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Chromatic assimilation measured by temporal nulling

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Abstract

Chromatic assimilation is the shift in color appearance *toward* nearby light. Assimilation was measured using nearby light with time-varying chromaticity. This light induced time-varying assimilation within the test area. Assimilation was quantified by the amplitude of temporally varying test-area light – in counter-phase to the induced assimilation – required to null the assimilation. Unlike previous studies of assimilation, observers here judged only the steadiness of the test area, not its color. The inducing light was varied in luminance, temporal frequency and chromaticity. The measured assimilation could not be explained by only optical factors affecting receptoral quantal absorption. This implies a neural process contributes to assimilation. The nulling measurements showed also that assimilation was not induced independently within the L/M- and S-cone pathways.

Keywords: Chromatic assimilation; Chromatic contrast; Spread light; Temporal nulling

1. Introduction

The color appearance of an object depends on the context that surrounds it. A well-known example is the phenomenon of color contrast, in which the appearance of an object shifts away from the color of its surround. For example, an object that appears yellow when viewed against a dark background appears greenish against a long-wavelength 'red' field (Shevell, 1982). Context also can cause the opposite phenomenon, called chromatic assimilation, in which the color shift is *toward* the appearance of nearby light (in this case, nearby long-wavelength light makes the object appear redder). The spatial frequency, chromaticity and relative luminances of the object and context determine whether context causes contrast or assimilation.

Chromatic assimilation, while perhaps more common than color contrast (De Valois & De Valois, 1988), is investigated infrequently and sometimes with only subjective reports or ordinal comparisons (de Weert & van Kruysbergen, 1997; Festinger, Coren, & Rivers, 1970). Some well-known experiments consider only achromatic shifts (Helson, 1963; Walker, 1978). Studies of assimilation that employ asymmetric color matches often use isoluminant stimuli (Fach & Sharpe, 1986; Smith, Jin, & Pokorny, 2001). Only recent asymmetric matches assess chromatic assimilation from inducing light varied systematically in width and repetition frequency (equivalently, spatial frequency and duty cycle), luminance contrast with respect to the test area, and chromaticity (Cao & Shevell, 2005).

The present study used a fresh approach to investigate the physiological mechanisms that mediate chromatic assimilation. No judgment of color appearance was required. Instead, nearby light causing chromatic assimilation was modulated in time, thereby causing a shift in test-area color appearance that varied in time. The perceived temporal variation in the color of the test was then nulled by an additional stimulus, added to only

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the test area, that also was modulated in time but in counter-phase to the perceived assimilation. In the experiments, therefore, the observer adjusted the physical modulation depth added to the test area to null the perceived modulation from induced assimilation. The amount of test-field modulation necessary for the null quantified the assimilation from nearby light. As the observer's perceptual criterion was simply a steady unvarying test field, no subjective judgment of color was required.

Temporal-nulling paradigms have a nearly 20-year history in studies of brightness and color *contrast* (De Valois, Webster, De Valois, & Lingelbach, 1986; Krauskopf, Zaidi, & Mandler, 1986; Rossi & Paradiso, 1996; Singer & D'Zmura, 1994). While nulling does not explicitly measure the perceived shift in appearance, it offers two advantages over asymmetric matching. First, the peak and trough of the time-varying inducing light allow presentation of two extreme chromaticities without causing long-term adaptation to either of them. Second, the temporal-nulling criterion is closer than asymmetric matching to an "indistinguishable" class A observation (Brindley, 1970, p. 133) because the observer's criterion is no perceived temporal change within the test area.

The experiments here used nulling to measure chromatic assimilation in order to address the following points. First, the perceived temporal modulation within the test area was examined to determine whether the nearby time-varying inducing light caused assimilation or contrast. Second, after confirming assimilation from the inducing light, the luminance of the inducing light was varied to test whether assimilation resulted from only non-neural optical imperfections that altered the physical image on the retina. Third, the generality of the conclusion from Experiment 2 was tested using other temporal frequencies of inducing light (cf. De Valois et al., 1986; Rossi & Paradiso, 1996). Finally, the chromaticity of the inducing light was varied to assess whether assimilation was induced independently within the L/M- and S-cone pathways.

2. Methods

2.1. Apparatus and stimuli

Stimuli were presented on a calibrated, high-resolution (1360 × 1024) 21-in. Sony Trinitron monitor controlled by a Macintosh G4 computer. A Radius video board provided 10-bit resolution for each of the R, G, and B guns. The refresh rate was 75 Hz non-interlaced. The monitor was viewed directly with both eyes at a distance of 70 cm. An adjustable chin rest maintained the observer's head position.

The stimulus (Fig. 1) was composed of a 3° uniform background with inserted concentric inducing rings and a dark center 36-min wide. The background served as the test field judged by the observer. Two background chromaticities were tested, specified by modified MacLeod and Boynton (1979) units ($l = L/[L+M]$, $s = S/[L+M]$): (0.665, 0.99), which was essentially metameric to equal-energy white (EEW), and (0.63, 0.99), which appeared bluish green and we refer to as the $-l$ test area. The modification from the original MacLeod–Boynton chromaticities was only the (arbitrary) unit of s, normalized here to 1.0 for EEW. Concentric inducing rings were 4 min wide, and repeated every 12 min (that is, 8 min separation between adjacent inducing rings, thus 5 cpd). Inducing-ring luminance was either 2.67 or 6.0 cd/m^2; the background level was 4.0 cd/m^2 (thus 0.20 Michelson contrast for either inducing luminance). An advantage of the lower luminance of inducer than background (2.67 compared to 4.0 cd/m^2) was enhanced assimilation over contrast (de Weert & Spillmann, 1995) and less spread light from the inducing rings into the test area.

