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# Spatial profile of contours inducing long-range color assimilation

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## Abstract

Color induction was measured using a matching method for two spatial patterns, each composed of double contours. In one pattern (the standard), the contours had sharp edges to induce the Watercolor Effect (WCE); in the other, the two contours had a spatial taper so that the overall profile produced a sawtooth edge, or ramped stimulus. These patterns were chosen based on our previous study demonstrating that the strength of the chromatic WCE depends on a luminance difference between the two contours. Low-pass chromatic mechanisms, unlike bandpass luminance mechanisms, may be expected to be insensitive to the difference between the two spatial profiles. The strength of the watercolor spreading was similar for the two patterns at narrow widths of the contour possibly because of chromatic aberration, but with wider contours, the standard stimulus produced stronger assimilation than the ramped stimulus. This research suggests that luminance-dependent chromatic mechanisms mediate the WCE and that these mechanisms are sensitive to differences in the two spatial profiles of the pattern contours only when they are wide.

**Keywords:** Watercolor effect; Assimilation; Long-range interaction

## Introduction

Long-range color and brightness assimilation in an enclosed surface has been demonstrated by the Watercolor effect (WCE). In this pattern, the enclosed area appears tinged with the color of the inner contour. For example, when a dark purple outer contour accompanies a lighter orange inner border, the area enclosed by the orange contour is perceived with an orange veil. This illusion has generally been demonstrated using a white background with a higher luminance than that of the two contours.

In previous work (Devinck et al., 2005), we have quantified color assimilation using a wide range of stimulus chromaticities with stimuli similar to those of Pinna et al. (2001). These contours had a square-edge spatial profile. When the two contours were equated in luminance, the WCE was present but weak (Devinck et al., 2005). The strength of the WCE increased with the luminance difference between the contours and, importantly, the chromaticity of the induced color more closely resembled the inner contour. We concluded that the WCE is mediated by luminance-dependent mechanisms of long-range color assimilation. The sensitivity of luminance and chromatic mechanisms to the spatial profile of the contours has not been tested in previous studies. It is well known that contrast sensitivity measured with luminance-modulated stimuli is bandpass (Campbell & Robson, 1968), whereas chromatic mechanisms are lowpass (Mullen, 1985). Chromatic

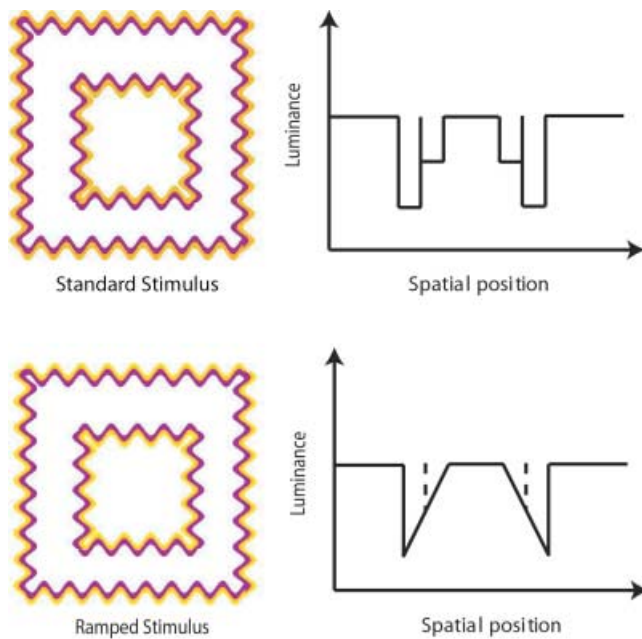
mechanisms have markedly diminished sensitivity above about 4 cycles per degree when artifacts from chromatic aberration are controlled (Hardy et al., 2005).

