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## Spatial dependence of color assimilation by the watercolor effect

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### Abstract

Color assimilation with bichromatic contours was quantified for spatial extents ranging from von Bezold-type color assimilation to the watercolor effect. The magnitude and direction of assimilative hue change was measured as a function of the width of a rectangular stimulus. Assimilation was quantified by hue cancellation. Large hue shifts were required to null the color of stimuli  $\leq 9.3$  min of arc in width, with an exponential decrease for stimuli increasing up to 7.4 deg. When stimuli were viewed through an achromatizing lens, the magnitude of the assimilation effect was reduced for narrow stimuli, but not for wide ones. These results demonstrate that chromatic aberration may account, in part, for color assimilation over small, but not large, surface areas.

### 1 Introduction

Color assimilation is a shift in the perceived color of a region toward the chromatic appearance of a nearby inducing stimulus. This effect has been obtained with different kinds of patterns since the pioneering study by von Bezold (1876). More recently Pinna et al (2001) demonstrated a new phenomenon, the watercolor effect (WCE). Here, chromatic assimilation occurs within an area enclosed by a light chromatic contour (eg orange), which in turn is surrounded by a darker chromatic contour (eg purple).

Studies of chromatic assimilation have generally dealt with the effects of the inducer configuration on a neutral test field in order to determine the direction of the chromaticity shift. Thus, the effect is strongest with narrow inducers as well as induction fields (Helson 1963; Steger 1969; Fach and Sharpe 1986; Smith et al 2001). Other factors, such as the luminance of the inducing stimuli, can also influence the strength of assimilation (Helson 1963; Shapley and Reid 1985; de Weert and Spillmann 1995; Hong and Shevell 2004).

Although the size of the induction area enclosed by the inducing contours is known to be important for assimilation strength, it has not been systematically explored. Devinck et al (2005) used hue cancellation to null the WCE on a surface area that was 1.43 deg in width. Reliable shifts in color appearance closely followed the direction of the inducing contour, but their vector length measured in CIE  $u'$ ,  $v'$  color space ranged from only 2.61% to 4.38% of the orange-inducing contour. Recently, Monnier and Shevell (2003, 2004) studied assimilation using patterns composed of concentric circles alternating between two chromaticities that stimulate the S-cones. They found a large shift in color appearance with thin inducing stimuli (9 min of arc) and induction fields. This difference in strength of color spreading could perhaps be explained by differences in the area of the induced region. Our goal here was to test directly the strength of the WCE as a function of the induction area width when the inducing contours

remain constant. To control for chromatic aberration we performed a separate experiment using an achromatizing lens.

## 2 General methods

### 2.1 Observers

There were three viewing conditions: (i) binocular, (ii) monocular, and (iii) monocular with achromatizing lens. The second condition was a control experiment because the achromatizing lens could only be used monocularly. The latter condition was intended to evaluate the role of chromatic aberration in the WCE. Three observers participated in condition (i), and two in conditions (ii) and (iii). One observer was one of the authors and the other two were naive to the purpose of the experiments. All had normal (or corrected-to-normal) visual acuity and were normal trichromats as assessed by the Neitz Anomaloscope, the HRR pseudoisochromatic plates, and the Farnsworth F-2 plates. Each observer provided written informed consent for a protocol approved by the Office of Human Research Protection of the University of California, Davis.

### 2.2 Apparatus

Stimuli were displayed on a color monitor (Sony Multiscan G220) controlled by a Macintosh G4 computer with an ATI Radeon 7500 video card (10 bits per gun). Stimuli were generated with Matlab 5.2.1 with the Psychophysics Toolbox (Brainard 1997; Pelli 1997). The monitor was calibrated with a Minolta colorimeter (CS 100 Chroma Meter) and procedures set out in Brainard et al (2002). Observer position was stabilized by a chin-rest so that the screen was viewed at a distance of 217 cm.

