

Mechanisms of simultaneous color induction

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A new method of measuring simultaneous contrast, or chromatic induction, is introduced and used to test the hypotheses that induction results from either multiplicative or subtractive interaction of either (1) like receptors or (2) like second-stage, opponent mechanisms. Predictions derived from these hypotheses do not predict the outcome of the experiments as well as the traditional notion that induced colors are in the direction complementary to the inducing color with respect to the test color. We conclude that simultaneous contrast is a consequence of interaction within higher-level chromatic mechanisms.

INTRODUCTION

Simultaneous contrast or induction is the influence of other visual stimuli in the field of view on the perceived color of a visual stimulus. For example, when a white disk is viewed on a red surround, the disk appears to be tinged with the complement of red, i.e., with green. We asked whether this phenomenon can be accounted for in terms of interaction between like receptors or between like second-stage mechanisms. We compared predictions from these hypotheses with the traditional description of induction, namely, that the test is tinged with the color complementary to the inducing color, and the traditional view prevailed.

Classically, colors are said to be complementary if their mixture, in appropriate proportions, matches some standard white. If we are to predict the results of induction when the test is other than a neutral stimulus and when the luminance of the test and inducing light differ, we need a general definition of complementarity. Two colors are complementary with respect to a reference color if the reference color is the average of the two colors in a three-dimensional color space. Let l , m , and s , respectively, denote the quanta absorbed by the long-, middle- and short-wavelength sensitive cone receptors from the reference light. Then two lights will be complementary with respect to the reference if the absorptions caused by one of them are al , bm , and cs , whereas those caused by the other are $(2-a)l$, $(2-b)m$, and $(2-c)s$, where a , b , and c vary between 0 and 2.

We used a nulling method of measuring chromatic induction.¹ When an observer fixates a white disk, the disk appears greenish when surrounded by a red annulus and the disk appears reddish when surrounded by a green annulus. The effects of the annulus can be neutralized by adding some red light to the disk in the first case and some green light to the disk in the second. The amount of light needed to make the disk appear white may be taken as a measure of induction. Performing these operations in successive experiments requires the observer to keep a standard white in mind. On the other hand, if the color of the annulus is modulated isoluminantly from red to green, the disk appears to be modulated in counterphase to the annulus. If a modulated component is added to the disk, the disk can be made

to appear steady. The nulling modulation can be used as a measure of induction. If induction is strictly complementary, the modulation added to the disk must be along the same line in color space as that applied to the annulus.

The new method has the following advantages. The observer looks at the central disk at all times. Except for small eye movements, the portion of the retina that receives the induced modulation is never exposed to the inducing field, so that successive contrast effects are kept to a minimum. This is a null method in that the observer is required to select conditions in which there is no apparent modulation of the critical part of the field. At the null point, the induced effects of all phases of the surround modulation are equally canceled. No memory demands are made. The chromaticity and luminance averaged over a cycle of modulation is the same for the whole display for modulation in all directions of color space. The steady-state adaptation is therefore constant throughout the experiments.

We specify our stimuli in terms of the three cardinal directions of color space defined by selective habituation experiments.² One chromatic cardinal axis is the constant B axis along which only R- and G-cone inputs vary isoluminantly and the other is a constant R&G axis along which only B-cone input varies. The third cardinal axis is the luminance axis. The two chromatic cardinal directions also correspond to the preferred directions of the two classes of parvocellular neurons found in the lateral geniculate of the monkey.³ To specify intermediate angles, a metric for each of the cardinal directions is needed. We used the maximum possible modulation in each cardinal direction permitted by our apparatus as the metric.

In the first experiment the new method was used to measure the amplitude of the nulling modulation as a function of the amplitude of the modulation of the inducing stimulus in the three cardinal directions. This experiment revealed that the nulling amplitudes are different functions of inducing amplitudes in the three cardinal directions. This result permitted a critical test of the hypothesis that second-stage mechanisms mediate induction. This was carried out in the second experiment, in which the amplitude and direction of the modulation needed to null the effect of an inducing stimulus in various noncardinal directions was measured.

The results of the second experiment argue against interaction at either the first, cone, stage or the second, opponent-mechanism, stage, and we conclude that higher-order chromatic mechanisms are responsible for chromatic induction.⁴

EXPERIMENT 1

In the first experiment the amplitude of the induced modulation was measured as a function of the amplitude of the inducing modulation for each of the three cardinal directions.