Unless stated otherwise, the light in the concentric inducing rings was modulated sinusoidally in time at 1.2 Hz either in the l chromatic direction with magnitude 0.03 (for example, from 0.635 to 0.695 with the EEW background) or in the s direction with magnitude 0.75, while maintaining constant luminance. The time-average chromaticity of the inducing light was the same as in the background.

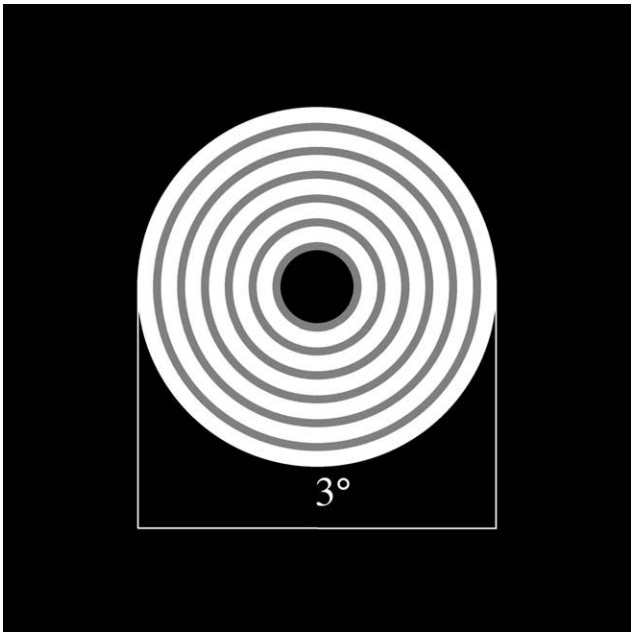

Fig. 1. Schematic drawing of the stimulus. A 3° uniform background was presented with inserted 4-min-wide concentric inducing rings, repeated every 12 min. The central 36 min was dark. Inducing rings were varied over time. The task was to null the perceived temporal variation in the background, which served as the test region judged by the observer.

2.2. Procedure

For contrast (not assimilation), temporal modulation of inducing light causes a counter-phase apparent modulation in the test field. For example, increasing *l* in the inducer (toward more redness) causes the test to shift toward an appearance characteristic of less *l* (less redness). The perceived modulation in the test can be nulled by adding to the test area light that is modulated in-phase with the inducing modulation (that is, 0° phase difference with respect to the inducing modulation; De Valois et al., 1986; Krauskopf et al., 1986). Temporally modulated inducing light that causes assimilation, on the other hand, results in apparent induced modulation in the test that is in-phase with the modulated inducing light. Thus, nulling the perceived modulation in the test area requires adding temporally modulated light to the test that is counter-phase to the apparent modulation, and therefore counter-phase to the temporally modulated inducing light. Temporal nulling of induced contrast modulation is shown schematically in Fig. 2(A) (0° phase difference between the nulling and inducing modulations); nulling of induced assimilation modulation is shown in Fig. 2(B) (180° phase difference between the nulling and inducing modulations).

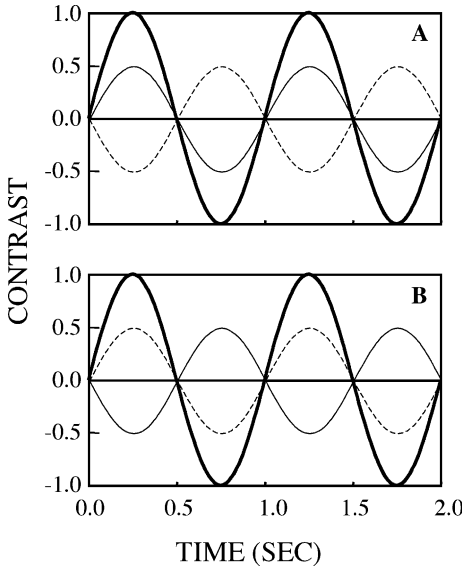

Fig. 2. Sinusoidal temporal modulation of inducing light (thick solid line in each panel) causes perceived temporal variation in the test area. The phase of the nulling modulation in the test area distinguishes contrast from assimilation. (A) *Contrast*. The percept induced in the test area (dashed line) varies in counter-phase to the inducing light. This induced temporal variation can be nulled by adding light in the test area (thin solid line) in-phase with the inducing modulation (that is, 0° phase difference between inducing and nulling lights; see the two solid lines). (B) *Assimilation*. The percept induced in the test area (dashed line) varies in-phase with the inducing light. This induced temporal variation can be nulled by adding light in the test area (thin solid line) in counter-phase to the inducing modulation (that is, 180° phase difference between inducing and nulling lights; see the two solid lines).

A basic question with any temporally modulated inducing light is whether it causes contrast or assimilation. If the apparent modulation in the test is in the direction of contrast, then the added nulling modulation must be in-phase with the modulation of the inducing light (0° phase difference, Fig. 2(A)). If, however, the apparent modulation in the test is in the direction of assimilation then the added nulling modulation must be in counter-phase to the modulation of the inducing light (180° phase difference, Fig. 2(B)). The direction of the apparent modulation in the test area – contrast or assimilation – for the stimuli used here was determined in Experiment 1 by varying the phase of the nulling light added to the test.

The measurements were conducted in a dark room. Before each session, the observer dark-adapted for three minutes. Measurements were replicated on four different days unless stated otherwise. The order of sessions was randomized. For null settings, two measurements for each condition within each session were averaged and recorded as the setting from that session. The means and standard errors of the null settings were determined from the null value from each of the four sessions on different days.

2.3. Observers

Three observers participated in the study: DC (male), LHJ (male) and TD (female). The observers' ages ranged from the mid-twenties to early thirties. Each observer had normal color vision as evaluated by a Neitz anomolascope. Observer DC, one of the authors, was an experienced psychophysical observer. The other observers were naïve regarding the design and purpose of this study. Each observer signed a consent form before participating in the study. The experimental procedures were approved by an Institutional Review Board at the University of Chicago.