### 2.3 Stimuli

Stimulus patterns used to produce the WCE consisted of a central test region (the induction region) surrounded by double contours arranged in rectangular patterns that were 5.35 deg in height and ranged between 5.4 min of arc and 7.4 deg in width (see figure 1). Intermediate widths used were: 9.3 min of arc, 30.6 min of arc, 1.43 deg, and 5 deg. The double contours were sinusoidally shaped at  $1.5 \text{ cycles deg}^{-1}$  (amplitude = 0.13 deg) with a width of 1.7 deg. They were composed of two different colors: an orange ( $u', v' = 0.231, 0.512; Y = 55 \text{ cd m}^{-2}$ ) inner contour, and purple ( $u', v' = 0.211, 0.375; Y = 20 \text{ cd m}^{-2}$ ) outer contour, presented on a neutral white background ( $u', v' = 0.189, 0.467; Y = 80 \text{ cd m}^{-2}$ ). The WCE is dependent on the luminance contrast between the two borders (Devinck et al 2005; Pinna 2005). Thus, the luminance of the orange contour was higher than that of the purple contour with a luminance ratio of 2.75 corresponding to the higher contrast used in a previous paper; this setting allowed us to obtain a stronger WCE (Devinck et al 2005). Under these conditions, uniform orange color spreading was readily seen within the enclosed surface area for all pattern widths tested.

### 2.4 Procedure

Observers were dark-adapted for 3 min before beginning the experiment. They were asked to adjust the chromaticity of the enclosed stimulus area until it appeared achromatic (hue cancellation). The results of an earlier study (Devinck et al 2005) showed no difference between color-matching and hue-cancellation tasks for the pattern used in the present paper. In addition, observers generally found the hue-cancellation task to be easier than matching and were able to perform this task relatively quickly. For this reason, all experiments in this paper used the hue-cancellation method. For nulling, the luminance of the induction area was held constant, while the chromaticity was adjusted by pushing appropriate buttons on a gamepad. Each button press changed the hue of the test area in equal steps along  $a^*$  and  $b^*$  chromaticity coordinates in CIE  $L^*a^*b^*$  color space. Observers were able to toggle between three step sizes by pressing

a separate button (0.5, 0.1, and 0.02 in CIE  $L^*a^*b^*$  color space) to optimize the efficiency of the task. To reduce adaptation to the stimulus pattern, stimuli were presented for 2 s, with an interstimulus interval of 2 s, during which a large blank field of the same luminance and color as the white background was interspersed. This sequence was repeated until the observers were satisfied with their settings and clicked a mouse to end the trial and start the next one. The order of the stimuli was randomized for each observer. Each subject made 10 settings for each induction area width tested. Practice trials preceded the data collection.

Possible effects of chromatic aberration were evaluated in a separate experiment in which the stimuli were viewed through a Powell achromatizing lens (Powell 1981). The apparatus was identical to that used in the previous condition, except that stimuli were viewed monocularly with and without the achromatizing lens. The position of the achromatizing lens was adjusted horizontally and vertically for each observer before each session with the use of an  $x - y$  micrometer stage to align a set of red–blue nonius lines.

### 3 Results

Figure 2 shows each observer's mean settings plotted in CIE  $u', v'$  coordinates for the six widths of the induction area. The mean color direction of the settings for hue cancellation is opposite to that of the inducing orange contour, but not perfectly. Therefore, we calculated the difference angle by subtracting the angle for the induced color vector from that of the orange contour vector in the opposite direction. Chromaticity settings were in the opposite color direction from the inducing contour with a mean difference ranging from 17.14 to 20.5 deg in comparison with the orange vector, for all induction area widths and whatever the condition used.

We also calculated the magnitude of the assimilation effect by dividing the shift vector size by the inducing contour vector. The results are presented in figure 3, and the data were fit by using the exponential function  $y = x^{a+b}$ , where  $a$  determines the shape of the exponential curve, and  $b$  is a constant that determines the position of the curve on the  $y$  axis. Fitting parameters are shown in table 1.

In figure 3, the ratio between the shift-size vector and the inducing-contour vector is plotted as a function of induction area width. Results in panel (a) show that there was a difference in chromaticity shift for the different induction area widths: when the size of the induction area increased, the vector shift required for hue cancellation decreased exponentially. For example, while relatively large chromaticity shifts of 38.11% and 18.04% were needed for the two narrowest columns (5.4 and 9.3 min of arc, respectively), shifts of only 4.61% and 1.75% were required for wider columns. Note that the magnitude of the effect for a stimulus width of 1.43 deg is similar to that found by Devinck et al (2005) under comparable conditions. We conclude that the WCE is most salient for stimuli with smaller enclosed areas.