Method

The observers fixated the center of a television monitor. Initially the whole 9 deg × 10 deg display was an equal-energy white of 100 cd/m². This was the time-averaged chromaticity and luminance of the display throughout the course of the experiments. The display was driven by an Adage frame buffer controller that permitted 10-bit specification of the intensity of each TV primary for 2³⁰ possible colors, of which any subset of 256 colors could be painted in the 480 × 512 visible pixels. The frame rate was 120 Hz, interlaced, or 60 complete frames per second.

The experiment conditions are illustrated in Fig. 1. The observer saw a 1-deg central disk surrounded by an annulus with an inner diameter of 1 deg and an outer diameter of 8 deg. The surround was modulated sinusoidally in time at a frequency of 1 Hz. The modulation was around equal-energy white along one of the cardinal directions, with amplitudes from 0.1 to 1.0. Observers were instructed to use a joystick to null the induced modulation by adjusting the amount of real modulation in the central disk. The direction of modulation of the center was the same as that for the surround. Observers reported that there was no residual modulation of the central disk at the null setting. The joystick served as a rate controller with a central dead zone; thus the observers received no positional cues. Nulling amplitudes were measured for 10 inducing amplitudes for each of the three cardinal directions.

The amplitude of modulation is defined as follows. Unit amplitude for a particular color direction is the maximum modulation around white achievable with the phosphors of the color monitor. The CIE *x* and *y* coordinates of the red, green, and blue phosphors were (0.64, 0.33), (0.29, 0.60), and

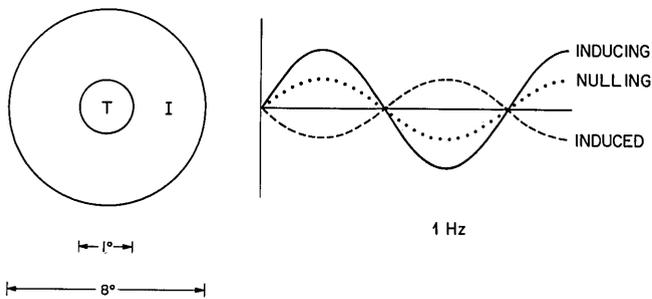


Fig. 1. Basic measurement technique. On the left, I indicates the inducing stimulus, T the test stimulus. On the right the solid line marked INDUCING depicts the variation in time of the color of the inducing annulus. The dashed line marked INDUCED depicts the modulated appearance of the test disk when it is, in fact, not modulated. The dotted line marked NULLING depicts the real modulation of the disk required to make it appear steady.

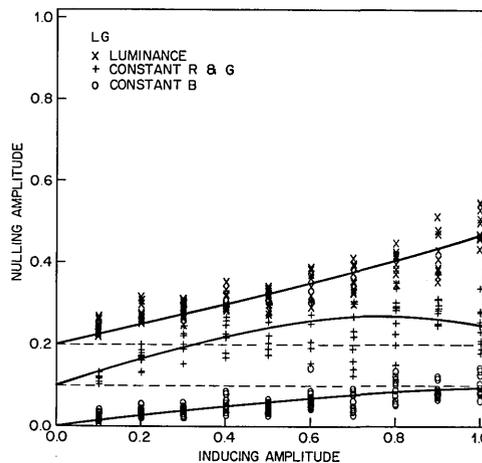


Fig. 2. Nulling amplitude as a function of inducing amplitude for observer LG. The results from top to bottom are for modulation along the luminance axis, along the constant R&G axis, and along the constant B axis. Note the displaced ordinates. Lines fitted to the data have parameters listed in Table 1. Observer, LG.

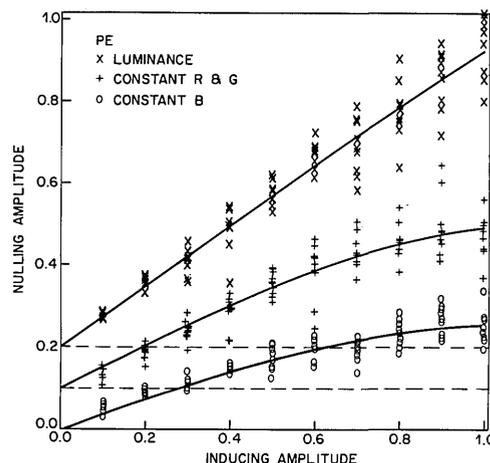


Fig. 3. Same as Fig. 2 for observer PE.

