criteria were adopted because neither subjective contours nor shape-from-shadows appears to be highly sensitive to color differences. When a subjective contour figure is presented in color, say, red on green, and the relative intensity of the two colors is adjusted, the subjective contour weakens or vanishes at one particular setting.¹³⁻¹⁶ Similarly, shape-from-shadows is eliminated at a particular setting of relative intensity between two colors in a colored figure.^{14,17} Since these two types of stimulus show minima in effectiveness at a particular setting of relative intensity, they must rely on achromatic contrast for some or all of their strength. The achromatic contrast between two colors must pass through a minimum if the relative intensities of the colors are varied over a wide enough range, and the goal of the study reported in this paper is to determine whether the settings of minimum effectiveness—zero achromatic contrast—correspond to equal luminance or to equal brightness. We also considered these two criteria appropriate because they are both based on judgments of form without involving especially high spatial or temporal frequencies.

In the first experiment, a subjective disk [Fig. 1(a)] was used as the stimulus. With the radiance of one of the colors in the figure held constant, observers adjusted the radiance of the other until the vividness of the subjective disk reached a minimum. The second experiment used a figure of a cup whose shape was revealed by shadows [Fig. 1(b)]. Observers again adjusted the radiance of one of the colors until the impression of depth caused by shadows disappeared. The stimuli of Fig. 1 are composed of sharp borders, and it could be argued that the perception of the subjective figure and the shadows is mediated by high spatial frequencies, somewhat negating the purpose of our experiment. However, subjective contours are visible in low-pass filtered images (containing only low spatial frequencies) as well as in unfiltered images,¹⁸ and we used blurred versions of the subjective disk in our experiment to verify that our measurements were relevant for images containing only low spatial frequencies. The perception of shape-from-shadows for figures such as Fig. 1(b) is also mediated by a fairly broad range of spatial frequencies.¹⁷

To determine whether the settings for subjective contour and shadow were based on luminance or brightness, we compared the settings in these tasks with both minimum flicker settings and brightness matches made by using the same stimuli in an additivity paradigm.

If luminance is the intensity dimension that mediates subjective contour and shape-from-shadows, we expect that the settings will be similar to the minimum flicker settings, whereas, if brightness is the intensity dimension that mediates the tasks, the settings should be similar to those of the brightness matches. Since different areas of these complex stimuli may be involved in making the judgments of the individual tasks, we do not compare absolute settings directly. We use the pattern of settings over the range of mixtures examined in the additivity paradigm to make the comparison.

We also examine the additivity of these different tasks. Brightness matches are most often nonadditive,¹⁹ whereas flicker matches are most often additive.^{20,21} The additivity of the shadow and subjective contour settings should therefore also reveal which intensity dimension is mediating form perception in these tasks.

In the additivity procedure that we use, one region of the image (reference) is filled with one of two colors, red, for example, at a fixed radiance, whereas the other region (test) is filled with a variable mixture of the first color, red, with a second, say, green. The experimenter varies the amount of red in the test field, and the observer adjusts the radiance of green, again in the test field, to equate, say, brightness between the test and reference fields. For each of several radiances of red mixed in the test field, the observer adjusts the additional amount of green required to make the brightness (or flicker, etc.) match. If additivity holds, a plot of the variations of these two radiances (red and green) in the test field should fall upon a straight line.⁴

Finally, we also examine the contribution of the short-wavelength-sensitive cones (B cones) to the settings in these tasks. B cones are assumed to contribute strongly to brightness matching²² but only weakly to luminance.²³⁻²⁵ We compare settings in the four tasks—minimum flicker, brightness matching, minimum shadow, and subjective contour settings—both with and without B cones. B-cone response is suppressed by bleaching with an intense violet light.

EXPERIMENT 1: SUBJECTIVE CONTOUR

We used the additivity paradigm to compare settings for minimum subjective contour, minimum flicker, and

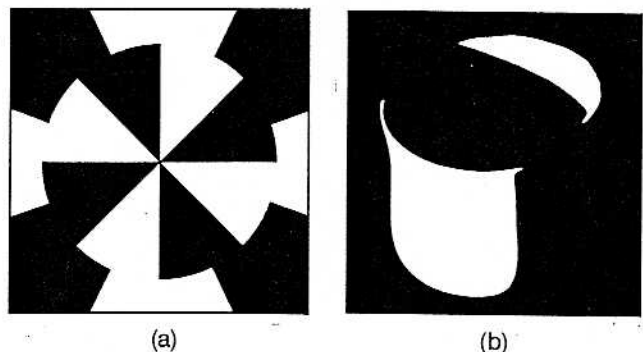


Fig. 1. (a) Stimulus figure used in Experiment 1. The disk is defined by four subjective arcs and four real arcs. (b) Stimulus figure used in Experiment 2. The shape of a cup is revealed when the black areas within the cup and on its right-hand side are interpreted as a shadow.

brightness matching, always using the same subjective disk figure shown as Fig. 1(a). The white parts of the figure were filled with a color mixture and used as the test field. The black parts were filled with the reference color and used as the reference field. When the test field was set distinctly either brighter and more luminous or darker and less luminous than the reference field, clear subjective arcs were seen between the real arcs of the stimulus. Observers saw a disk rather than the four irregular polygons that were bordered by real contours [Fig. 1(a)]. When the test and reference areas approached equal intensity, the strength of the subjective disk decreased to a minimum or disappeared completely. In these instances, the stimulus figure was often organized as four polygons.

