CHAPTER 12

CHROMATIC ASSIMILATION: EVIDENCE FOR A NEURAL MECHANISM

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Introduction

A single wavelength presented on a dark background has a characteristic color but the same wavelength can appear a very different hue when seen within a context of other nearby light. Context affects the neural representation of the visual stimulus, and thus its appearance.

Chromatic induction is the shift in color appearance caused by nearby light. Most research on chromatic induction has focused on *color contrast*, which is a shift in appearance away from the color of the nearby light (e.g. Jameson and Hurvich 1964; Ware and Cowan 1982; Shevell 1987; Zaidi *et al.* 1992). For example, a patch that appears achromatic in the dark is perceived as greenish when viewed within a large long-wavelength, red-appearing surround. With more complex context composed of repetitive patterns, however, appearance can shift in the opposite direction, toward the color of nearby light (Wyszecki 1986); this is *chromatic assimilation.* Assimilation has been studied surprisingly little, despite the clear shifts in appearance that it causes (Fig. 12.1).

Two general classes of explanation have been proposed for assimilation: non-neural and neural. Non-neural explanations include eye movements, chromatic aberration, and spread light. These factors cause a fraction of the contextual light to fall in the retinal area of the stimulus judged in color. Smith *et al.* (2001) found that assimilation from isoluminant square-wave gratings at higher spatial frequencies can be accounted for by spread light. Most studies of assimilation, however, conclude that neural processes contribute to it (Helson 1963; Fach and Sharpe 1986; Moulden *et al.* 1993; De Weert and Spillmann 1995). The nature of the neural mechanism, however, is often vague or untested.

The present study has two aims. First, a new stimulus is introduced to minimize the influence of prereceptoral factors. Most previous studies of assimilation used contextual light covering half or more of the whole stimulus area (e.g. inducing and test fields that were alternating bars of a square-wave grating). In comparison, the inducing light in various conditions here covers only 9–37 per cent of the whole area. The measurements

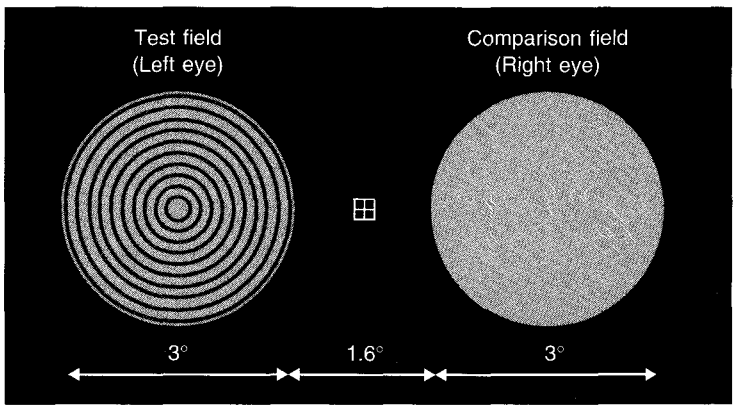

Figure 12.1 See also colour plate section. Schematic of haploscopically presented test and comparison fields. Observers set the uniform comparison field to match the appearance of the test background.

show that chromatic assimilation from this contextual light cannot be explained by prereceptoral factors. Second, the proportion of the whole area covered by inducing light was varied systematically to test for neural summation over the stimulus area. The measurements are generally consistent with neural summation.

Method

Apparatus

Stimuli were presented on a colorimetrically calibrated Radius PressView 17-inch video display, which was controlled by a Macintosh G4 computer. The resolution was 832 × 624 pixels and the refresh rate was 75 Hz non-interlaced. Stimuli on the display were viewed through a haploscope (viewing distance 115 cm). An adjustable chin and forehead rest was used to maintain a stable head position. For details of calibration, see Shevell and Wei (1998).

Stimuli

Separate comparison and test fields were perceived to appear side by side, separated by 1.6° (Fig. 12.1). The comparison field was a uniform circular disk with diameter 3°. The test field was a circle of the same diameter but with inserted inducing light composed of thin concentric rings. The test field had luminance 4 cd/m^2 and l, s chromaticity 0.62, 0.14 (MacLeod and Boynton 1979; units of s here are normalized to 1.0 for equal energy white). Without the inducing-rings, the circular test appeared green. Test luminance and chromaticity were held fixed throughout the experiments.