(0.15, 0.06), respectively. The coordinates of the white used in the experiments were *x* = *y* = *z* = 0.333. Other amplitudes are given as fractions of the maximum amplitude.

Results

The amplitude of the nulling modulation versus the amplitude of the surround modulation is shown in Figs. 2 and 3 for two observers for each of the three cardinal directions. The lines in Figs. 2 and 3 were fitted to the points by a least-squares regression of the form

$$A_N = aA_I + bA_I^3.$$

The inducing and nulling amplitudes are represented by *A_I* and *A_N*, respectively. The values of *a* and *b*, the linear and cubic coefficients, respectively, are given in Table 1 along with the values of *R*², the proportion of the variances accounted for by the fits. The worst of these fits accounted for more than 88% of the variance. These fits were somewhat better than those obtained to a simple linear model. These curves can be compared with one another without converting to threshold units, because both the nulling and the inducing stimuli are expressed in the same units, and a multiplicative change of scale would leave the curves un-

Table 1. Linear and Cubic Coefficients and R^2 for Curves in Figs. 2 and 3

	LG			PE		
	Linear	Cubic	R^2	Linear	Cubic	R^2
Constant B	0.125	-0.029	0.91	0.368	-0.114	0.98
Constant R&G	0.325	-0.177	0.88	0.523	-0.133	0.97
Luminance	0.245	0.022	0.96	0.747	-0.026	0.99

changed. The magnitude of the nulling amplitudes differ by about a factor of 2 between the two observers, but the general trend of the results is similar for these and other observers that we have tested. The curve for the luminance direction is the steepest, followed by that for the constant R&G direction, and that for the constant B direction is the shallowest. The important fact is that the functions relating inducing and nulling amplitudes were sufficiently different to allow experiment 2 to be a critical test of the locus of induction effects.

EXPERIMENT 2

The second experiment is concerned with the question whether induction takes place solely within independent second-order mechanisms. If this were true, induction would not, in general, result in changes of appearance in a strictly complementary direction. In the stimulus domain, modulation in a direction intermediate between two cardinal directions is equivalent to the vector sum of modulations of the appropriate amplitudes in the two cardinal directions. If induction took place solely within cardinal mechanisms, then the induced effect of this modulation could be nulled by a modulation that simultaneously nulled the induced effect in each of the cardinal directions. However, because the nulling functions are not identical for the cardinal directions, the induced effects in the two directions will be different multiples of the projected amplitudes. The predicted nulling modulation will therefore not be in the same color direction as the intermediate inducing direction. If induction took place in higher-order color mechanisms tuned maximally to the inducing direction, then the best nulling modulation would be in the same direction as the inducing modulation.⁴ These predictions are depicted graphically in Fig. 4.

Consider an inducing stimulus modulated in the direction T . In physical terms, such a stimulus is the vector sum of stimuli modulated along the cardinal axes, C_i and C_j , respectively, with amplitudes p_i and p_j , as shown in the left-hand panel of Fig. 4. The amplitudes of the modulations of the disk that will null the modulations induced by p_i and p_j can be read off the curves depicted in the right-hand panel as N_i and N_j . If induction resulted from independent processes in the second-stage mechanisms, the induced effect caused by modulation in the direction T would be canceled by a modulation that is the vector sum of N_i and N_j , namely, N_C . On the other hand, if the observers are allowed to vary the nulling stimulus only in the direction of T , they will pick some point N_T as the best null. Whenever the functions plotted in the right-hand panel are different from one another, N_C and N_T will be different.