Note that the observers' task was to minimize the vividness of the subjective disk. They did not pay attention to the sharpness of the real borders of the figure (although the same mechanism may control both precepts). In fact, the criterion of vividness was easily adopted for the blurred version of the subjective figure in our experiment, suggesting that minimum subjective contour settings are not based on the strength of sharp edges.

Stimuli and Apparatus

A computer-controlled image processor displayed the stimulus on a video monitor. Two stimulus sizes were used: $10^\circ \times 10^\circ$ and $2^\circ \times 2^\circ$ of visual angle with 512×480 and 100×95 pixels, respectively, and the diameter of the subjective disk was 8° for the 10° stimulus and 1.6° for the 2° stimulus. For both sizes, the monitor was 154 cm in front of the observer in an otherwise dark room. Two color pairs were used: one red/green with red in the reference field and the other yellow/blue with blue in the reference field. Both of the reference colors were set to a fixed luminance (15 cd/m^2). The x and y values in CIE color coordinates are 0.611, 0.344 for red; 0.301, 0.607 for green; 0.499, 0.440 for yellow; and 0.151, 0.074 for blue. Red, green, and blue were generated by the individual red, green, and blue phosphors of the monitor, and their CIE coordinates were measured by spectroradiometry. Yellow was a mixture of lights from the red and green phosphors with each phosphor producing equal luminance, and the CIE coordinates were calculated in this case for the equiluminant mixture of red and green. The color names—red, green, yellow, and blue—refer hereafter to these colors generated on the monitor. The minimum step of intensity change on the display was 0.24 cd/m^2 or less for yellow and 0.18 cd/m^2 or less for green when these were the colors with variable intensity in the task.

Procedure

The observers adjusted the radiance of green (for the red/green pair) or yellow (for the yellow/blue pair) in the test field, to minimize the vividness of the subjective disk in Fig. 1(a). The proportion of red (for the red/green pair) or blue (for the yellow/blue pair) mixed in the test field was set at 0.0, 0.2, 0.4, 0.6, or 0.8 with respect to the radiance of the reference color. In addition to the minimum subjective contour setting, heterochromatic flicker photometry and direct brightness matching were performed for comparison in the same figure. In the brightness-

matching task, the observers were instructed to consider the brightness of all areas in the figure. For minimum flicker, the subjective contour figure was alternated at 15 Hz with a uniform red field (for the red/green pair) or a uniform blue field (for the yellow/blue pair). The radiance of these uniform fields was the same as that of reference red or blue, so only the test fields were used to minimize flicker perception. For the 10° stimulus, a small (0.4° -diameter) bull's-eye was located on the center of the figure as a fixation spot, while the observers were asked to fixate the 2° stimulus on its center without any fixation spot. Consequently, the arcs of the stimulus disk fell entirely outside the central visual field where macular pigments might influence the settings ($<1.5^\circ$ eccentricity) for the 10° condition, whereas they fell completely within the macular pigmentation area for the 2° stimulus. For minimum flicker settings in the yellow/blue pair of 10° figures, however, filtering macular pigments caused the least-flickering parts of the stimulus figure to shift from the central visual field to the periphery as the intensity of the yellow light increased. Observers set the minimum flicker while attending to the area around the arcs (outside the macular pigmentation area) and kept their criterion constant throughout the task. The observers made all settings monocularly with the right eye.

A single session tested only one of two color pairs at one of the two sizes. Before each session, the observers were adapted to the darkness in the experimental room for ~ 5 min. First in a session, red (or blue) was mixed in the test field in the proportion of 0.0, and the observers adjusted the radiance of green (or yellow) to satisfy a given criterion (minimum flicker, minimum subjective contour or brightness matching). This was repeated five times sequentially, with a 3-s presentation of a uniform white field (15 cd/m^2) between settings. Then the proportion of red (or blue) was increased one step (0.2) to repeat the setting with this new amount of mixed red (or blue). After a series of settings for five proportions (0.0, 0.2, 0.4, 0.6, and 0.8), which were completed without changing task, the observers started the settings for the next series using another criterion. Three different tasks (minimum subjective contour, minimum flicker, and brightness matching) were completed in the same session.

Observers

The two authors, SS and PC, who have normal color vision and normal or corrected-to-normal acuity, served as observers. Observer SS participated in the conditions of two different stimulus size (10° and 2°), while observer PC completed the settings only with the 10° stimulus.

Results and Discussion

Figure 2 shows the relative radiance of the adjustment of green (for a red/green pair) or yellow (for a yellow/blue pair) as a function of the proportion of red or blue mixed in the test field. These values are normalized so that the radiance of green (or yellow) is 1.0 when no red (or blue) was mixed in the test fields. This produces the conventional plots for the additivity test. Results from all conditions (four for observer SS and two for observer PC) are plotted in separate panels for the two observers. Squares represent the settings for brightness matching, crosses