For each observer, a minimum motion technique (Anstis & Cavanagh, 1983) was used to measure the relative luminance of each phosphor of the color CRT. The luminance of each stimulus for each observer was adjusted using these minimum-motion measurements. Also, a minimally distinct border technique (Tansley & Boynton, 1978) was used to verify that each observer's tritan line did not deviate significantly from theoretical values that isolate S cones.

3. Results

3.1. Experiment 1: Verification of assimilation

For assimilation, the theoretical phase of added modulation in the test area to achieve a null is 180° relative to the inducing modulation. At the beginning of each

session, the phase of the added modulation in the test was set to 180° and the amplitude of the added modulation set randomly between zero and half of the magnitude of the inducing modulation. The observer then adjusted the amplitude of the added modulation to achieve minimal fluctuation in test-field appearance.

Next, using this measured amplitude of modulation, a pair of stimuli was presented in separate temporal intervals. In one interval, the phase of the added modulation was the initial one (180°) and in the other interval the phase was randomly selected from 0°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5°, or 180°. The ordering of the two intervals was randomized. The presentation duration for each interval was 2 s, with an inter-interval duration of 2 s. After the pair of stimuli was presented, the observer indicated which interval had the steadier test field by pressing a button on a game pad. In each session, each phase was presented 10 times, in a random order. Each session was repeated on three different days. For each of the 9 comparison phases, the proportion of trials judged more steady at 180° phase was averaged over the three sessions.

The comparison between 180° phase (theoretical assimilation) and all other phases from 0° to 157.5° is shown in Fig. 3 (solid symbols). Each point shows the proportion of times that 180° phase was perceived to give a steadier test-field percept than the phase shown on the horizontal axis. The left [right] column has results

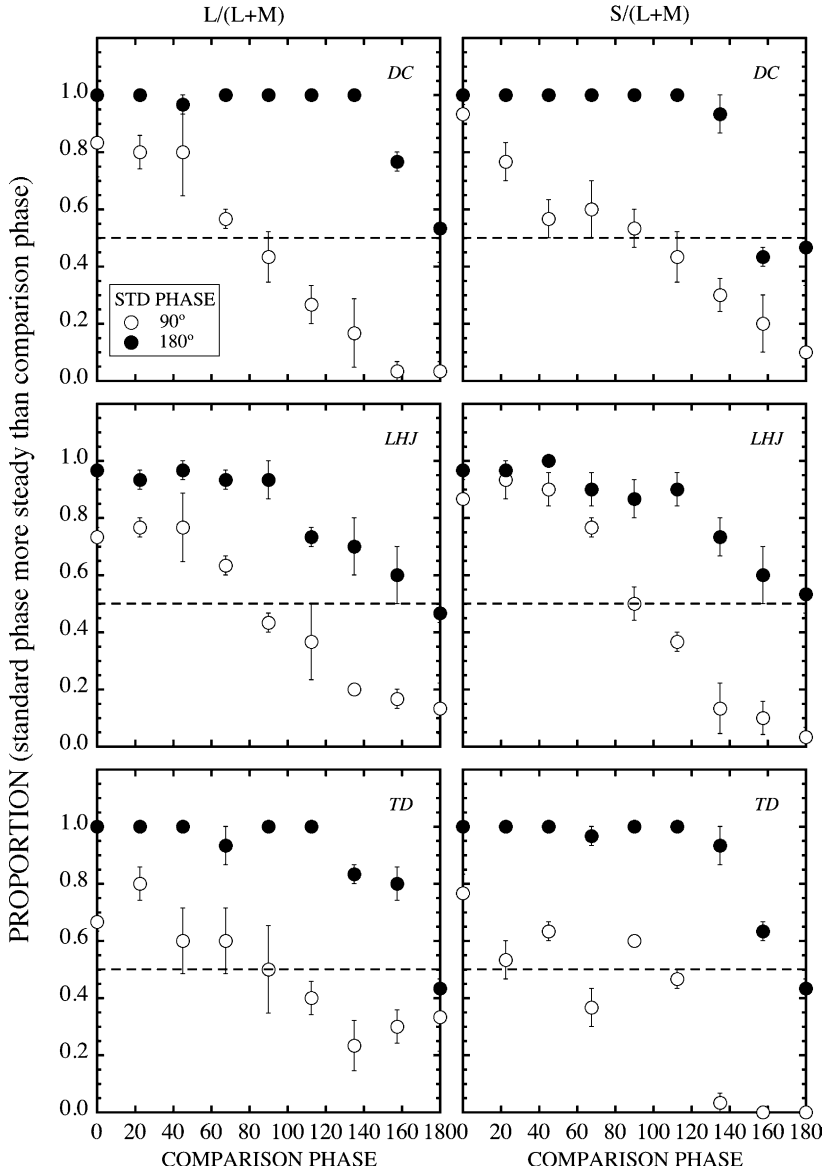

Fig. 3. The proportion of trials on which the standard phase of test-area nulling modulation gave a more steady percept than the comparison phase (horizontal axis). The standard phase was either 180° (solid symbols) or 90° (open symbols); phase was relative to the temporal modulation of the inducing light. The inducing modulation was along either the L/(L+M) or S/(L+M) chromatic direction (left or right column, respectively). Each row shows results for a different observer.

with temporal inducing light modulated along the L/(L+M) [S/(L+M)] chromatic direction. Each row shows measurements for a different observer. On almost *every trial*, the interval with 180° phase was preferred to any phase between 0° and 112.5° (proportions at or near 1.0). From 135° to 180°, the proportion fell toward 0.5, as expected, because the 180° measurement must be at chance (0.5) as both intervals of the pair comparison had the identical phase. The results in Fig. 3 indicate the inducing modulation caused chromatic assimilation.