Figure 3b shows the results for monocular viewing as a function of stimulus width. Data were similar for binocular and monocular conditions without the achromatizing lens. When the stimulus was viewed through the achromatizing lens (figure 3c), the shift in chromaticity decreased exponentially with increasing induction area width. Data for larger induction area widths ( $\geq 30.6$  min of arc) were similar to those for monocular viewing without the achromatizing lens. However, results for the smaller induction area width ( $\leq 9.3$  min of arc) differed from those obtained with binocular and monocular viewing without the achromatizing lens. Indeed, the perceived color was less saturated than in the non-achromatizing lens conditions. Thus, the chromaticity shift required was around 16.5%–17.1% (5.4 min of arc) and 5.1%–8.6% (9.3 min of arc).

## 4 Discussion

Several studies have shown that the magnitude of color assimilation depends upon the induction area (Fach and Sharpe 1986; de Weert and Spillmann 1995; Smith et al 2001; Monnier and Shevell 2003; Devinck et al 2005). The present experiment demonstrates the importance of induction area width for the WCE. Whereas the wider stimuli ( $\geq 30.6$  min of arc) exhibited small shifts in color appearance, the narrower ones ( $\leq 9.3$  min of arc) produced larger shifts. Thus, chromatic aberration contributes to the stronger assimilation effect obtained for narrow stimuli, but not for wide stimuli.

### 4.1 The role of chromatic aberration in color assimilation

The stronger assimilation obtained in the WCE for narrow stimuli can be explained, at least in part, by chromatic aberration, while assimilative color perceived over wider stimuli cannot. If chromatic aberration would fully explain the WCE, the resulting curves in figure 3c would be expected to have no chromaticity shift, whereas the results for both monocular conditions diverged only slightly for the wider induction area, and decreased with the narrow stimuli when an achromatizing lens was used.

Smith et al (2001) suggested that chromatic aberration contributes to assimilation, but that there must be additional factors. Others have argued against a substantial contribution of aberration (Fach and Sharpe 1986; Moulden et al 1993). This difference is reflected in studies suggesting that assimilation is present (Pinna et al 2001; Monnier and Shevell 2003) or absent (Broerse et al 1999) depending on whether or not stimuli were observed through an achromatizing lens. Our data show that chromatic aberration cannot account for the WCE in the wider stimuli that have been used in previously published work. The present study may link these studies with classical color assimilation by taking stimulus width into consideration. Bradley et al (1992) found chromatic aberration to be more important at higher spatial frequencies than at lower spatial frequencies. Thus, the aberration will not be different, but the impact would be more important at higher spatial frequencies. For example, if a very thin blue bar is next to a very thin yellow bar (high spatial frequency), then a small offset due to chromatic aberration could cause them to overlap on the retina. This may result in the perception of a light bar and a dark bar rather than of blue and yellow bars. For wider contours, the impact would not be as great because only the edges would overlap.

Notwithstanding the effect of chromatic aberration, our data are consistent with those of investigators who concluded that a neural process contributed to assimilation (Hurvich and Jameson 1974; Shevell and Cao 2003), although the neural locus is still unknown (Shevell and Cao 2004).

### 4.2 Relation to previous assimilation studies

Pinna et al (2001) pointed out that the induced color in the WCE continues to be seen up to about 45 deg. Our results show that with large stimuli the effect is present with an achromatizing lens. Under our conditions, we showed that the color shift reached an asymptotic level by about 7 deg.

Recently, Monnier and Shevell (2003, 2004) reported large shifts in color appearance when using a patterned chromatic background composed of a concentric inducing circle, but not for a uniformly colored background. Thus, they showed that color appearance depends on the spatial configuration of the context. Nevertheless, the present study might help explain the strong assimilation effect found by these authors: their induction area was small (9 min of arc). With stimuli exceeding 1 deg, assimilation strength might have decreased.