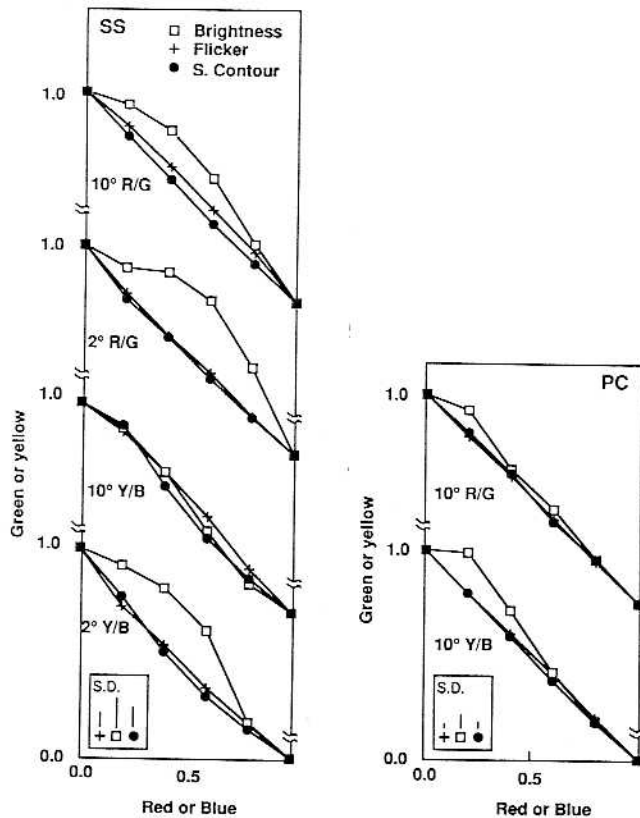


Fig. 2. Proportion of green (for the red/green pair) or yellow (for the yellow/blue pair) in the test field for minimum flicker, brightness match, or minimum subjective contour settings as a function of the proportion of red (for the red/green pair) or blue (for the yellow/blue pair) mixed in the test field. The values of the green or yellow settings are normalized so that the radiance of green or yellow is 1.0 when no red or blue is mixed in the test field. The data for the brightness matches are shown as squares, those for minimum flicker as crosses, and those for minimum subjective contour as filled circles. Median standard deviations (not standard errors) for each setting are shown in the small insets for each observer.

those for minimum flicker, and filled circles those for minimum subjective contour. Each point is the average of 15 adjustments (from three sessions) for SS and 5 adjustments (from one session) for PC. The standard deviation (not standard error) calculated from all the conditions for each of three tasks is shown in the inset for each observer.

For all conditions and both observers, the normalized settings of minimum subjective contour and minimum flicker are always fairly close to each other and lie near the diagonal additivity function (the line connecting 0, 1, and 1, 0). In contrast, the settings for brightness matching often (though not always) deviate from the other two as well as from the additivity function. There are notable exceptions, however, in the 10° data for observer SS for the yellow/blue pair, where the results from the all three settings are similar. In addition, there are substantial differences between the brightness-matching data for the two observers. The brightness settings of PC showed more additivity than those of SS and deviate from the flicker and subjective contour settings for only one or two points in each condition. Interobserver differences in brightness perception were reported previously,¹⁰ and the magnitude of additivity failure for brightness matches has been found to vary for different observers.²⁶ Despite the

interobserver differences in our data, it is clear that the flicker and subjective contour settings are quite similar and that, wherever large deviations occur among the three settings, they only involve brightness matches.

To make the subjective contour settings, observers minimized the visibility of the illusory contours. However, it may have been the presence of high spatial frequencies in the stimulus that made luminance more influential than brightness for these settings. In particular, it has already been shown that settings for minimally distinct borders, which may also depend on high-spatial-frequency components (but see Lindsey and Teller¹¹), follow luminance settings more closely than brightness settings: border distinctness is minimized for settings close to those for equal luminance (minimum flicker) even when the observer sees a difference in brightness.^{4,5} If the subjective contour settings were dominated by luminance because of the high-spatial-frequency content of the stimuli, then our results could change if the high spatial frequencies were removed from the stimulus figure. To eliminate the possible contribution from high-spatial-frequency components, we blurred the subjective-contour figure.

Blurred Image

Using a Gaussian filter, we removed frequencies higher than 0.72 cpd (the half-amplitude frequency) from the 10° figure and those greater than 1.6 cpd from the 2° figure. Observer SS repeated all conditions with the blurred images, whereas the other observer, PC, was used only in the red/green conditions with the 10° figure.

Figure 3 shows the results for the blurred image. It is clear that blurring the image had little effect on the settings for either minimum subjective contour or minimum flicker. Some reduction in the deviation from additivity is seen for brightness matching, and again for observer PC, brightness matches showed little deviation from linearity. The matches were nevertheless consistently higher than both the flicker and subjective contour settings, which themselves were extremely close to each other.

The agreement of the results for blurred images with those for the nonblurred images also suggests that luminance artifacts from chromatic aberration did not affect the minimum subjective contour settings. If chromatic aberration had affected the perception of subjective contours in our experimental conditions, the results would have been altered by filtering the stimulus image, since chromatic aberration is spatial frequency dependent and at 1.0 cpd the luminance artifact in the red/green condition that is due to chromatic aberration is less than 0.5% for the red and green phosphors of our condition.²⁷

Statistical Test

In order to determine whether the subjective contour settings were more similar to the flicker or to the brightness judgments, we examined the differences between the settings from each of the tasks. A one-way analysis of variables was run with three levels of the task variable—flicker, brightness, and subjective contour. The different conditions (all combinations of field size, blur, and reference field mixture, a total of 24 for observer PC and 64 for observer SS) were taken as equivalent to a subjects factor, and the task variable was a repeated measure. The tasks were compared two at a time as planned comparisons with