In the paired comparisons for steadiness of the test field, described above, the amplitude of the added modulation at phases from 0° to 157.5° was fixed at the optimal amplitude for 180° phase. The observers might have preferred a different amplitude at phases other than 180°. One might consider a control that repeats the pair-comparison experiment but with the amplitude determined from nulling at 0° phase, which is the phase expected for a null of induced contrast rather than assimilation. If the induced modulation is assimilative, however, adding any modulation at 0° phase increases rather than reduces the perceived fluctuation in the test field because the induced and added modulations would be in-phase with each other. In this case, no amplitude could null the perceived test-field modulation but the most-steady percept would occur at zero amplitude of added modulation (that is, no added test modulation). Of course varying phase at zero amplitude has no effect. Pilot results at 0° phase confirmed that a non-zero added amplitude could not reduce the perceived modulation in the test.

An alternative control condition used the optimal amplitude of added modulation at 90° phase. Observers, on average, set the amplitude in the test area at 90° phase to 39% of the amplitude set at 180° phase. They could reduce but not completely null the perceived variation in the test area when phase was fixed at 90°. If the induced apparent modulation was in the direction of assimilation, phases greater than 90° should be judged as more steady than 90° phase because at phases greater than 90° the magnitude of the summed modulations in the test field would be reduced. A control condition, therefore, repeated the pair-comparison experiment with 90° phase at its optimal amplitude. The procedure was identical to that with 180° phase except that each of the 9 phases was paired with modulation at 90° phase at its optimal amplitude. The results are shown by open symbols in Fig. 3. From 0° to 90°, the proportion fell to 0.5, which is the chance proportion at 90° when both intervals were identical (both 90° phase). From 90° to 180°, the proportion continued to fall to values well below 0.5, often approaching proportion 0.0 at 180° phase (that is, 180° phase always preferred to 90° phase, even though the nulling amplitude was optimal for 90° phase). Again, these results confirmed that the temporal inducing modulation caused chromatic assimilation in the test area.

The phases in these experiments were varied from 0° to 180° with a step size of 22.5°. Note that these measurements could not detect a lag in a neural process of assimilation of less than 26 ms, which corresponds to 11° phase at 1.2 Hz.

3.2. Experiment 2: Temporal nulling of assimilation from 1.2 Hz inducing light

With assimilation confirmed (Experiment 1), the phase of the temporally varying light added in the test area was fixed at 180° with respect to the inducing-light modulation. The amplitude of the optimal nulling modulation was measured with the inducing light at 2.67 or 6.0 cd/m^2 (open and filled bars, Fig. 4). Recall that the luminance of the test area was 4.0 cd/m^2, so both inducing luminances had Michelson contrast 0.20. Each panel shows measurements for three observers. Results with the EEW test area [$-l$ test area] are in the left [right] column. The top [bottom] row has measurements with inducing modulation along the L/(L+M) [S/(L+M)] chromatic direction.

Two inducing luminances were tested in order to assess whether optical factors that blurred the retinal image could account for assimilation. A measured magnitude of assimilation that exceeded the effects of optical factors would imply that a neural process contributed to chromatic assimilation.

We used two separate approaches to assess the magnitude of assimilation attributable to the optics of the eye. First, the retinal image was calculated using the method of Marimont and Wandell (1994). Their model takes account of both wavelength-independent spread light and wavelength-dependent chromatic aberration. The model was used to predict the nulling amplitude by searching for the added amplitude in the test area that minimized temporal variation in a central 1-min region of each test "band". This took account of optical factors affecting both the inducing light and the added nulling modulation.[1] The thin [thick] dashed lines in

[1] The Marimont and Wandell (1994) model incorporates a wavelength-independent spread light function (Williams, Brainard, McMahon, & Navarro, 1994) with the wavelength-dependent optical transfer function of a model eye for a given pupil size. The pupil diameter was set to 3.6 mm, which is the pupil size at 4 cd/m^2 given by Degroot and Gebhard (1952). For each given combination of inducing and test area chromaticity and luminance, the spectral distributions at the peak and at the trough of the sinusoidally varied inducing modulation were calculated at every location of the physical stimulus, based on the spectral distribution of the R, G, and B guns for our calibrated video display. The modulation amplitude in the test area was varied to find the amplitude that minimized the difference between the peak and trough of inducing modulation within the central 1-min region of each "band" of the test (that is, between each pair of adjacent inducing rings). Temporal modulation in the test area was counter-phase to the inducing modulation. The spatial resolution used for calculations was approximately 0.2 min per pixel.