The contribution of luminance-sensitive spatial mechanisms may be influenced by the sharp edges in the contours of the WCE. Indeed, Pinna et al. (2001) suggested that the strength of the WCE decreases with increasing edge width. Similarly, we predict that the chromaticity shift will vary in a fashion similar to that described by Pinna et al. (2001) for the standard stimulus. Moreover, this result is similar to other assimilation patterns (Helson, 1963; Fach & Sharpe, 1986; DeWeert & Spillmann, 1995; Smith et al., 2001). Consequently, it might be possible that the WCE is stronger also with high-spatial frequency components.

Chromatic mechanisms, in turn, would not be expected to be dependent on the sharp edges of a watercolor stimulus. Indeed, chromatic mechanisms might filter the sharply stepped edges. Consequently, the low-pass filtering makes the sharp edges disappear and renders them comparable to a saw tooth as in the Craik-O'Brien-Cornsweet effect (Ratliff, 1985) and as shown in Fig. 1 on the bottom. However, a luminance contour is necessary for watercolor spreading and this input from an achromatic mechanism to a luminance-dependent color mechanism may require high spatial frequency information.

Fig. 1 shows examples of two spatial profiles having sharp or smooth transitions between the two contours. The WCE stimulus at top is identical to that used in previous research (standard stimulus), whereas the lower panel shows a ramped stimulus. The latter pattern is similar to those found in the literature under the term “cusp” (Kingdom, 1996). The aim of this study was to examine the strength of color spreading for these two types of

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**Fig. 1.** Stimulus patterns used for measuring the WCE with square and saw-tooth luminance profiles as depicted to the right of each pattern.

stimuli while the width of the contours was varied. To that end, we used a color-matching task with results quantified in CIE  $u'v'$  chromaticity space. This method was chosen to facilitate comparison with previous studies (Fach & Sharpe, 1986; Reid & Shapley, 1988; DeWeert & Spillmann, 1995; Smith et al., 2001). The results show that the magnitude of color spreading is stronger for the standard stimulus than for the ramped WCE stimulus, only with wider contour width.

## Materials and methods

### Observers

Three observers ranging in age from 24–35 years were tested. All had normal color vision (assessed by the Neitz anomaloscope, the HRR pseudoisochromatic plates and the Farnsworth F-2 plates), and had normal or corrected-to-normal visual acuity. Informed consent was obtained following the Tenets of Helsinki, and with the approval of the Office of Human Research Protection of the University of California, Davis.

### Apparatus

Stimuli were presented on a color CRT display (Sony Multiscan G220, Shinagawa-ku, Tokyo) driven by a Macintosh G4 computer with a 10-bit graphics board (ATI Radeon 7500, Marlborough, MA). Stimuli were generated using MatLab 5.2.1 and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997). Chromaticities and luminances were calibrated with a handheld colorimeter (Minolta, CS 100) and procedures set out in Brainard et al. (2002). The computer screen was viewed from a distance of 217 cm in a dark room.

### Stimuli

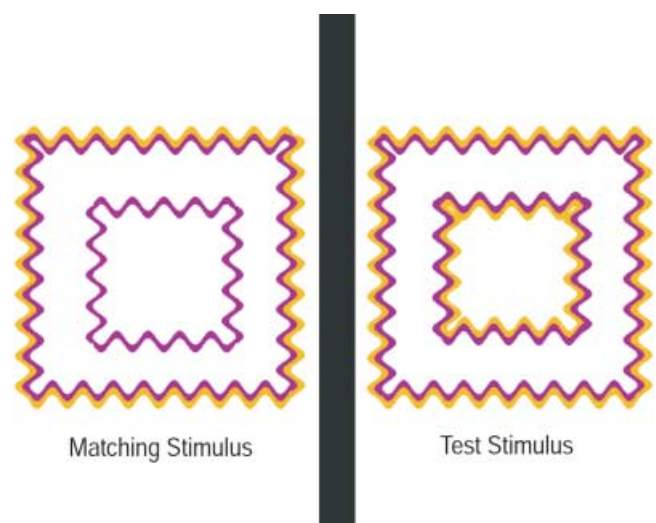
The stimulus patterns used to produce standard and ramped stimuli are presented in Fig. 1. They were each composed of two  $3.4^\circ$  outer

squares surrounding a small inner square of  $1.7^\circ$ . The contours defining the squares were sinusoidally curved at 2.35 cycles of curvature per degree (peak-to-trough amplitude =  $0.13^\circ$ ).