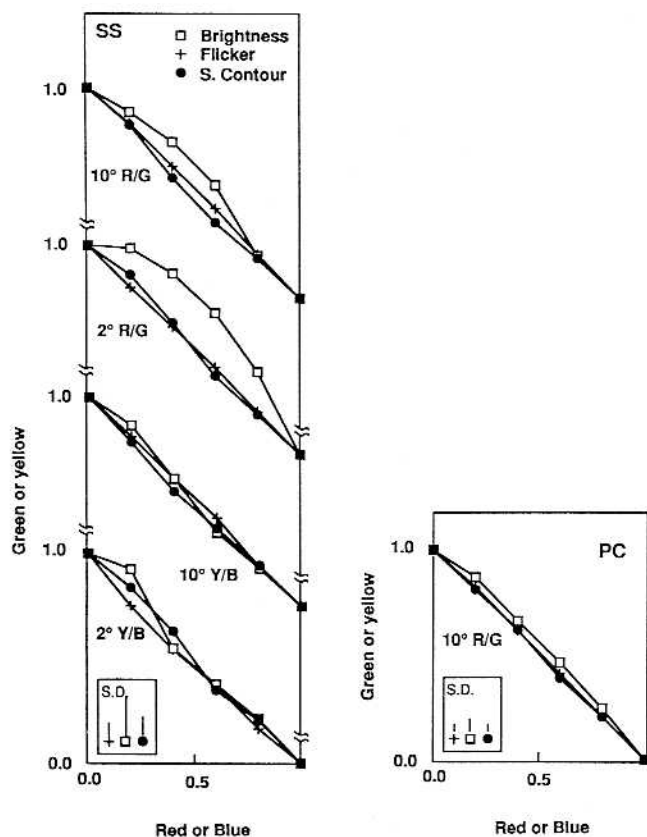


Fig. 3. Minimum subjective contour, flicker, and brightness settings for the blurred disk stimulus. Squares, crosses, and filled circles represent the brightness matches, minimum flicker, and minimum subjective contour settings, respectively. Conventions otherwise as in Fig. 2. The 10° figure is filtered by a low-pass Gaussian with a half-amplitude frequency of 0.72 cpd, and the 2° figure is filtered by a low-pass Gaussian filter with a half-amplitude frequency of 1.6 cpd.

the total number of comparisons taken into account in the significance level. This analysis is similar to, but more reliable than, three separate t tests, since the data are used only once to compute a single error term for each observer. The results indicate that the minimum subjective contour settings did not differ significantly from the minimum flicker settings [$F(1, 22) = 0.07$ for observer PC and $F(1, 62) = 1.78$ for observer SS, both nonsignificant]. On the other hand, the brightness settings differed strongly from the minimum subjective contour settings [$F(1, 22) = 21.59$ for PC and $F(1, 62) = 14.52$ for SS, both $p < 0.001$] and from the minimum flicker settings as well [$F(1, 22) = 19.17$ for PC and $F(1, 62) = 26.46$ for SS, both $p < 0.001$].

EXPERIMENT 2: SHAPE FROM SHADOWS

Stimuli

The cup shown in Fig. 1(b) was used in the second experiment. The figure could be seen in either of two ways, depending on the relative radiance of the figure area (shown as white parts) and the background (shown as black parts). When the background was darker and less luminous, the cup was seen as empty and the dark area inside was seen as a shadow. When the background was brighter and more luminous the cup could be seen either as a cup filled with some material having a slanted surface or as two dis-

jointed pieces having no obvious connection. The relative radiance of the figure and the background areas was adjusted by the observer to the point at which the figure organization changed between the shadow and nonshadow interpretations. In the first condition, the background [black parts in Fig. 1(b)] was used as the test field and filled with the mixture of red/green or yellow/blue, while the figure area (white parts) was used as the reference with a fixed radiance of red or blue [designated the positive condition, since test color was in the black parts, which were interpreted as shadow in Fig. 1(b)]. In the second condition (negative condition), these assignments were reversed: the figure area (white parts) was used as the test field and the background (black parts) as the reference.

Procedure

The procedure was the same as in Experiment 1, but the disappearance of depth owing to shadows was the judgment used instead of minimum subjective contour. The observer adjusted the radiance of green (for red/green pair) or yellow (for yellow/blue pair) in the test fields to find the point where the form organization changed. Minimum flicker and brightness matching were also tested as in Experiment 1. For brightness matching, the observers were asked to ignore the smaller piece of the figure and to match the brightness of the larger piece (lower left-hand piece) with that of the background area. Similarly, the observers were asked to concentrate on flicker sensations in the larger piece of the cup when making settings in the negative condition. In this condition, flicker was present only in the figure area [white parts in Fig. 1(b)]. In the positive condition, the observers concentrated on the whole area of the background, where flicker was seen in this condition.

The fixation spot for the 10° stimulus was placed at the center of the larger patch instead of at the center of the stimulus, so that all figure borders would be outside the macular pigmentation area. As in Experiment 1, filtering by macular pigments caused the least flickering parts of the stimulus figure to shift from the central visual field to the periphery as the intensity of the yellow light for yellow/blue pair increased. Observers chose an area closed to the contour of the larger piece to set minimum flicker and kept their criterion constant throughout the task. For 2° stimulus, observers fixated the same point without any fixation spot. The same two observers participated.

Results and Discussion

Figure 4 shows the results analyzed and plotted in the same way as in Fig. 2 with the same conventions. Each point is the average of 15 adjustments for observer SS and 5 adjustments for observer PC. Standard deviations calculated from settings of all the conditions are shown by vertical bars in the inset of each panel.