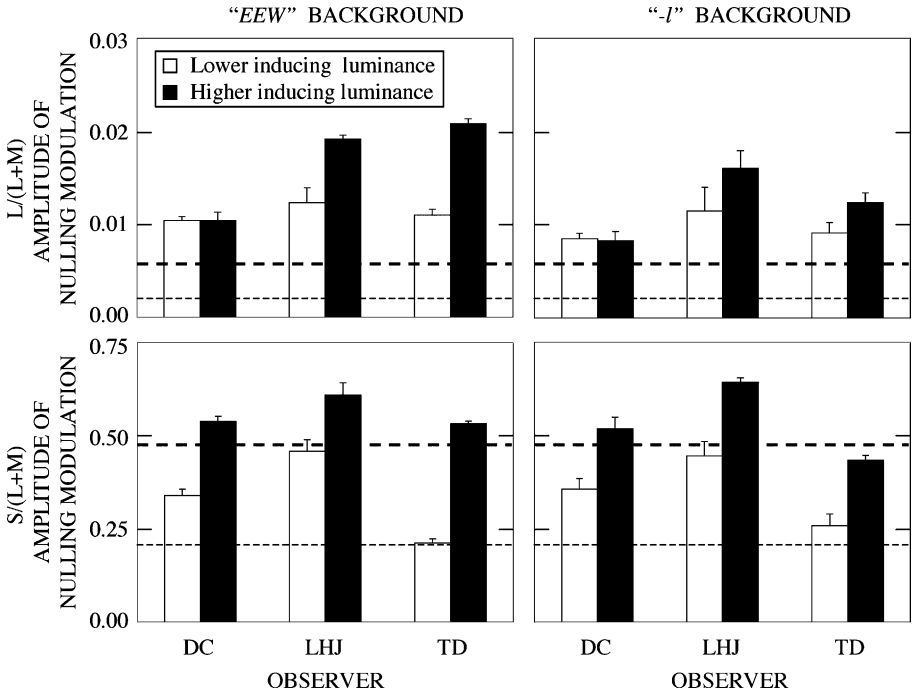

Fig. 4. The optimal amplitude of test-area modulation to null assimilation from the inducing light. The inducing modulation was along either the L/(L+M) or S/(L+M) chromatic direction (top or bottom row, respectively). Results are shown for two background chromaticities (left and right columns) and two luminances of inducing light (2.67 or 6.0 cd/m^2; open and filled bars, respectively). Each panel has results for three observers. Thin [thick] dashed lines show the predicted amplitude with 2.67 [6.0] cd/m^2 inducing luminance if assimilation were due to optical factors causing both wavelength-independent spread light and wavelength-dependent chromatic aberration (see text).

Fig. 4 show the predicted nulling amplitude for optical factors with inducing luminance 2.67 [6.0] cd/m^2. Assimilation induced by temporal modulation along the L/(L+M) chromatic direction always was nulled by a larger amplitude than predicted by optical factors (two top panels, Fig. 4). Assimilation in S/(L+M) always was nulled by an amplitude larger than the optical prediction for observers DC and LHJ though not for observer TD (bottom panels). In most cases, therefore, assimilation was stronger than specified by optical factors. This implies a neural process contributed to the perceived assimilation.

If assimilation were meditated by optical factors, the change in nulling amplitude with inducing-light luminance would be specified quantitatively from a principle of optics: the retinal distribution of a light affected by an optical factor scales linearly with the light's luminance. The nulling amplitudes implied by optics (dashed lines, Fig. 4) imply a specific ratio of nulling amplitudes for the two luminances of inducing light. The measured and predicted nulling-amplitude ratios are shown in Fig. 5 (bars and dashed lines, respectively). The top [bottom] panel shows results for inducing modulation in the L/(L+M) [S/(L+M)] direction. They show the measured ratio was smaller than implied by optics for all observers in every condition, except for observer TD in the single case of S/(L+M) inducing modulation with the EEW background.

A second approach was used to examine whether optical factors could account for chromatic assimilation, based on an extreme assumption: complete spatial averaging of all light in the stimulus. This assumed complete blurring of all light in the visual field, which of course did not occur but provided an extreme reference point for assessing the observed magnitude of assimilation. In the experiment, the inducing-light area covered 31% of the whole stimulus, so complete spatial summation implied nulling amplitudes in the L/(L+M) direction of 0.009 and 0.020 for the 2.67 and 6.0 cd/m^2 inducing lights, respectively; analogous nulling amplitudes in the S/(L+M) direction were 0.22 and 0.50 (Cao, 2003). The null hypothesis was that the measured nulling amplitude was less than or equal to the amplitude implied by complete spatial averaging. It was evaluated with a *t*-test at 0.05 probability of a Type I error (i.e., $p < 0.05$). There were 12 tests for each chromatic-inducing direction (2 background chromaticities × 2 inducing luminances × 3 observers). In the L/(L+M) direction, 2 of 12 tests rejected the null hypothesis; in the S/(L+M) direction, 8 of 12 tests rejected it. In all, therefore, 10 of 24 tests rejected even the extreme hypothesis of complete spatial blurring (the chance number of rejected tests was 5% of 24 tests, or 1–2 rejected tests). This is further evidence against a non-neural account of chromatic assimilation.

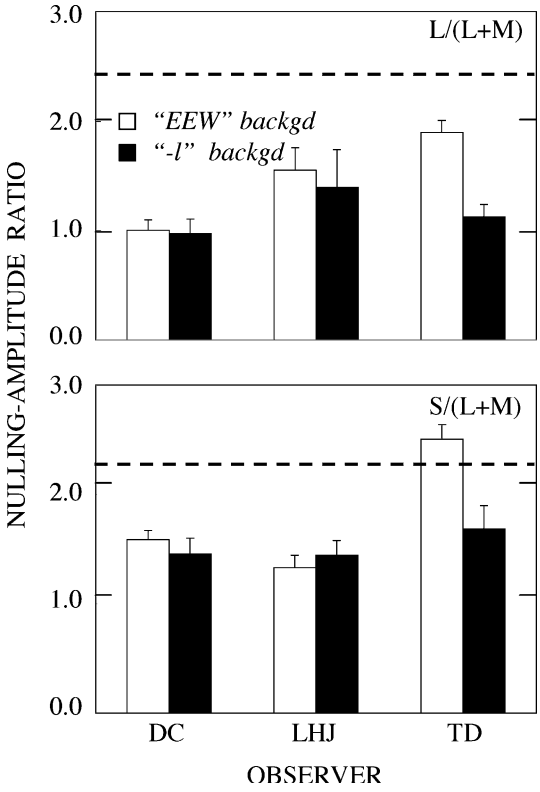

Fig. 5. The ratio of nulling amplitudes of test-area modulation (from Fig. 4) for the two inducing luminances (6.0 and 2.67 cd/m^2). The inducing modulation was along either the L/(L+M) or S/(L+M) chromatic direction (top or bottom panel, respectively). Within each panel, results are shown for two background chromaticities (open and filled bars) and three observers (horizontal axis). The dashed line shows the predicted ratio if assimilation were due to optical factors causing both wavelength-independent spread light and wavelength-dependent chromatic aberration (see text).