Inducing-rings inserted into the circular test were varied in width, spacing, chromaticity, and luminance. Ring width was 2 or 4 min, and spacing between rings was 4, 6, 8, 12,

or 16 min. For the 2-min-wide rings, the proportion of the stimulus covered by inducing light ranged from 9 per cent (16-min separation) to 32 per cent (4-min separation); for 4-min-wide rings, the analogous values were 13–37 per cent (the smallest separation was 6 min with 4-min-wide inducing-rings). The inducing-rings appeared either blue (l, s chromaticity 0.53, 9.5) or red (l, s chromaticity 0.83, 0.09). The luminance of the rings was 3, 5, or 8 cd/m^2.

Procedure

The appearance of the test field with inserted inducing-rings was measured by haploscopic matching. In each session, the rings' width and separation were fixed, with chromaticity and luminance varied randomly from trial to trial. Observers dark adapted for 3 min at the beginning of each run. Each chromaticity and luminance combination then was repeated four times within the session. At the beginning of each trial, the comparison field was assigned a random starting chromaticity and luminance. Observers matched the perceived color of the test by adjusting the hue, saturation and brightness of the uniform, haploscopically presented comparison field, by pressing buttons on a pad sensed by the computer. Each condition was repeated in four separate sessions, on different days. The order of sessions was randomized. Results from the four days' measurements were averaged for each inducing-ring width, separation, chromaticity, and luminance. Standard errors were calculated using the mean value from each of the four sessions.

Observers

Two observers participated in the study. Both D. C., an author, and P. M., who was naïve about the purpose of the experiments, were experienced psychophysical observers. The observers were age 30 and 32, and had normal color vision as determined using an anomaloscope.

Results and discussion

Inducing-field luminance

Prereceptoral processes cause some fraction of the inducing light to fall in the retinal area of the test region judged in color. This implies that scaling the luminance of inducing light has a lawful effect on light in the test region, so if this light mediates chromatic assimilation then matches set by the observer will lawfully follow the inducing-light luminance. Measurements for two observers, however, show that the inducing luminance fails to show this lawful relation (Fig. 12.2).

Consider the magnitude of assimilation with "blue" 2-min-wide inducing-rings (4-min spacing between rings) at luminance 3 cd/m^2 (smallest open square). Calculation shows that increasing inducing luminance 2.67 times from 3 to 8 cd/m^2, should increase the matching s coordinate by at least two-fold, if prereceptoral processes mediate assimilation (see Appendix). For both observers, the measured increase is far less (31 per cent for observer P. M., 36 per cent for D. C.; large open squares in Fig. 12.2). For the "red"

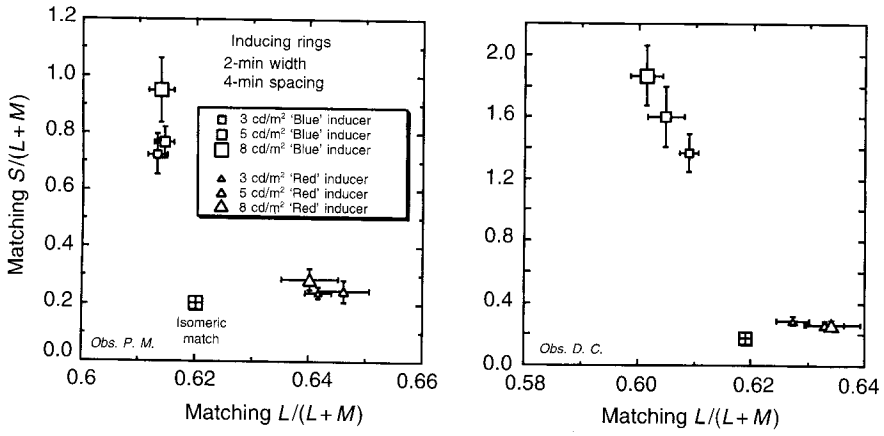

Figure 12.2 Haploscopic matches to the test background, presented with no inducing rings (isomeric match, square-with-plus), "blue" inducing rings (squares) or "red" inducing rings (triangles). Inducing rings were 2-min wide and spaced 4 min apart, at luminance 3, 5, or 8 cd/m^2 (see legend). Each panel shows results for a different observer.

inducing rings, the color matches do not differ significantly as a function of inducing luminance (triangles); for observer P. M., assimilation did not increase monotonically with inducing luminance. A similar conclusion follows from results with 4-min-wide "blue" inducing rings (data not shown): rather than the lawful increase of at least two-fold, the increase with 6-min spacing was −0.08 per cent (nonmonotonic) for P. M. and 41 per cent for D. C.; with 8-min spacing, analogous values were 7 per cent for P. M. and 40 per cent for D. C. None of these measurements is consistent with a prereceptoral explanation for assimilation.