Finally, different stimulus configurations (Fach and Sharpe 1986; de Weert and Spillmann 1995; Smith et al 2001; Monnier and Shevell 2003, 2004) may be encoded differently by the visual system. Consequently, one may expect different amounts of assimilation for each.

#### 4.3 Relation to previous assimilation theories

Jameson and Hurvich (1975, 1989) proposed that color assimilation depends upon the diameters of both center and surround regions of the underlying neural receptive fields. Accordingly, if the stimulus elements are small relative to the receptive field centers, then assimilation occurs owing to neural color mixing; and if the stimulus elements are larger, then assimilation gives way to spatial contrast. Thus, the chromaticity shift should vary with the width of the stimulus. Indeed, a larger assimilation shift should be obtained with the small widths because the inducing contour adjacent to the induced area will be weighted strongly in the center of the receptive field. Moreover, assimilation should decrease, then lead to a contrast effect with larger stimuli because of the inhibitory surround of the receptive field.

Monnier and Shevell (2003, 2004) showed that a patterned background, composed of concentric inducing circles alternating between two chromaticities that stimulate the S-cones, produced a large shift in color assimilation. This result is consistent with an S-cone antagonistic center-surround (+S/-S) receptive field (Monnier and Shevell 2004). Such neurons are not found in the retina (Dacey 2000), but have been reported in the visual cortex (Conway 2001; Solomon et al 2004). The transition from assimilation to contrast suggested by Jameson and Hurvich (1975, 1989) might be related to S-cone spatial antagonism. Further experiments are necessary to test the generality of this model for the WCE to determine if a large shift will be also obtained with S-cone modulated patterns.

In our experiments, the chromaticity shift decreased with increases in induced area as expected from the spatial structure of receptive fields. However, we did not show a contrast effect for the larger widths. Thus, conventional receptive field organization seems unlikely to explain the WCE. Several hypotheses might be proposed related to color filling-in that involves networks derived from receptive fields. Long-range signals arising at the contour and propagated from the boundary to the enclosed region (with no neural response) are required for color perception over extended areas (Gilbert 1996; Spillmann and Werner 1996). This may culminate in a symbolic color representation such that signals from edge detectors are integrated at a higher level to produce a response that represents the color of the surface (von der Heydt et al 2003).

A neuro-computational model has been fully developed by Grossberg and Mingolla (1985) to explain color filling-in. This theory distinguished two parallel processing modes, the boundary contour system (BCS) which generates contour information, and the feature contour system (FCS) which involves filling-in processes by which color and brightness spread. In this model, a weakening of the boundary is a prerequisite for the outflow of color. In the case of the WCE, the FCS within the inner contour will induce the orange color; at the same time, the BCS will inhibit the boundary between the orange contour and the background. Consequently, the weakened boundary will allow orange color to flow out and spread, but the presence of a strong boundary (eg the purple contour) will be able to contain color spreading in one direction. This approach is consistent with the perception of the orange veil in the WCE.