For all experiments, a neutral white background was used ( $u' = 0.189$ ;  $v' = 0.467$ ;  $Y = 45 \text{ cd/m}^2$ ). The luminance contrast of the contours was specified in terms of Weber contrast,  $\Delta L/\bar{L}$ , where  $\bar{L}$  is the luminance of the background field. Contours were adjusted to obtain a luminance contrast of  $-0.44$  relative to the background luminance. Thus, the luminance contrast between the background and the inducing contour was the same for all patterns. For the standard stimulus, the outer contour had a luminance level of  $25 \text{ cd/m}^2$  and the inner contour had a luminance level of  $35 \text{ cd/m}^2$ . The luminance ramp of the ramped stimulus changed linearly from  $45 \text{ cd/m}^2$  to  $25 \text{ cd/m}^2$ . The colors of the contours were: “orange” ( $u' = 0.231$ ;  $v' = 0.512$ ) and “purple” ( $u' = 0.211$ ;  $v' = 0.375$ ). The “orange” color was always the inside contour. For the ramped stimulus, the orange contour varied from  $45$  to  $35 \text{ cd/m}^2$ , and the purple contour from  $35$  to  $25 \text{ cd/m}^2$ . The width of the two contours was defined as the angular distance across which the luminance distribution differed from that of the background, and was  $0.18$ ,  $0.36$ , or  $1.36^\circ$  over their span of their widths.

### Procedure

Using free viewing, observers adjusted the chromaticity of the inner square of the matching stimulus until it looked identical to the comparison stimulus. The adjustable area was the inner square with the “inducing” (orange) contour removed (see left side of Fig. 2). Observers used a computer gamepad to vary the chromaticity along  $a^*$  and  $b^*$  axes in a CIE  $L^*a^*b^*$  color space. Three step sizes were provided ( $0.5$ ,  $0.1$ , and  $0.02$  in CIE  $L^*a^*b^*$  color space) to optimize the match. In each run, the initial coordinates of the test center were chosen randomly because the starting chromaticity of the test patch is known to have an effect on the final settings (Brainard, 1998). Starting points were picked randomly within a color range of  $\pm 10$  units of the white point in CIE  $L^*a^*b^*$  space. Individual variation in the luminosity function was not compensated; however, in previous research with two of the observers



**Fig. 2.** Stimulus patterns: the left square is the test side, and the right side is the standard (in this example, the regular stimulus).

tested in this study, they were found to differ from the CIE standard observer's luminance efficiency by <3.5% for the CRT phosphors used in this study.

Observers were dark-adapted for 3 minutes before beginning the experiments. The matching and comparison stimuli appeared simultaneously on each trial; the matching side was alternated on successive trials. To reduce adaptation to the stimulus pattern, all stimuli were presented for 2 s and immediately followed by a background of uniform luminance that also lasted for 2 s. This sequence was repeated until the observer clicked a mouse to end the trial and start the next one.