Inducing-field relative area

Several authors have suggested assimilation is mediated by some kind of neural summation (Helson 1963; Hurvich and Jameson 1974; Moulden *et al.* 1993). This can be tested directly by varying the fraction of the test-eye stimulus covered by inducing light, using a fixed inducing chromaticity and luminance ("blue" inducing-rings at 5 cd/m^2 are used here). While simple spatial averaging of light cannot account for assimilation, because physical averaging implies a lawful effect of inducing luminance that was not found in Fig. 12.2, averaging of neural signals that do *not* linearly increase with luminance is a viable model. For example, inducing luminance would not affect the appearance of the test if neural averaging occurs in luminance-independent chromatic pathways $s = S/(L + M)$ and $l = L/(L + M)$. More generally, measurements of color appearance with fixed inducing-light chromaticity, width, and luminance (but with varying ring spacing) can be used to test for neural spatial averaging, regardless of the relation between neural response and luminance.

Suppose the neural signal mediating the appearance of the test is the spatial average of neural response $f(I)$ for inducing light I of fixed size, chromaticity, and luminance; and response $g(T)$ for light T in the test region. The neural responses $f(I)$ and $g(T)$ can be arbitrary nonlinear functions. If the inducing light covers proportion P of the whole area, then the average neural response over the whole area is $f(I) \times P + g(T) \times (1 - P)$. Rearranging terms, the neural average is $g(T) + P[f(I) - g(T)]$, a linear function of the proportion of area, P, covered by the inducing light. With no inducing light ($P = 0$), the neural "average" is simply $g(T)$. Thus, the change in the neural average caused by introducing inducing light covering area P is $\{g(T) + P[f(I) - g(T)]\} - \{g(T)\} = P[f(I) - g(T)]$.

A parameter free test of the neural summation model follows from normalizing each change in neural average by the change in the neural average when P is largest (P_{max}). For example, with the 4-min-wide inducing-ring, P_{max} is 0.37. Normalizing in this way gives the relative change in average neural response for inducing light that covers area P:

$$\{P[f(I) - g(T)]\}/\{P_{max}[f(I) - g(T)]\} = P/P_{max}. \quad (1)$$

Thus, if chromatic assimilation depends on the average of the neural responses from inducing light and test light, weighted by their relative areas, then the shift in appearance should be directly proportional to P/P_{max}.

This can be tested directly with the color assimilation measurements, which were found to be in the direction of the inducing chromaticity. The magnitude of assimilation, therefore, can be quantified by the distance between the appearance match with a particular inducing light and the match with no inducing light (isomeric match). The neural summation model implies greatest assimilation when the inducing light covers the largest proportion of the test area (i.e. at P_{max}). This was indeed the case empirically. Color shifts for other areas of inducing light were normalized to this value, giving relative measurements of assimilation scaled between 0 (no inducing light, isomeric match) and 1.0 (P_{max}). The relative magnitude of assimilation is plotted in Fig. 12.3 as a function of P/P_{max}, for 2-min-wide and 4-min-wide inducing-rings (open and solid circles, respectively). The values fall close to the 45° line, as required by the neural summation model.

In sum, chromatic assimilation scales closely with inducing-light relative area but not with luminance. While assimilation tends to increase with inducing luminance, the magnitude of increase is far less than predicted by prereceptoral factors. Assimilation, therefore, depends on a neural process. Failure of the lawful relation between color appearance and inducing luminance, however, does not imply that no inducing light falls in the test area. The combined effects of (i) neural summation within luminance-independent chromatic pathways and (ii) non-neural factors that cause a fraction of inducing light to fall in the test area may account for the proportional relation between assimilation and relative inducing area, and the weak relation between assimilation and luminance.