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## References

- Bezold, W von. *The Theory of Color and Its Relation with Art and Art-Industry*. Boston, MA: Prang; 1876.
- Bradley A, Zhang X, Thibos L. Failures of isoluminance caused by ocular chromatic aberrations. *Applied Optics* 1992;31:3657–3667.
- Brainard DH. The psychophysics toolbox. *Spatial Vision* 1997;10:433–436. [PubMed: 9176952]
- Brainard, DH.; Pelli, DG.; Robson, T. Display characterization. In: Hornak, J., editor. *The Encyclopedia of Imaging Science and Technology*. New York: Wiley and Sons; 2002. p. 172-188.
- Broerse J, Vladusich T, O’Shea RP. Colour at edges and colour spreading in McCollough effects. *Vision Research* 1999;39:1305–320. [PubMed: 10343844]
- Conway BR. Spatial structure of cone inputs to color cells in alert macaque primary visual cortex. *Journal of Neuroscience* 2001;21:2768–2783. [PubMed: 11306629]
- Dacey DM. Parallel pathways for spectral coding in primate retina. *Annual Review of Neuroscience* 2000;23:743–775.
- Devinck F, Delahunt PD, Hardy JL, Spillmann L, Werner JS. The watercolor effect: Quantitative evidence for luminance-dependent mechanisms of long-range color assimilation. *Vision Research* 2005;45:1413–1424. [PubMed: 15743611]
- Fach C, Sharpe L. Assimilative hue shifts in color gratings depend on bar width. *Perception & Psychophysics* 1986;40:412–418. [PubMed: 3808908]
- Gilbert CD. Plasticity in visual perception and physiology. *Current Opinion in Neurobiology* 1996:6269–274.
- Grossberg S, Mingolla E. Neural dynamics of form perception: Boundary completion, illusory figures, and neon color spreading. *Psychological Review* 1985;92:173–211. [PubMed: 3887450]
- Helson H. Studies of anomalous contrast and assimilation. *Journal of the Optical Society of America* 1963;53:179–184. [PubMed: 13953661]
- Heydt, R von der; Friedman, HS.; Zhou, H. Searching for the neural mechanism of color filling-in. In: Pessoa, L.; De Weerd, P., editors. *Filling-in: From Perceptual Completion to Cortical Reorganization*. New York: Oxford University Press; 2003. p. 106-127.
- Hong SW, Shevell S. Brightness contrast and assimilation from patterned inducing backgrounds. *Vision Research* 2004;44:35–43. [PubMed: 14599569]
- Hurvich LM, Jameson D. Opponent processes as a model of neural organization. *American Psychologist* 1974;40:1–22.
- Jameson D, Hurvich LM. From contrast to assimilation: in art and in the eye. *Leonardo* 1975:8125–131.
- Jameson D, Hurvich LM. Essay concerning color constancy. *Annual Review of Psychology* 1989:401–22.
- Monnier P, Shevell SK. Large shifts in color appearance from patterned chromatic backgrounds. *Nature Neuroscience* 2003;6:801–802.
- Monnier P, Shevell SK. Chromatic induction from S-cone patterns. *Vision Research* 2004;44:849–856. [PubMed: 14992830]
- Moulden B, Kingdom F, Wink B. Colour pools, brightness pools, assimilation, and the spatial resolving power of the human colour-vision system. *Perception* 1993;22:343–351. [PubMed: 8316521]
- Pelli DG. The VideoToolbox software for visual psychophysics: transforming numbers into movies. *Spatial Vision* 1997;10:437–442. [PubMed: 9176953]
- Pinna B. The role of the Gestalt principle of similarity in the watercolor illusion. *Spatial Vision* 2005;18:185–208. [PubMed: 15856936]
- Pinna B, Brelstaff G, Spillmann L. Surface color from boundaries: a new ‘watercolor’ illusion. *Vision Research* 2001;20:2669–2676. [PubMed: 11520512]
- Powell I. Lenses correcting for chromatic aberration of the human eye. *Applied Optics* 1981;20:4152–4155.
- Shapley R, Reid RC. Contrast and assimilation in the perception of brightness. *Proceedings of the National Academy of Sciences of the USA* 1985;82:5983–5986. [PubMed: 3862112]