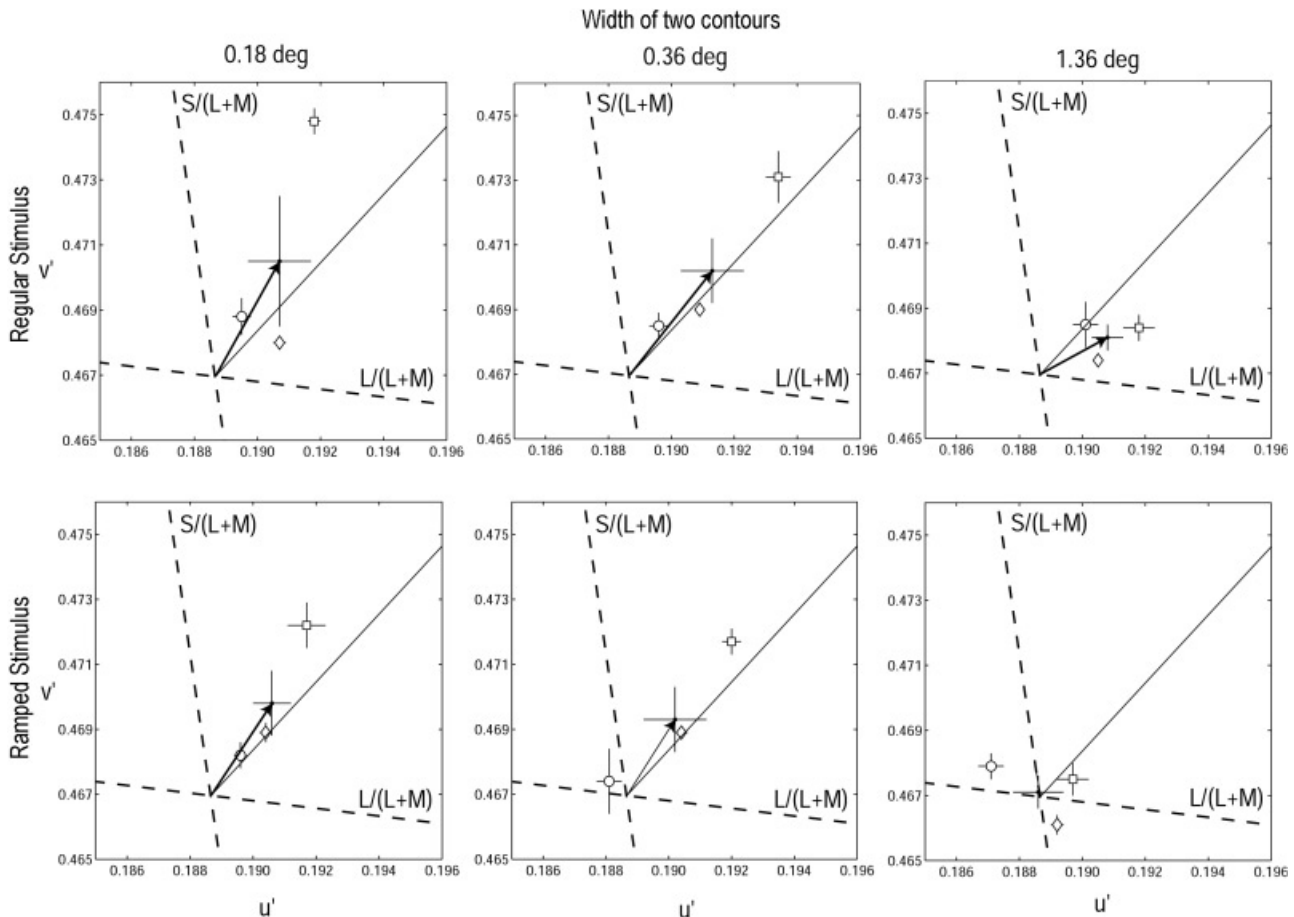
**Results**

*Color spreading as a function of edge width*

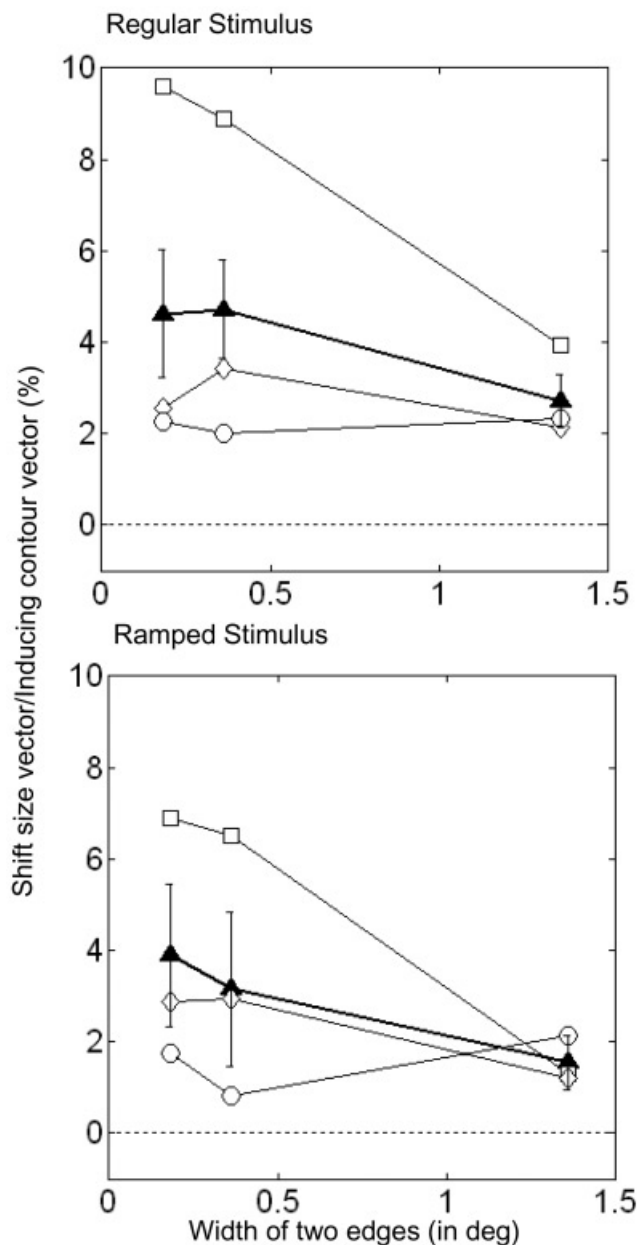
Fig. 3 compares the standard and ramped patterns with a color-matching experiment varying the width of contours. The results are plotted in CIE  $u'v'$  coordinates. For all patterns, we estimated the magnitude of assimilation by dividing the shift vector length by the inducing vector length. The chromaticity of the induced color is much less saturated than the inducing contour with mean shifts of

2.72% to 4.72% (standard stimulus) and 0.16% to 3.89% (ramped stimulus) of the inducing orange vector length. The mean vector shifts of each observer for the two stimuli are presented in Fig. 4. The chromaticity shift of the standard pattern diverged slightly for the two smaller widths, thereafter the shift decreased for the larger width (1.36°). However, individual data showed that this decrease is caused by the results of one observer. Consequently, the strength of watercolor spreading, for the standard stimulus, diverged slightly whatever the width of the two edges. For the ramped pattern, the shift in color diverged slightly when the width of the edges increased.

Table 1 shows the difference angle obtained by subtraction of the induced-color vector from the orange contour vector. For the standard pattern, the watercolor spreading was closer to the orange border for the two smaller contours, with a mean difference from 13.96° (contour = 0.18°) to 4.6° (contour = 0.36°). For the larger width of the double contour (contour = 1.36°), the strength of color spreading became less similar but was still close to that of the orange contour. For the ramped pattern, the watercolor spreading was closer for the two smaller widths, then the difference angle from the orange border shifts away for the larger width (contour = 1.36°). Note that in this case, the chromaticity shift is different for



**Fig. 3.** Color matches for the three observers in a CIE  $u'v'$  diagram. The mean vector required for matching is shown by the arrow originating at the white background. Results for the standard and ramped stimuli are displayed in separate rows. Columns represent the data for three different contour widths (0.18, 0.36, and 1.36°). Symbols denote color shifts for different observers: subject 1 ( $\diamond$ ), subject 2 ( $\square$ ), and subject 3 ( $\circ$ ). Solid line shows the direction of  $\pm 1$  the orange (inner) contour chromaticities. Dotted lines represent cone-opponent axes,  $S/(L+M)$  and  $L/(L+M)$ . Error bars are  $\pm 1$  SEM.