At first glance, the results are quite similar to those of Experiment 1. That is, the shadow and minimum flicker settings are often similar and fall near the additivity function, whereas whenever there are large deviations among the three settings it is the brightness matches that deviate from the other two. This pattern is clearest for the negative red/green test images [Fig. 4(b)]. However, there are

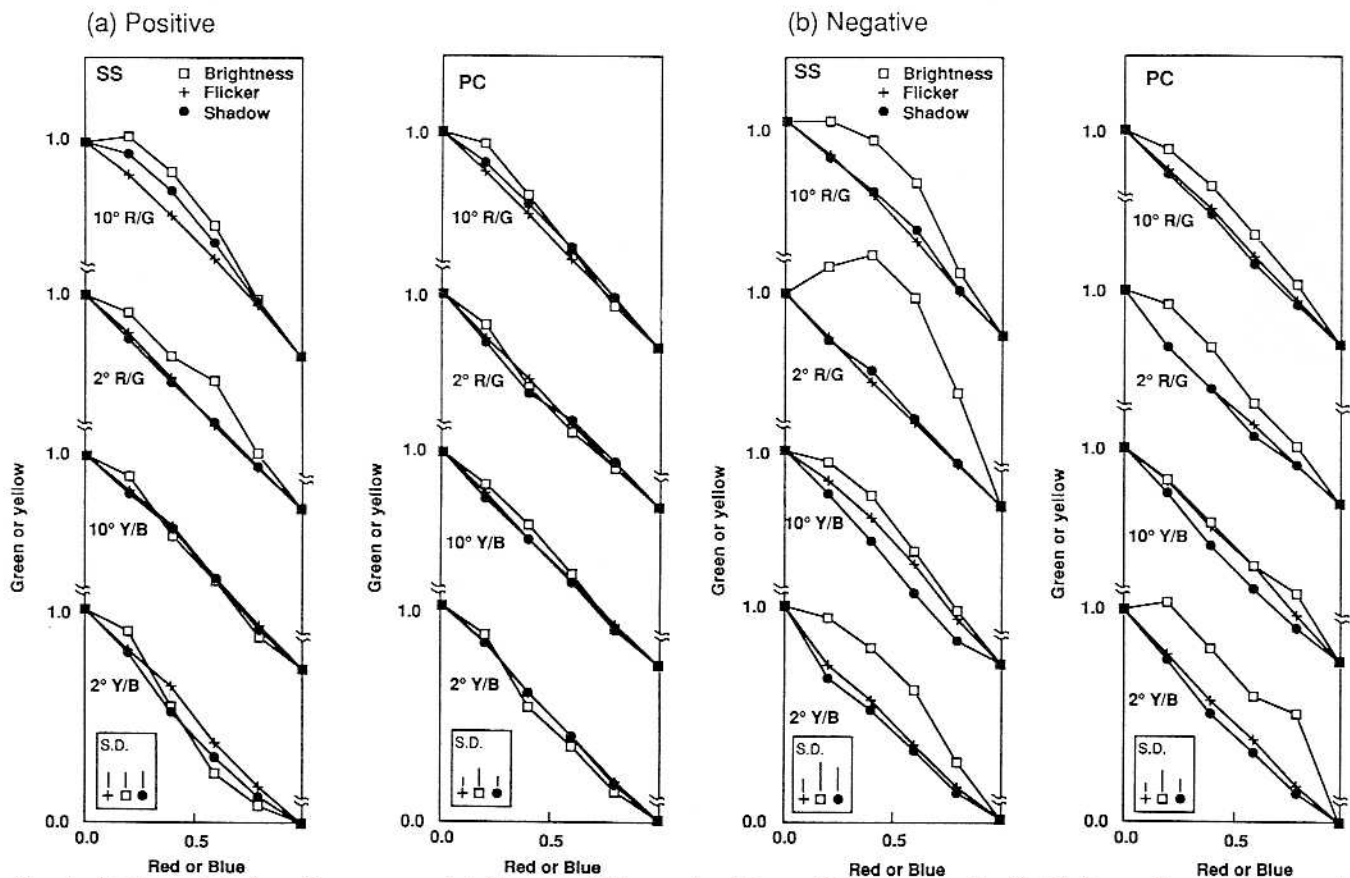


Fig. 4. Settings of shadow disappearance, brightness matching, and minimum flicker measured with (a) the positive cup figure and (b) the negative cup figure. Squares, crosses, and filled circles represent the brightness matches, minimum flicker, and shadow disappearance settings, respectively. Conventions otherwise as in Fig. 2.

notable exceptions in the other conditions. With the positive test images for observer PC, all three settings are virtually superimposed, and all lie close to the additivity function. In addition, for 4 of the 16 conditions (the negative 10° yellow/blue tests for both observers, and the positive 2° yellow/blue test and the positive 10° red/green test for observer SS), the shadow settings deviated noticeably from the flicker settings. For one of these conditions (positive, 10° red/green test for observer SS), the shadow settings were systematically closer to those for brightness matching than they were to those for flicker. This condition is considered in more detail below.

Interestingly, larger subadditivity (settings lying above the additivity function) is seen in negative conditions than positive conditions. One could speculate that this is because of the difference in retinal location of test and reference areas between the two conditions (the reference was in central visual field and the test was more eccentric in the positive condition and vice versa in negative condition); however, we have no additional evidence that would support or reject this possibility.