3.3. Experiment 3: Temporal frequency of inducing light

In previous experiments, the temporal frequency of inducing modulation was fixed at 1.2 Hz. This experiment tested whether pre-receptoral factors rather than a neural mechanism could account for chromatic assimilation at higher temporal frequencies (2.4 and 4.8 Hz). With a low spatial-frequency stimulus (1° wide test within a surround several degrees wide), temporally induced chromatic contrast falls rapidly above 3 Hz (De Valois et al., 1986). If the neural process of chromatic assimilation has a similar low-pass characteristic then non-neural optical factors alone may account for assimilation at these higher temporal frequencies.

The amplitude of the added modulation in the test area required to null assimilation from the inducing light is shown in Figs. 6 and 7, for inducing light varied in the L/(L+M) or S/(L+M) direction, respectively. The phase of the nulling modulation was 180°. Measurements shown in each panel are for inducing frequencies of 1.2, 2.4, and 4.8 Hz, for three observers. For inducing modulation in the L/(L+M) direction (Fig. 6), there was no significant effect of inducing-light temporal frequency. Only one of 12 separate ANOVAs (one for each inducing luminance, background chromaticity, and observer) reached statistical significance (6.0 cd/m^2 inducing field with the EEW background for observer TD). The *F*-statistic and statistical significance (probability of a Type I error) for each ANOVA are shown in the figure. The single significant result, which was near chance for 12 tests (5% of 12 tests is 0.60), reflected a small and non-systematic change of nulling modulation with temporal frequency. We conclude there is no statistically reliable change in L/(L+M) assimilation with temporal frequencies in the range 1.2–4.8 Hz.

A similar analysis for inducing modulation in the S/(L+M) direction revealed statistical significance for six of 12 tests, which was substantially above chance. With the lower inducing luminance (left column, Fig. 7), there was a clear trend toward greater, not less, assimilation at the highest temporal frequency of 4.8 Hz. Overall, the 4.8 Hz inducing frequency caused the greatest assimilation in nine of 12 cases ($p < 0.012$ by binomial test). Note, however, there was no indication that chromatic assimilation fell with temporal frequency, as found for chromatic contrast though at a lower spatial frequency than used here (cf. De Valois et al., 1986).

The dashed line in each panel of Figs. 6 and 7 shows the predicted assimilation from optical factors alone (cf. Fig. 4). The measured assimilation in the L/(L+M) chromatic direction (Fig. 6) was always larger than expected from optics (all 24 new cases: 2 higher temporal frequencies, 3 subjects, 2 inducing luminances, 2 background chromaticities). Induced assimilation in S/(L+M) always exceeded the optical prediction for observers DC and LHJ and for observer TD at the lower inducing luminance (but not the higher inducing luminance). Overall, assimilation with these higher temporal frequencies of inducing light could not be accounted for by optical factors, as was found also with the 1.2 Hz inducer in the previous experiment.

3.4. Experiment 4: Simultaneous inducing modulation in the L/(L+M) and S/(L+M) chromatic directions

Results from previous experiments showed that a neural process contributed to chromatic assimilation. This experiment investigated whether assimilation could be explained by independent neural responses in the L/(L+M) and S/(L+M) pathways. First, consider assimilation from chromatic inducing light varied in time along only (i) the L/(L+M) chromatic direction or (ii) the S/(L+M) direction. Such assimilation can be nulled by counter-phase test-area modulation in only L/(L+M) or S/(L+M), respectively. Next, consider the test-area nulling modulation required with an inducing light varied simultaneously in the L/(L+M) and S/(L+M) directions. If assimilation is mediated by