Method

In this experiment we tested the hypothesis that induction takes place solely within second-stage mechanisms versus the hypothesis that the test stimulus is tinged with the complement of the inducing color. The experimental conditions are illustrated in Fig. 5. The basic paradigm and the stimulus configuration were the same as in experiment 1. Only the inducing modulations were different. In each session we first measured N_i , N_j , and N_T for one of 10 intermediate directions, six in the isoluminant plane common to the two chromatic cardinal axes, two in the plane common to the luminance and constant B axes, and two in the plane common to the luminance and constant R&G axes. As shown in the top panel of the figure, first an intermediate direction T was chosen. The projections p_i and p_j were calculated by the computer program. In the first part of a session, the observer adjusted the modulation of the center with the joystick to reduce its apparent modulation to a minimum. The annulus was modulated in one of the three directions, C_i , C_j , or C_T , selected at random, and, as in experiment 1, the center was also modulated only in that direction. Five trials were run with the annulus modulated in the T direction, and five in the direction C_i with an amplitude of p_i , and five in the direction C_j with an amplitude of p_j . The vector sum of the means of N_i and N_j was used to estimate N_C , the predicted nulling modulation from the second-stage hypothesis. As shown in the bottom panel of Fig. 5, the mean of the nulling modulations in the test direction N_T was used as the competing prediction in the forced-choice phase of the ex-

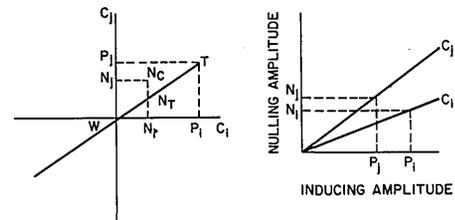


Fig. 4. Prediction of results for experiment 2. See text.

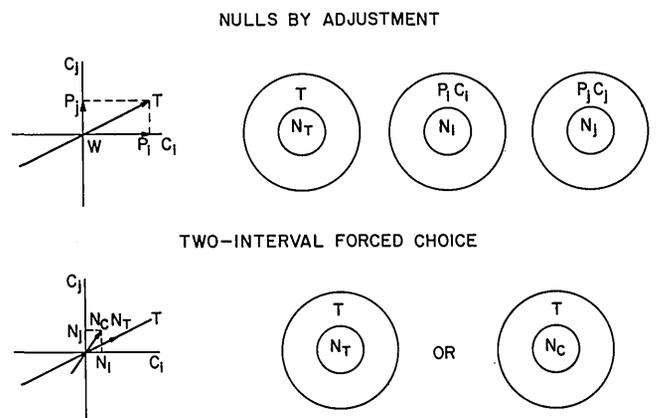


Fig. 5. Conditions for experiment 2. Upper panel shows the stimuli used in the first part of each session of experiment in which observers determined the values of N_T , N_i , and N_j by adjusting the modulation of the central disk to produce the least-apparent modulation. Lower panel shows stimuli pitted against one another in the second part of a session of experiment 2 in which the observers made a forced choice of the stimulus that produced the lesser-apparent modulation.

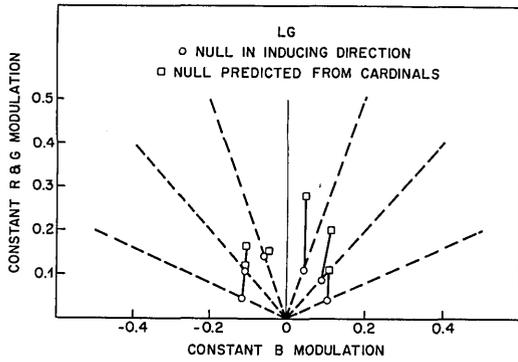


Fig. 6. Mean location in color space of the isoluminant stimulus pairs in the forced-choice part of experiment 2. The mean null stimuli obtained by adjustment along the actual inducing direction are shown by the circles. The locations of the nulls predicted by the setting along the cardinal directions are shown by the squares. The lines connect pairs of stimuli that were pitted against one another in the forced-choice trials. Observer, LG.