Statistical Test

We examined the differences between conditions, using the same test as in Experiment 1. The results indicate that the shadow disappearance settings did not differ significantly from the minimum flicker settings [$F(1,62) = 1.48$ and 0.378 for observers PC and SS, respectively, both nonsignificant]. On the other hand, the brightness set-

tings differed strongly from the shadow disappearance settings [$F(1,62) = 35.22$ and 41.91 for PC and SS, respectively, both $p < 0.001$] and again from the minimum flicker settings [$F(1,62) = 22.27$ and 34.39 for PC and SS, respectively, both $p < 0.001$].

Brightness Contribution to Shadow

For the shadow disappearance setting, a strong departure from flicker settings in the direction of the brightness settings was seen for the red/green, positive condition for observer SS with the 10° stimulus. Since this is the first evidence suggesting that a form judgment may be related to brightness matches, we replotted the results of the condition, using absolute values, in order better to investigate the relationship among the settings. Figure 5 shows the settings for three tasks in terms of relative radiance, normalized so that the setting for minimum flicker with no red in the test mixture was 1.0. The right-hand panels show results for the positive condition [the test field was the black part of Fig. 1(b)], and the left-hand panels show results for the negative condition [the test field was the white parts of Fig. 1(b)]. Different symbols represent different tasks: open squares for shadow disappearance, filled squares for minimum flicker, and filled triangles for brightness matching. The hatched regions indicate radiance levels where shape from shadows was seen. The shadow disappearance settings seem to follow the settings of brightness matching in the positive condition, whereas they are aligned with those of minimum flicker in the

negative condition. The results of the positive condition indicate that shadow was not seen when the background area was *brighter* than the figure area (even for settings for which the background was less luminous than the figure area—the stippled region in the right-hand panel of Fig. 5). On the other hand, the results of the negative condition indicate that shadow was not seen when the background area was more *luminous* than the figure area (even for settings for which the background was less bright than the figure area—the stippled region in the left-hand panel of Fig. 5).

These results suggest that large shadow areas may need both less luminance and less brightness than the non-shadow areas, at least for this one observer.

ABSOLUTE SETTINGS ACROSS TASKS

In these two experiments we have used an additivity paradigm that normalizes settings to a value of 1.0 when the

test field contains only the second color. We could have compared the absolute settings for luminance, brightness, shadows, and subjective contours. In many cases the absolute settings for the form organization tasks and minimum flicker were close; however, in many others, they differed substantially. Do these differences in absolute settings indicate that different processes are involved in different tasks? This is a difficult issue to examine, because there are several other factors that can produce differences between the absolute settings even when only one process is involved.

First, the temporal characteristics of the stimuli affect the equal-sensation-luminance point.^{24,28} Minimum flicker settings were based on high temporal frequencies, while those for shadows and subjective contours were based on low temporal frequencies. Second, the difference in the spatial characteristics of stimulus also affects the equal-sensation-luminance point. We attempted to minimize this effect by using the same stimulus for the