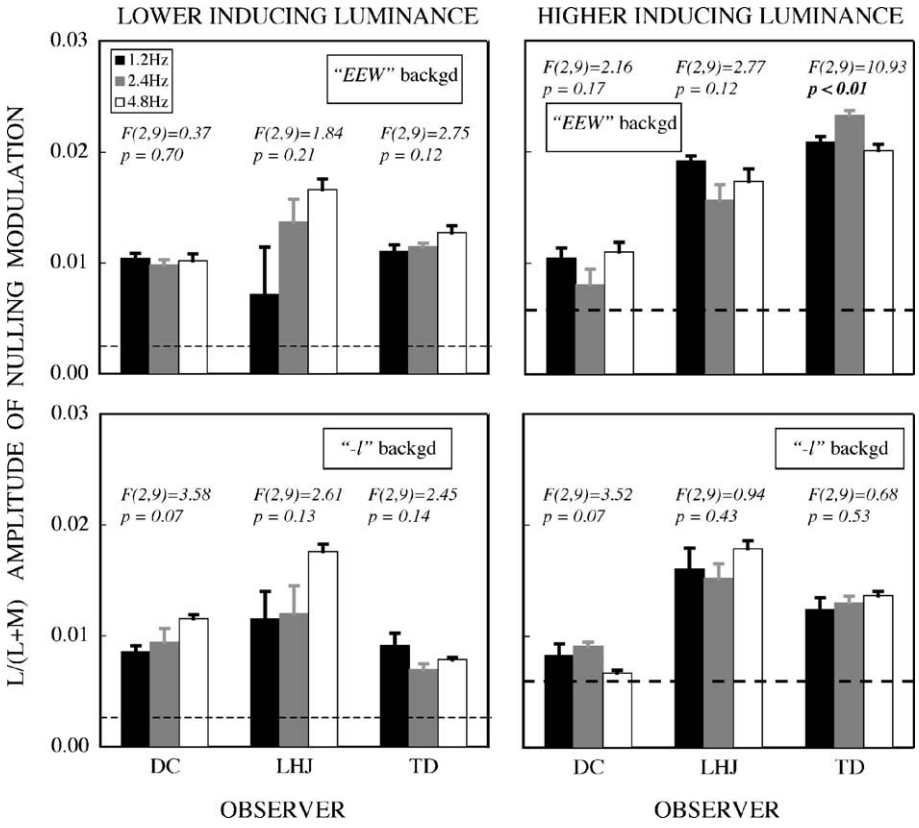

Fig. 6. The optimal amplitude of test-area modulation to null assimilation from inducing light at three temporal frequencies (1.2, 2.4, or 4.8 Hz; black, grey, or white bars). Inducing modulation was along the L/(L+M) chromatic direction. Results are shown for two background chromaticities (top and bottom rows), two luminances of inducing light (2.67 or 6.0 cd/m^2; left and right columns, respectively) and three observers (horizontal axis). *F* values and probabilities (*p*) test the null hypothesis of no difference due to temporal frequency, separately for each observer, inducing luminance and background chromaticity. Thin and thick dashed lines as in Fig. 4.

optics and/or independent neural processes of the L/(L+M) and S/(L+M) pathways, then simultaneous inducing modulation in the L/(L+M) and S/(L+M) directions should be nulled by the same amplitude of L/(L+M) [S/(L+M)] test-area modulation found with L/(L+M) [S/(L+M)] inducing modulation alone.

Nulling amplitudes with 1.2 Hz inducing modulation along only the L/(L+M) or S/(L+M) chromatic direction, and with the EEW background, are shown by open symbols along the axes in Fig. 8 (squares and circles, respectively, replotted from Fig 4; each panel is for a different observer). The smaller (larger) symbol size indicates measurements with the lower (2.67 cd/m^2) [higher (6.0 cd/m^2)] inducing luminance. If optics and /or independent L/(L+M) and S/(L+M) pathways mediated assimilation, then simultaneous inducing modulation along both directions should be nulled by the same test-area amplitudes shown by the open symbols (that is, at the intersection of the dashed lines in Fig. 8). The measured nulling modulation with simultaneous inducing modulation in L/(L+M) and S/(L+M) is indicated by the solid triangles. While some measurements were close to the independence prediction (e.g., lower luminance inducer for observer DC), there were clear deviations from independence in many conditions. Specifically, simultaneous inducing modulation in S/(L+M) and L/(L+M) often affected the nulling amplitude of S/(L+M), compared to the same level of S/(L+M) inducing modulation alone.

The interaction between the L/(L+M) and S/(L+M) pathways was assessed quantitatively with two-sample, unequal-variance *t*-tests (Rice, 1995), separately for each chromatic direction, inducing luminance and observer (12 tests in all). Recall that there were four replications of each measurement on separate days. The L/(L+M) nulling amplitude was compared with or without simultaneous S/(L+M) inducing modulation. None of six *t*-tests (two inducing luminances × three observers) reached statistical significance ($p > 0.13$ or higher). There was no evidence, therefore, that the L/(L+M) nulling amplitude was affected by simultaneous S/(L+M) inducing modulation. The S/(L+M) nulling amplitude, however, showed a different characteristic. Three of six *t*-tests reached statistical significance ($p < 0.03$ or smaller) and a fourth test was marginal ($p < 0.07$), which indicated the amplitude of S/(L+M) nulling modulation was affected by simultaneous L/(L+M) inducing light. Overall, therefore, the

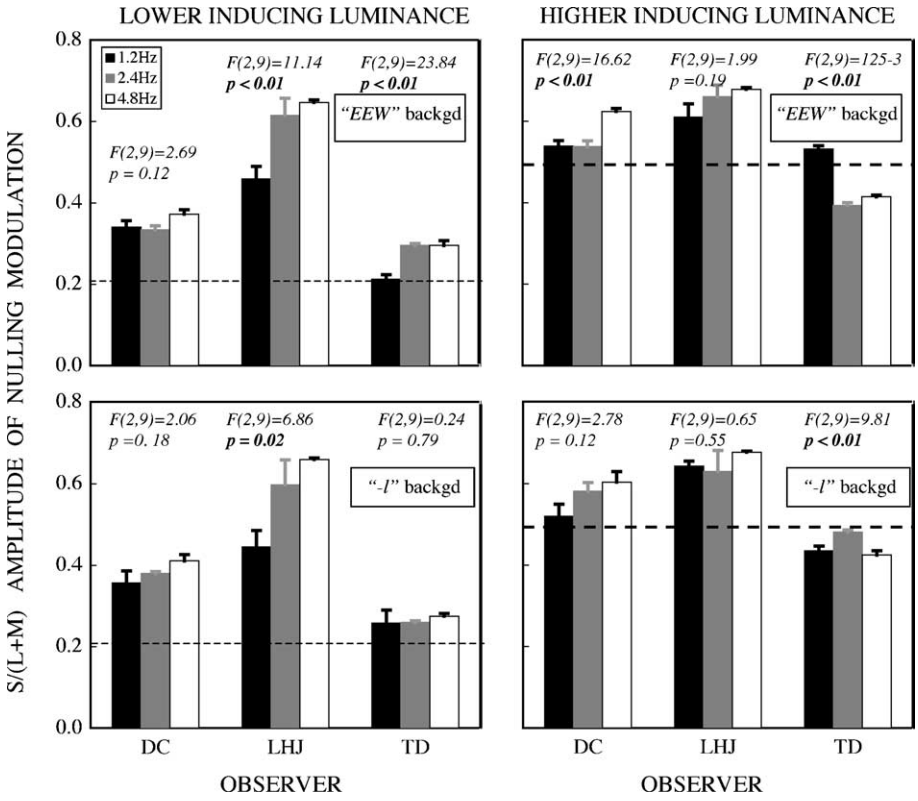

Fig. 7. As Fig. 6 but for inducing modulation along the S/(L+M) chromatic direction.

measurements revealed a violation of independence characterized by an asymmetry: L/(L+M) inducing modulation affected the nulling amplitude of S/(L+M) but S/(L+M) inducing modulation did not significantly alter the nulling amplitude of L/(L+M).