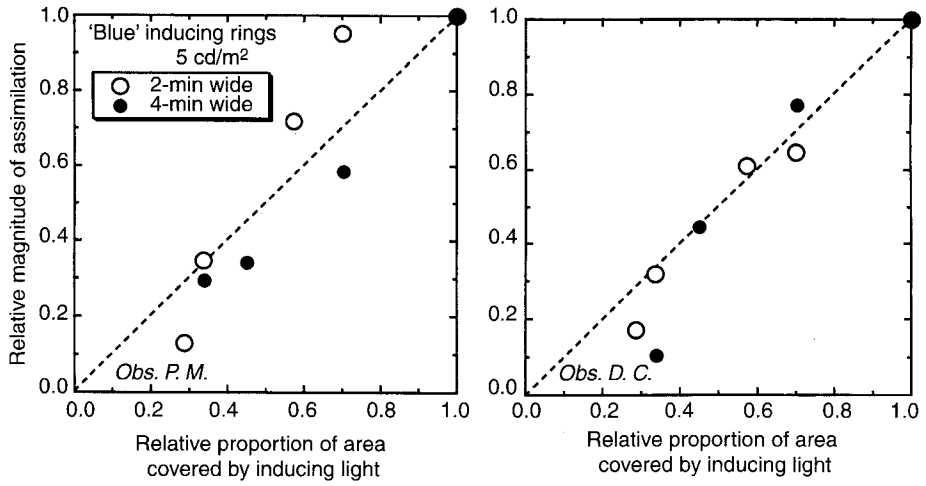

Figure 12.3 Relative magnitude of assimilation (defined in text) as a function of the relative proportion of the test-field area covered by inducing light. Results are shown for 5 cd/m^2 "blue" inducing rings, 2-min wide (open circles) or 4-min wide (solid circles). Each panel shows results for a different observer.

Acknowledgment

This research was supported by NIH grant EY-04802. Publication supported in part by an unrestricted grant to the Department of Ophthalmology & Visual Science from Research to Prevent Blindness.

Appendix

Let the L-, M-, and S-cone stimulations from the test (inducing) light be L_T, M_T, and S_T (L_I, M_I, and S_I). Prereceptoral processes cause some of the inducing light to fall in the retinal area of the test. If the fraction of inducing light, α, that falls in the test region is independent of wavelength (an assumption relaxed below), then the total cone stimulations in the test region are $L_{TOTAL} = L_T + \alpha L_I$, $M_{TOTAL} = M_T + \alpha M_I$ and $S_{TOTAL} = S_T + \alpha S_I$. As $s = S/(L + M)$ by definition, and $L + M$ is luminance (LUM), $S = s$ LUM. Therefore,

$$\begin{aligned} s_{TOTAL} &= (S_T + \alpha S_I)/(L_T + \alpha L_I + M_T + \alpha M_I) \\ &= (s_T \mathrm{LUM}_T + \alpha s_I \mathrm{LUM}_I)/(\mathrm{LUM}_T + \alpha \mathrm{LUM}_I) \end{aligned} \quad (1)$$

The lawful prediction concerns the level of s that should be set with inducing level 8 cd/m^2 ($S_{TOTAL,8}$), given the setting of s with inducing level 3 cd/m^2 ($s_{TOTAL,3}$). With the measurement of $s_{TOTAL,3}$ and known quantities s_T, s_I, LUM_T, and LUM_I set by the experimenter, the value of α can be determined from eqn (1).

The ratio of the s settings, $s_{TOTAL,8}/s_{TOTAL,3}$, predicted by prereceptoral processes is specified from eqn (1), given the value of α determined from the measurement $s_{TOTAL,3}$. Substituting the luminance of the test (4 cd/m^2), the ratio is

$$s_{TOTAL,8}/s_{TOTAL,3} = [(4s_T + 8\alpha s_I)/(4 + 8\alpha)]/[(4s_T + 3\alpha s_I)/(4 + 3\alpha)]. \quad (2)$$

The range of α determined for all of the 'blue' inducing-ring conditions at luminance 3 cd/m^2 over both observers is 0.050–0.235, which from eqn (2) gives a smallest predicted ratio $s_{TOTAL,8}/s_{TOTAL,3}$ of 2.03 (more than a two-fold increase).

As a generalization, suppose that prereceptoral processes result in a larger proportion of inducing light absorbed by S cones than M or L cones in the test area. Then, $L_{TOTAL} = L_T + \alpha L_I$ and $M_{TOTAL} = M_T + \alpha M_I$ are unchanged, but S_{TOTAL} can be larger: $S_{TOTAL} = S_T + (\alpha + \delta)S_I$, where $0 \leq \delta$. Now the ratio is

$$s_{TOTAL,8}/s_{TOTAL,3} = [(4s_T + 8(\alpha+\delta)s_I)/(4+8\alpha)]/[(4s_T + 3(\alpha+\delta)s_I)/(4+3\alpha)]. \quad (3)$$

For all values of δ greater than 0, the value of the ratio $s_{TOTAL,8}/s_{TOTAL,3}$ increases with δ (i.e. $d(s_{TOTAL,8}/s_{TOTAL,3})/d\delta > 0$). Therefore, if a larger proportion of inducing light is absorbed by S than by M or L cones in the test area, the ratio $s_{TOTAL,8}/s_{TOTAL,3}$ will be even larger than the ratio found by assuming α is identical for all three cone-types.

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