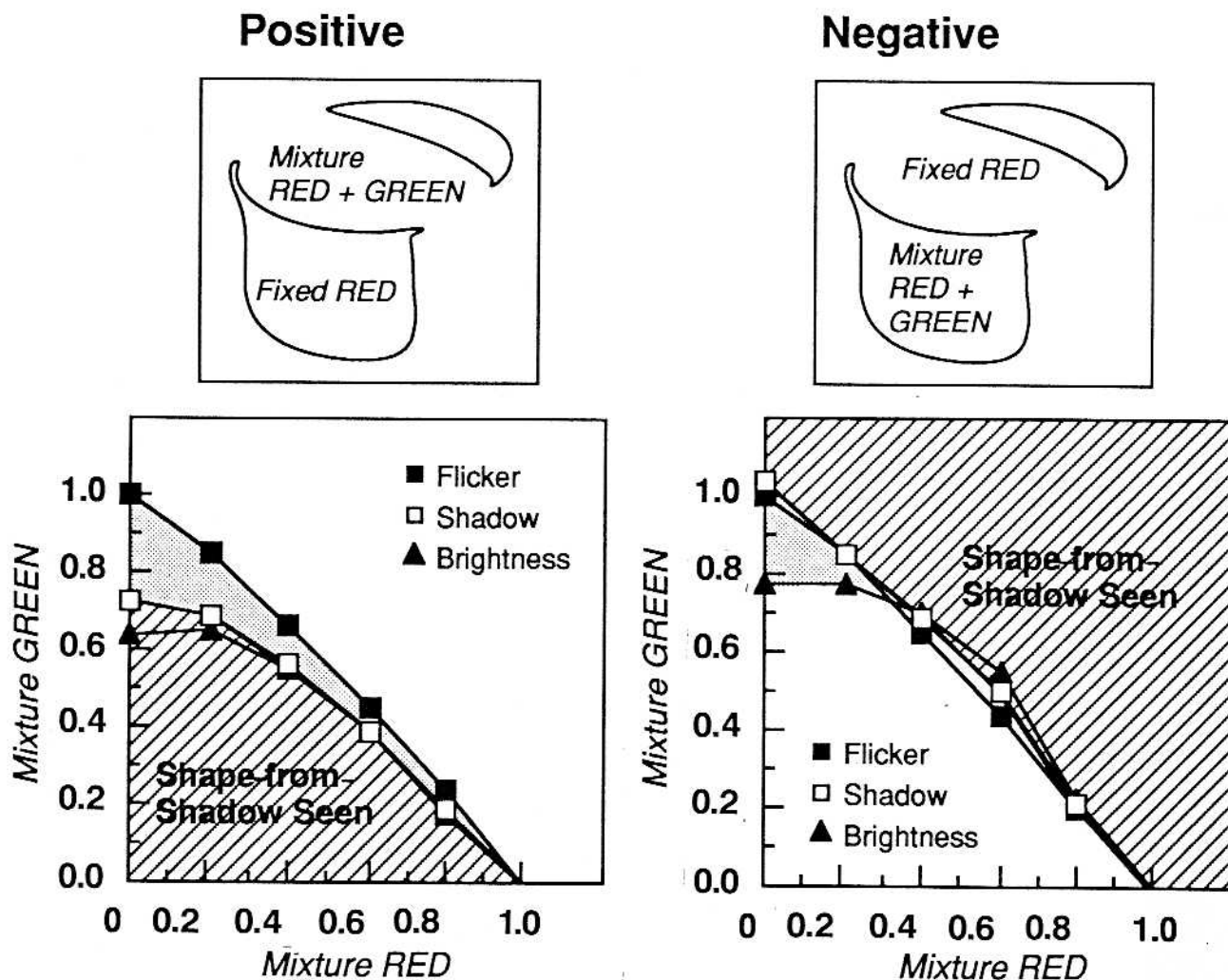


Fig. 5. Relative settings of minimum flicker, brightness matching, and shadow disappearance for red/green pair of observer SS with 10° stimulus of the cup figure. The radiance of all conditions is normalized so that the radiance of green for minimum flicker setting is 1.0 for the settings with 0.0 proportion of red mixed in the test field. The left-hand panels are for the positive condition [i.e. the test field was the black part of Fig. 1(b)], and the right-hand panels are for the negative condition [the test field was the white parts of Fig. 1(b)]. Open squares are for shadow disappearance, filled squares for minimum flicker, and filled triangles for brightness matching. The hatched areas indicate the radiance levels for which shape-from-shadows was perceived, and these levels correspond fairly closely to the shadow region's being less bright than the nonshadow region in the positive condition but less luminous in the negative condition. The stippled areas indicate radiance levels where shadows were not seen even though they were less luminous (but not less bright) in the positive condition and less bright (but no less luminous) in the negative condition.

different tasks: the subjective disk was used for minimum flicker, brightness, and subjective contour settings, and the cup was used for shadow, brightness, and flicker settings. Even though the form of the stimulus was identical, we could not control the possibility that different regions of the stimulus were used in different tasks. For example, retinal inhomogeneities make it impossible to achieve a uniform minimum flicker setting across an entire extended stimulus. The inhomogeneities were most pronounced for the yellow/blue stimuli where macular pigmentation had a large effect but were also present for red/green stimuli.²⁸⁻³⁰ To minimize this problem, we instructed observers to concentrate only on one area in the cup figure, and they made a similar choice to monitor only one particular retinal area for the subjective contour figure. In general, therefore, it seems impossible to avoid stimulus differences among tasks, so the comparison of absolute settings may never be appropriate.

The additivity paradigm with its normalization step therefore seems to be the more appropriate method for exploring the pattern of settings in a task as chromaticity is changed.

EXPERIMENT 3: B-CONE CONTRIBUTION

It has been suggested that short-wavelength-sensitive cones (B cones) do not contribute to the settings of minimum flicker^{23,31,33} or minimally distinct border.^{32,33} Although the evidences for contribution of B cones to border perception^{34,35} and to flicker settings²⁵ have been reported recently, the contribution seems to be small in comparison with that of the long- and middle-wavelength-sensitive cones.²⁴ However, B cones do strongly contribute to brightness perception.²² In Experiment 3 we explored the contribution of B cones to the minimum subjective contour and the shadow disappearance settings, using a bleaching technique.

Method

In order to bleach B cones, the observer exposed his right eye to violet light of approximately 4800 Td for 1 min. The light was produced by focusing the beam of a 300-W Kodak carousel with a reflector-type lamp through a reversed $f/2.8$, 35-mm lens and filtering it through a 435-nm interference filter having a 7-nm half-bandwidth at half-amplitude. The resulting beam was viewed through a natural pupil, which was measured at approximately 3 mm. The CIE x and y coordinates of the light were $x = 0.16$ and $y = 0.01$ (measured by a Minolta chromameter).

The nonblurred figure of subjective contour and the positive figure of the cup were investigated for the yellow/blue pair with the 10° stimulus. For the subjective-contour figure, no blue was mixed in the test field, while the blue of 0.4 proportion was mixed for the cup figure. These values of blue in the mixture field were chosen because they provided a large difference of settings between the brightness matching and the minimum flicker settings in the previous experiments.

For each experimental condition, the observer first exposed himself to the bleaching light for 1 min and then moved immediately to the stimulus display and made settings for one of the four tasks as long as 1 min or until he observed a change of the chrominance in the display. If

the observer noticed any chromatic changes before the minute had elapsed, he stopped making settings. At least four settings were made in each condition. SS and PC again served as observers.

Results and Discussion

Figure 6 shows the ratio of bleached to nonbleached settings for the subjective contour figure (top) and the cup figure separately (bottom). The ratio was approximately 1.0 for minimum flicker, minimum subjective contour, and shadow disappearance settings, whereas it was less than 1.0 for the settings of brightness matching.