**Fig. 4.** Results of the color-matching experiment shown by two panels for the standard stimulus (above) and the ramped stimulus (below). Results are expressed by the shift size vector divided by the inducing contour vector as a function of the width of the edges. In this case, the chromaticity shift equal to zero is similar to the background (shown by the dotted line). Symbols indicate the chromaticity shift for each observer, and are the same as in Fig. 3. Error bars are  $\pm 1$  SEM.

each observer as shown in Fig. 3 (bottom panel on the right). In this case, the assimilative effect decreased for this pattern only for larger width.

## Discussion

Chromatic assimilation effects were compared for a range of stimulus widths having different spatial profiles of the contours, the standard stimulus with a square-edge profile and a ramped

**Table 1.** Average score and standard deviation of the difference angles for both patterns and for each condition

Pattern	Size of two edges	Angle difference (in deg)	Standard errors
Regular stimulus	0.18°	13.96	4.24
	0.36°	4.60	2.55
	1.36°	-18.60	4.34
Ramped stimulus	0.18°	9.80	4.33
	0.36°	11.63	9.67
	1.36°	29.09	19.13

stimulus. Using a color-matching task, it was found that the chromatic assimilation produced by the standard pattern closely matched the chromaticity of the inducing contour with an increase in the width of the double contour. However, for a larger width (1.36°), the WCE is close to the inducing contour but rotated to appear more reddish. In contrast, chromatic assimilation for the ramped pattern is perceived in the same fashion from the inducing contour for the two smaller widths, and it appears dissimilar for each observer with the larger width of the double contour. This effect of rotation in color space of the matched color away from the chromaticity of the inducing edge is similar to that reported in our previous experiments (Devinck et al., 2005). This study showed that the relation between the chromaticity shifts (the assimilation effect) depends to a great extent on the relative luminance values of the inducing contours. Thus, this rotation in color direction of the induced color appears to depend not only on the luminance contrast, but also on the width of the double contour.

The chromaticity shift for both patterns was similar whatever the widths. As a consequence, this result indicated that both patterns are perceived with the same strength for these widths. It is well known that chromatic contrast sensitivity is low pass (Mullen, 1985). Thus, it might be possible that the visual system filters the double contour of the standard stimulus to render it comparable to the ramped stimulus. This idea is confirmed by the fact that the shift in chromaticity is different for each observer when the width of the double contour is large (1.36°). In this way, the edge between the two contours in the standard stimulus needs to be distinguished for the larger widths to obtain an assimilation effect, whereas it is not necessary for the smaller one.

Chromatic aberration might account for the null difference between the two patterns for smaller widths, although this would not explain assimilative color perceived over wider contours. Devinck et al. (2006) measured the magnitude and direction of assimilative hue change as a function of the width of the enclosed area when the size of the double contour was the same. Results indicated that the chromaticity shift decreased when the width of the enclosed area increased. Moreover, when stimuli were viewed through an achromatizing lens, the magnitude of the assimilation effect was reduced for narrow stimuli, but not for wide ones. This result suggested that chromatic aberration might account, in part, for color assimilation over small, but not large, enclosed areas. Thus, it might be possible that chromatic aberration is not involved only as a function of width of the enclosed area, but also as a function of the width of the double contour as in the present experiment. Indeed, Bradley et al. (1992) showed chromatic aberration to be more important at higher spatial frequencies, than at lower spatial frequencies. In the case of the double contour, if a

very thin purple bar is next to a very thin orange bar (high spatial frequency), then a small offset caused by chromatic aberration could cause them to partially overlap on the retina. For wider contours, the impact would not be as large because only the edges would overlap (Broerse et al., 1999). In this experiment, it could explain why no difference was observed between the two patterns for a narrow double-contour condition (high spatial frequency conditions). However, neural smoothing of the WCE is not supported with wider contours (low spatial frequency condition) where the effects of chromatic aberration are diminished and differences between the two spatial profiles are evident. The diminished effect of chromatic aberration for larger contour widths is consistent with results of other investigators who concluded that a neural process contributes to assimilation (Hurvich & Jameson, 1974; Shevell & Cao, 2003).

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