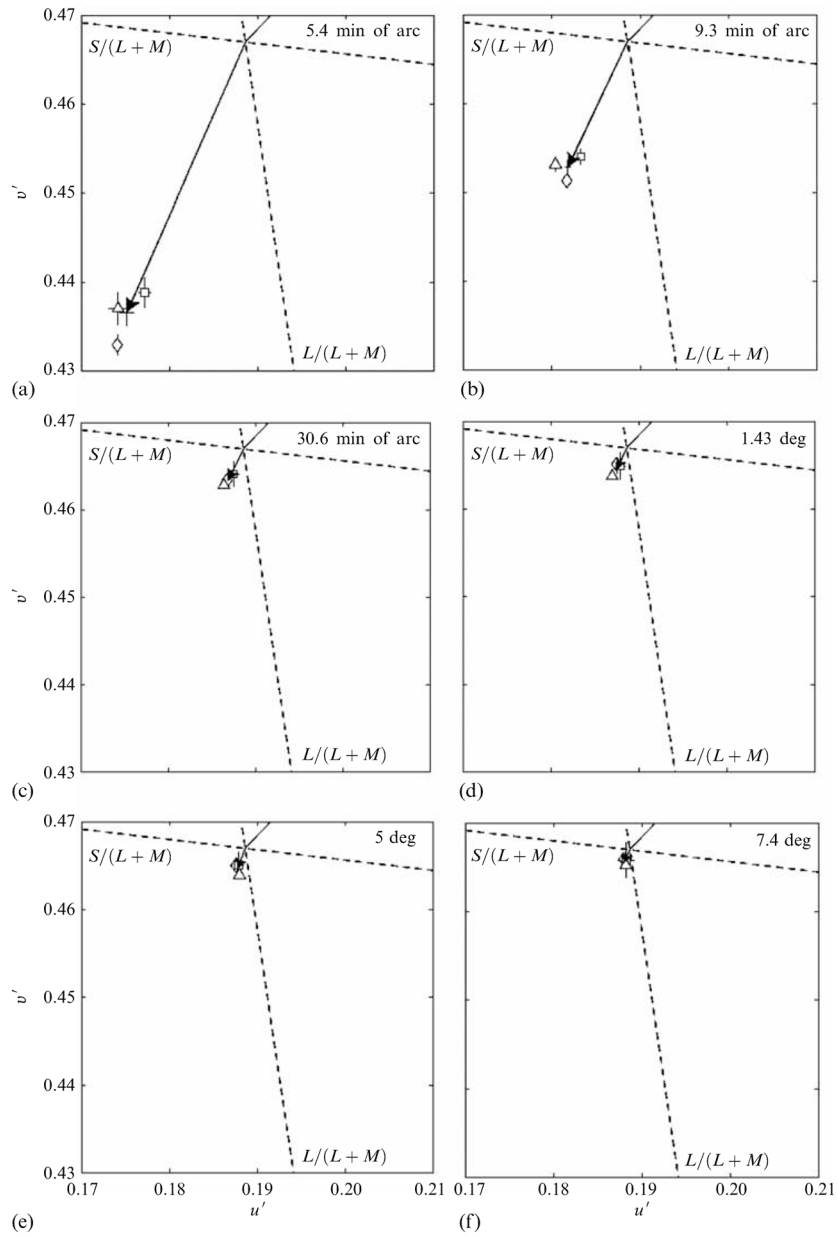


- Shevell, SK.; Cao, D. Chromatic assimilation: evidence for a neural mechanism. In: Mollon, JD.; Pokorny, J.; Knoblauch, K., editors. Normal and Defective Colour Vision. New York: Oxford University Press; 2003. p. 114-121.
- Shevell SK, Cao D. Chromatic assimilation unaffected by perceived depth of inducing light. *Visual Neuroscience* 2004;21:373–376. [PubMed: 15518216]
- Smith VC, Jin PQ, Pokorny J. The role of spatial frequency in color induction. *Vision Research* 2001;41:1007–1021. [PubMed: 11301075]
- Solomon SG, Peirce JW, Lennie P. The impact of suppressive surrounds on chromatic properties of cortical neurons. *Journal of Neuroscience* 2004;24:148–160. [PubMed: 14715948]
- Spillmann L, Werner JS. Long-range interactions in visual perception. *Trends in Neurosciences* 1996;19:428–434. [PubMed: 8888520]
- Steger JA. Visual lightness assimilation and contrast as a function of differential stimulation. *American Journal of Psychology* 1969;82:56–72. [PubMed: 5810462]
- Weert CM, de M, Spillmann L. Assimilation: asymmetry between brightness and darkness? *Vision Research* 1995;35:1413–1419. [PubMed: 7645270]