4. Discussion

A fundamental question is whether chromatic assimilation – the shift in color appearance toward nearby light – results from physical or neural processes. While the imperfect optics of the eye can cause assimilation at high spatial frequencies, the experiments here at 5 cpd demonstrated that a neural mechanism contributed to chromatic assimilation. The neural process was revealed by three independent pieces of evidence, using a temporal-nulling procedure that did not require an observer to judge the color change caused by assimilation. First, with inducing light at a lower luminance than the test area, the magnitude of assimilation was far larger than predicted by spread light and chromatic aberration (Fig. 4). Second, raising the inducing luminance 2.25-fold increased assimilation much less than predicted by optics (Fig. 5). Third, with a fixed amplitude of inducing modulation in S/(L+M), the magnitude of induced chromatic assimilation in S/(L+M) changed with the inducing amplitude in the L/(L+M) direction (Fig. 8). None of these findings can be explained by optical factors that image light on the retina.

The results also imply assimilation is not explained by neural responses within independent L/(L+M) and S/(L+M) pathways. This lack of independence is consistent with neural processes of chromatic adaptation that mediate detection and discrimination (Krauskopf, Williams, Mandler, & Brown, 1986), perceived chromatic contrast (Singer & D'Zmura, 1994) and suprathreshold color appearance (Webster & Mollon, 1994). While adaptation is chromatically selective, causing the strongest effect in the chromatic-adaptation direction, adaptation often is not nil in orthogonal directions. Further, the selectivity can be asymmetric. Consider, for example, perceived contrast (Singer & D'Zmura, 1994). Achromatic adaptation affects sensitivity in the achromatic direction and both chromatic directions; however, purely chromatic adaptation does not affect achromatic sensitivity. Further, adaptation along the L/M chromatic direction causes strongest adaptation in the same direction and substantial though weaker adaptation in the S direction; similarly, S adaptation has its strongest influence on S and a weaker influence on L/M. In sum, an interaction between the two chromatic directions, as found here for chromatic assimilation, is common for other aspects of color perception.

The results here using temporal nulling corroborated the conclusion from an earlier study in which chromatic

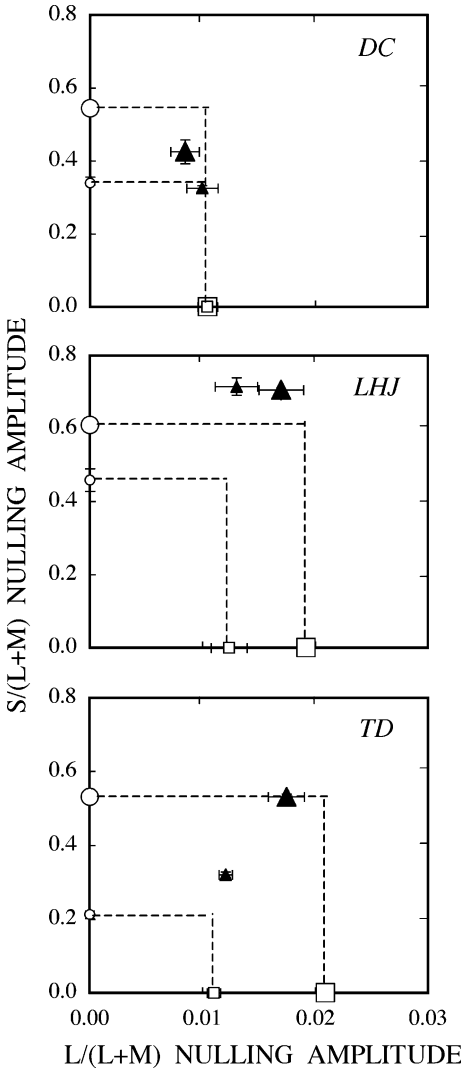

Fig. 8. The optimal amplitude of test-area modulation (EEW background) to null assimilation from 1.2 Hz inducing light, modulated along (i) only the L/(L+M) chromatic direction (squares on horizontal axis), (ii) only the S/(L+M) chromatic direction (circles on vertical axis), or (iii) both the L/(L+M) and S/(L+M) chromatic directions simultaneously (solid triangles). Measurements are shown for 2.67 and 6.0 cd/m^2 inducing light (smaller and larger symbols, respectively). Each panel shows results for a different observer. If optics and/or independent L/(L+M) and S/(L+M) neural pathways mediate assimilation, the nulling amplitudes for simultaneous L/(L+M)-and-S/(L+M) inducing modulation (triangles) should be at the intersection of the dashed lines (see text)

assimilation was measured with asymmetric color matching (Cao & Shevell, 2005). In that study, assimilation was evaluated under an extensive set of conditions: eight inducing chromaticities, two inducing luminances, and 11 inducing-ring width-and-separation combinations covering spatial frequencies from 3 to 20 cpd. Those measurements revealed a neural contribution to chromatic assimilation as well. There is an important difference, however, between the assimilation from a steady inducing light (Cao & Shevell, 2005) and a temporally varying inducing light (this study). Steadily presented inducing rings at the width and separation used here (4 and 8 min, respectively) and luminance 6.0 cd/m^2 caused contrast in L/(L+M), not assimilation, while the temporally varying inducing rings of the same size and luminance caused assimilation. Steady presentation, therefore, can attenuate chromatic assimilation, which is further evidence that a neural process contributes to assimilation.

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