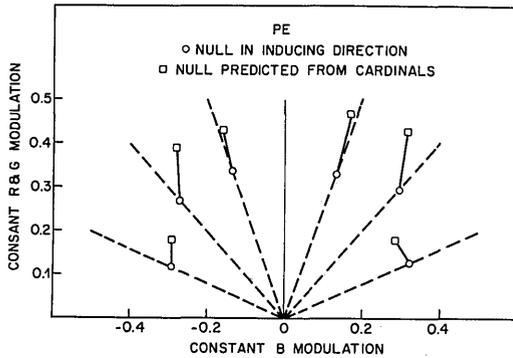


Fig. 7. Same as Fig. 6. Observer, PE.

periment in which the observers made 16 choices between N_T and N_C . For each choice, the surround was modulated along the intermediate direction T for four cycles. At the same time, the center was modulated along one of the candidate nulls N_T or N_C , randomly chosen, for the first two cycles and the other candidate null for the last two cycles. The first interval was accompanied by a beep. The observer indicated by pressing buttons which interval had the least-perceived modulation in the center. Three such sessions were run for each of the 10 intermediate directions for observer LG and five such sessions each for observer PE.

Results

The null settings for intermediate directions in the isoluminant plane are shown in Figs. 6 and 7. The origin represents the midwhite point, the abscissa the constant B axis, and the ordinate the constant R&G axis. The dashed lines radiating out from the white point represent the intermediate test directions. For each intermediate direction, the figures show the mean of the null settings in the inducing direction and the nulls predicted from the mean setting of the nulls in the cardinal directions. It is important to note that the circles must fall on the radiating lines since the nulling stimuli were modulated only in those directions. The predicted null from the settings in the cardinal directions is always above the setting of the nulls in the inducing direction consistent with Figs. 2 and 3, where the nulling function

for the constant R&G direction is above the nulling function for the constant B direction.

The critical results of this experiment are the forced-choice judgments for intermediate directions in the isoluminant plane shown in Fig. 8. The proportion of times that the null in the inducing direction was preferred to the null predicted from the cardinal directions is plotted against the angle of the inducing stimulus. The line at 0.5 indicates no preference between the two nulls. Observer LG preferred the null in the inducing direction for all six test directions. The proportion of times the null in the inducing direction was preferred, pooled for all six directions, was 0.79 for 285 binary choices. Observer PE preferred the null in the inducing direction for five of the six test directions. The pooled proportion of preference for this observer was 0.64 of 481 binary choices. The null hypothesis of equal preference may be rejected at the 1% level of confidence for both observers.

The null settings for inducing modulations in directions intermediate between the luminance axis and one of the chromatic axes are shown in Figs. 9 and 10. Consistent with the nulling functions in Figs. 2 and 3, in each case, the

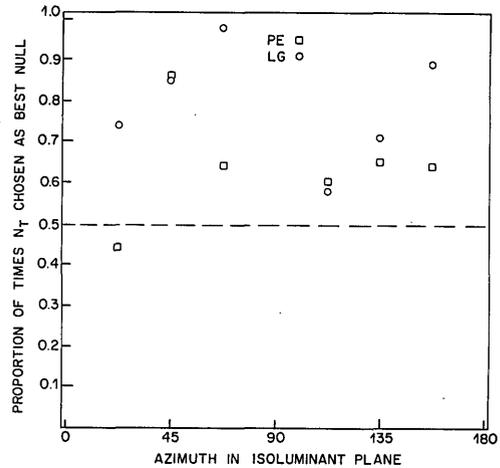


Fig. 8. Proportion of times when observers chose the mean adjustments that they made along the direction of modulation of the inducing stimulus in preference to the nulls predicted from the settings of nulls for inducing stimuli along the cardinal directions. Result for both observers for isoluminant stimuli are plotted against the azimuth of the inducing modulation.

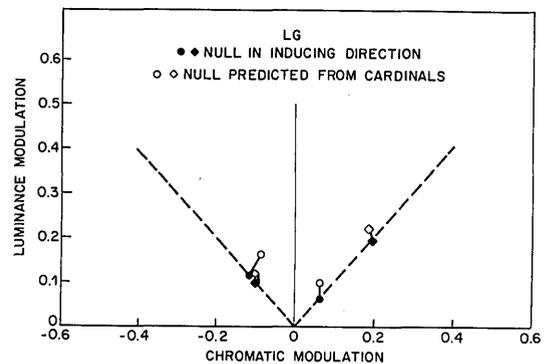


Fig. 9. Same as Fig. 6 for stimuli out of the isoluminant plane. Chromatic modulation along the constant B direction is represented by circles and along the constant R&G direction by diamonds. Observer, LG.