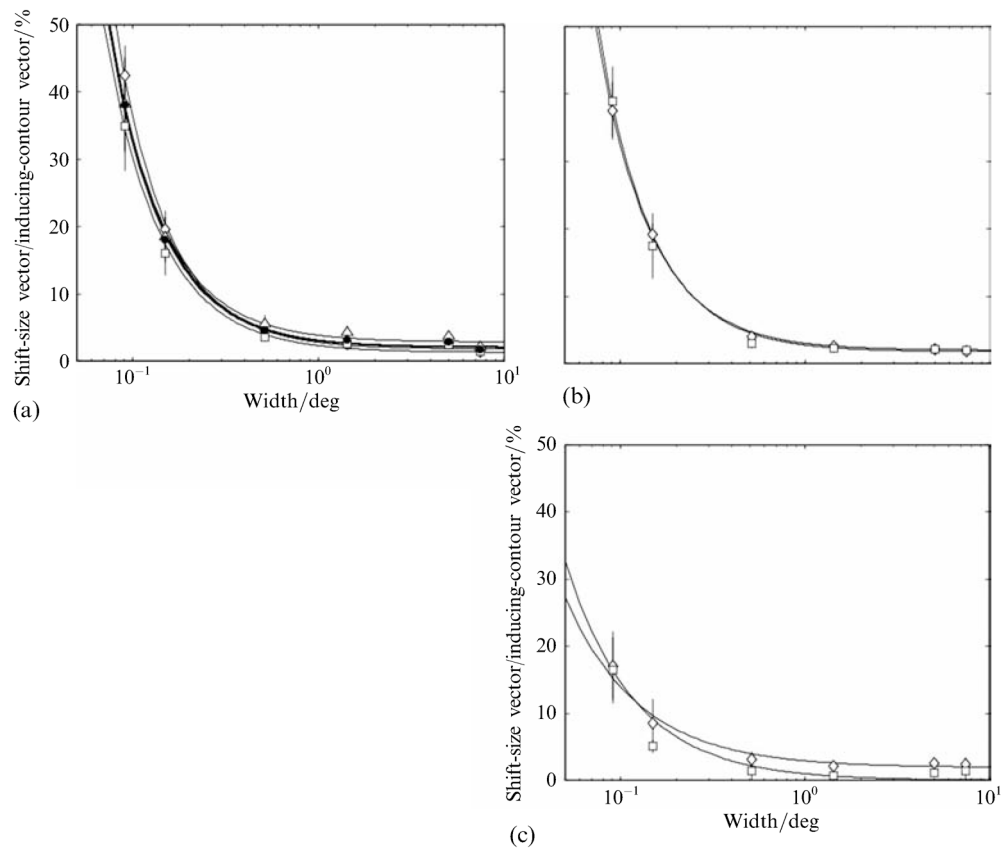


**Figure 1.**  
Two examples of WCE stimuli used in this study.





**Figure 2.** Hue-cancellation data plotted in CIE  $u'$ ,  $v'$  chromaticity space. Each panel shows a different width of the induction area: (a) 5.4 min of arc, (b) 2.3 min of arc, (c) 30.6 min of arc, (d) 1.43 deg, (e) 5 deg, (f) 7.4 deg. The mean vector required for cancellation is shown by the arrow originating at the white background (top center). Results for different widths are displayed separately. Symbols denote color shifts for three observers: subject 1 ( $\diamond$ ), subject 2 ( $\square$ ), and subject 3 ( $\blacktriangleright$ ). The solid line shows the direction of the orange (inner) contour chromaticity while the broken lines represent cone-opponent axes,  $S/(L+M)$  and  $L/(L+M)$ . Error bars are  $\pm 1$  SEM.



**Figure 3.**

WCE quantified by color cancellation and expressed by the shift-size vector divided by the inducing-contour vector as a function of stimulus width. Results of hue cancellation are displayed for the three viewing conditions: (a) binocular, (b) monocular, and (c) monocular with an achromatizing lens. Individual observers are marked as in figure 2; mean is shown by bold line and symbol •. Error bars are  $\pm 1$  SEM.

**Table 1**

Fitting parameters for all observers and experimental conditions.

Experimental condition	Observer	<i>a</i>	<i>b</i>
Binocular	1	-1.54	1.80
	2	-1.46	1.30
	3	-1.48	2.84
	<i>Mean</i>	-1.49	2.02
Monocular	1	-1.48	2.02
	2	-1.50	1.75
Monocular with achromatizing lens	1	-1.08	1.92
	2	-1.16	1.85