The difference between bleached and nonbleached settings was significant only for brightness matching [$t(8) = 5.290$ and $t(11) = 3.326$ for observer SS and $t(20) = 4.436$

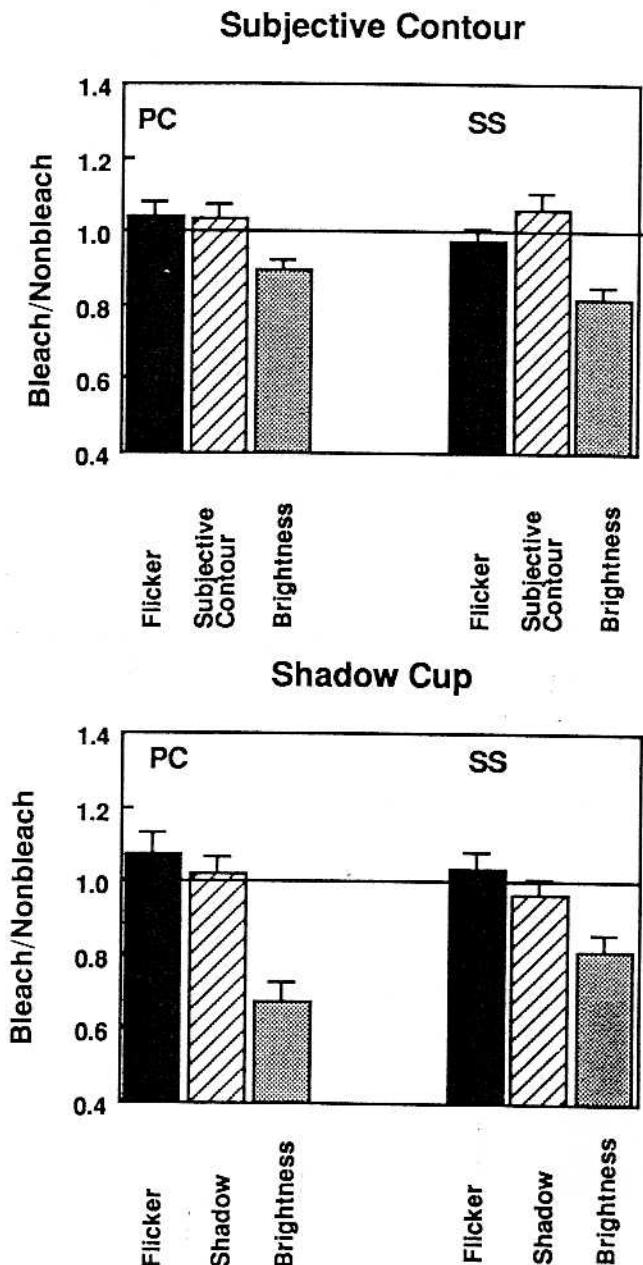


Fig. 6. Ratio of bleached to nonbleached settings for each task and both observers. The top panel shows the results for the subjective contour figure, and the bottom panel those for the cup figure. The vertical bars show the standard error for the ratio.

and $t(26) = 6.918$ for observer PC; all $p < 0.01$, all other t tests nonsignificant]. The observers set the radiance of yellow significantly smaller in the bleached condition than in the nonbleached condition to match brightness to the same reference blue. These results indicate that B cones contribute little or not at all to subjective contours, shadows, and flicker perception. Although our bleaching experiment may not have been sensitive enough to register the small B-cone contribution to the luminance mechanism,^{25,34-36} it was certainly able to distinguish between the relatively large contribution of B cones to brightness and the much smaller one to minimum flicker, minimum subjective contour, and shadow disappearance. These results again support our conclusion that flicker, subjective contours, and shadows are mediated by a common intensity dimension and that dimension is luminance and not brightness.

GENERAL DISCUSSION

Our first two experiments showed that the variations of shadow and subjective contour settings with chromaticity of the test field were more similar to those of the minimum flicker task than to those of the brightness matching task. The additivity results themselves were less consistent, perhaps because of the complex stimulus shapes that we used. Nevertheless, large deviations from additivity were more evident for the brightness task than for the other three. Finally, bleaching the B cones strongly affected brightness matches but did not affect the flicker, shadow, or subjective contour settings. Overall, these results suggest that achromatic form vision is mediated by the intensity dimension measured by flicker photometry, not by that measured by brightness matching. It could be argued that minimally distinct border^{4,5} and visual acuity⁶ are two other tasks for which form perception plays a basic role in the judgment made in the task. Results from these tasks also agree with our evidence that form perception is based on a luminance dimension.

The tasks that we have used extend the realm of luminance to figures that do not depend specifically on high spatial (minimum border, acuity) or high temporal (minimum flicker) frequencies. Both shadows¹⁷ and subjective contours¹⁸ are mediated by a broad range of spatial frequency components and, for subjective contours, our results for blurred images support this conclusion directly. Our results suggest that the difference between brightness and luminance cannot be attributed solely to the differences in the spatial and temporal aspects of the stimuli. This result is consistent with the study of minimally distinctness of blurred edges¹¹ that shows additivity for borders made of low spatial frequencies.

The difference between luminance and brightness is more likely due to the contribution of opponent-color channels to brightness, as is suggested by the fact that difference between luminance and brightness is larger for more-saturated lights.^{19,37-41} If this is the case, the characteristics of the color channels should determine the magnitude of the difference between luminance and brightness. Thus the smaller differences between luminance and brightness for shorter-duration⁹ and smaller-size^{9,10} tests are consistent with the low temporal and spatial resolution of color channels.

In summary, we conclude that subjective contours, shadows, and minimum flicker are mediated by luminance-type additive mechanism(s). Whether one common mechanism works for all aspects of the achromatic form processing remains to be examined.

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