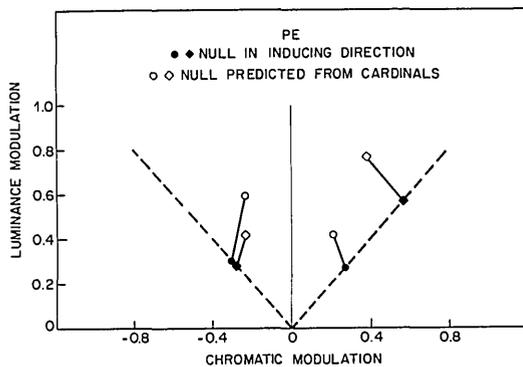


Fig. 10. Same as Fig. 9. Observer, PE.

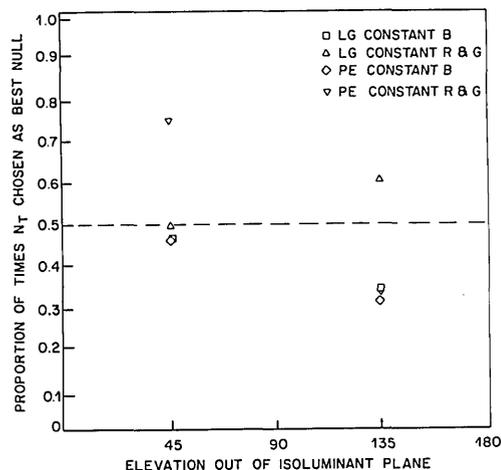


Fig. 11. Same as Fig. 8 for stimuli out of the isoluminant plane.

predicted null from the cardinal directions is above the mean of the settings in the inducing direction.

The results of the forced-choice judgments for these directions are shown in Fig. 11. The results are different from those for stimuli confined to the isoluminant plane. The pooled proportion of times that the null in the inducing direction was preferred was 0.47 of 193 choices for observer LG and 0.47 of 320 choices for observer PE. Neither of these proportions is significantly different from 0.5.

DISCUSSION

The results support, for isoluminant stimuli, the complementary nature of chromatic induction. They also serve to underscore the difficulties with previous theories of induction. Induction implies that the effects of a stimulus falling on one part of the retina are modified by stimuli falling on another part of the retina at some level in the visual system. For example, it has been supposed that stimulation of cones of one class in one part of the retina results in the desensitization of cones of the same class in other parts of the retina.⁵ Alternatively, a similar form of lateral interaction might take place between second-stage opponent mechanisms.⁶

The results of experiment 2 rule out interaction at both of these levels as an explanation of induction. The experiment was set up as a direct test of the hypothesis that induction results from independent processes in the second-stage mechanisms. The observers preferred the settings in the

direction of the inducing stimuli to those predicted from the cardinal-direction settings. The same experiment also rules out explanations in terms of independent first-stage mechanisms because modulation along the constant B axis varies the input only to the long- and middle-wavelength-sensitive cones, whereas modulation along the constant R&G axis only varies the input to the short-wavelength-sensitive cones.

It is worth noting in passing that, if the responses in the test area were modified in proportion to the ratio of the quantal catches in the test and inducing regions, the change in appearance would not be toward the complement of the inducing stimulus. That is, von Kries adaptation does not predict complimentary induction.

It has been clear for some time that three independent linear mechanisms are not sufficient to account for data on a variety of color phenomena including hue cancellation⁷ and the loci of constant hue.⁸ To account for such data, some investigators have postulated nonlinear second-stage mechanisms.⁸ Such models have been shown to be flawed.⁹ An alternative direction was taken by Krauskopf *et al.*⁴ They argued that chromatic habituation occurred beyond the interaction of independent linear cardinal mechanisms, in mechanisms preferentially tuned to many different directions of color space. This scheme is in accord with data from recent electrophysiological studies. While recordings in the parvocellular layers of the lateral geniculate nucleus have revealed two major classes of cells,³ similar experiments on the visual cortex reveal a diversity of cells.¹⁰ The largest proportion of cells are luminance cells. The cells that respond to pure chromatic modulation have maximal responses in many directions in color space rather than only in the cardinal directions. Since chromatic induction cannot be explained in terms of lateral interaction at either the primary, cone, level or at the second, opponent, stage, it seems likely that the cause of this phenomenon lies in the higher-order mechanisms.⁴

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