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Chromatic induction in space and time

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Abstract

The color appearance of a light depends on variation in the complete visual field over both space and time. In the spatial domain, a chromatic stimulus within a patterned chromatic surround can appear a different hue than the same stimulus within a uniform surround. In the temporal domain, a stimulus presented as an element of a continuously changing chromaticity can appear a different color compared to the identical stimulus, presented simultaneously but viewed alone. This is the flash-lag effect for color, which has an analog in the domain of motion: a pulsed object seen alone can appear to lag behind an identical pulsed object that is an element of a motion sequence. Studies of the flash-lag effect for motion have considered whether it is mediated by a neural representation for the moving physical stimulus or, alternatively, for the perceived motion. The current study addresses this question for the flash-lag effect for color by testing whether the color flash lag depends on a representation of only the changing chromatic stimulus or, alternatively, its color percept, which can be altered by chromatic induction. Methods: baseline measurements for spatial chromatic induction determined the chromaticity of a flashed ring within a uniform surround that matched a flashed ring within a patterned surround. Baseline measurements for the color flash-lag effect determined the chromaticity of a pulsed ring presented alone (within a uniform surround) that matched a pulsed ring presented in a sequence of changing chromaticity over time (also within a uniform surround). Finally, the main experiments combined chromatic induction from a patterned surround and the flash-lag effect, in three conditions: (1) both the changing and pulsed rings were within a patterned chromatic surround; (2) the changing ring was within a patterned surround and the pulsed ring within a uniform surround; and (3) the changing ring was within a uniform surround and the pulsed ring within a patterned surround. Results: the flash-lag measurements for a changing chromaticity were affected by perceptual changes induced by the surrounding chromatic pattern. Thus, the color shifts induced by a chromatic surround are incorporated in the neural representation mediating the flash-lag effect for color.

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1. INTRODUCTION

Chromatic induction is the altered color appearance of a stimulus caused by light in surrounding spatial regions [1–3]. A surrounding chromaticity may cause the color of a fixed light to appear more similar to its surround (assimilation) or more different from it (contrast). Low spatial frequencies in both the inducing region and test region tend to give contrast, while high spatial frequencies are associated with assimilation [4–6].

Concentric rings of various chromaticities that surround a test ring may synergistically produce assimilation and contrast in the test area, resulting in a stronger induced color shift than caused by a uniform surround. With a uniform unpatterned surround, contributions from contrast and assimilation may be antagonistic so tend to cancel each other [7,8]. With a patterned surround, however, concentric rings contiguous with the test ring can cause assimilation, while non-contiguous rings cause contrast. If these rings have appropriately chosen sizes and chromaticities, then both assimilation and contrast can influence the color of the test ring in the same direction, resulting in unusually large induced color shifts.

Neither optical factors (spread light, chromatic aberration) nor retinal receptive fields fully explain the hue shifts from patterned chromatic surrounds [7,8]. Instead, the shifts can be accounted for by S-cone center-surround antagonism, as found in the visual cortex [9]. A patterned surround composed of concentric rings can differentially stimulate central and surrounding regions of a receptive field [10]. The current study uses chromaticities in the surround that vary in only S-cone excitation to take advantage of the large hue shifts induced by surrounding S-cone patterns [7,8].

Chromatic induction occurs over time as well as space, including a substantial flash-lag effect for color. The flash-lag phenomenon is best known for motion: a brief isolated pulse of light is perceived to be in a different location compared to an identical pulse presented as part of a moving stimulus sequence [11]. Specifically, the perceived location of the briefly pulsed stimulus appears to lag behind the position of an identical pulse presented as a frame of a moving object (thus the “flash-lag” moniker), even though both pulses are presented simultaneously in physically identical positions (see [12] for a review of the flash-lag effect).

The flash-lag effect has been studied also in the presence of illusory motion [13]. The intersection of moving vertical and horizontal lines appears to rotate opposite to its physical direction of rotation (chopstick illusion; [14]). This perceived motion may be derived from neural signals representing the ends of the lines. The flash-lag effect with illusory motion, however, is in the direction of the physical, not the perceived (illusory), movement [13]. This implies the flash-lag percept follows from a neural process before the representation of perceived motion.

Other studies, however, show that the flash-lag effect can depend on higher-level motion cues, for example the ability to detect the direction of motion of occluded objects [15]. Also, motion percepts defined by binocular disparity show a flash-lag effect [16,17] so the flash lag can be mediated by cortical responses that combine signals from both eyes. Yet, induced changes in perceived orientation, such as the tilt illusion [18] or the tilt aftereffect [19], are negligibly affected by the flash-lag effect. Thus, the neural representation for perceived

orientation that results in the tilt illusion and tilt aftereffect is not the same as the neural representation for flash lag [18,19].

Experiments here address the neural representation for the color flash-lag effect. Color is used as a model system because of its large flash-lag duration compared to other domains. A number of different continuously changing stimulus features, such as chromaticity, luminance, spatial frequency, and pattern entropy, reveal a perceived lead in feature space compared to an identical but isolated briefly pulsed stimulus [20]. Importantly, the magnitude of the temporal lag is not the same for all features, being longest for color compared to other features (over 250 ms compared to 80 ms or less) [20,21]. The flash lag for color, therefore, provides a large time span to test for variation in the flash-lag duration as experimental conditions are varied to test specific hypotheses. The current study, therefore, tests whether the flash-lag effect for a continuously changing chromaticity is affected by a fixed chromatic-patterned surround, which is well known to shift the color appearance of a fixed surrounded light. If the flash-lag percept depends on only the chromaticities of the continuously changing stimulus itself, not the color induced by its surround, then no difference is expected in the flash-lag effect for a changing chromaticity within a patterned versus a uniform unpatterned surround. This is the predicted outcome if the color flash lag, like the motion flash lag [13], depends on a neural representation of the changing stimulus, not its percept. On the other hand, if a chromatic-patterned surround alters the flash-lag effect for color, then the flash-lag percept includes the induced color shift caused by a surround.

2. METHODS

A. Observers

Three observers participated in the study, including one of the authors (AC) and two naïve observers. All observers had normal color vision as assessed by a Neitz anomaloscope. Each observer gave informed consent to participate in the study as required by the University of Chicago Institutional Review Board.

B. Apparatus

Stimuli were presented on a cathode ray tube (CRT) monitor (NEC AccuSync 120) driven by an Apple iMac computer. The monitor was set for a refresh rate of 75 Hz non-interlaced and pixel resolution of 1280×1024 . The spectral output of each of the red, green, and blue phosphors was measured using a spectroradiometer (PhotoResearch PR 650), and the light level at each digital value of the phosphors was determined with a radiometer (International Light 1700). Observers used a game pad to indicate their responses. A chin rest was located 55 cm from the monitor.

C. Stimuli

Stimuli consisted of two circular fields, each with a test ring that could be surrounded by concentric rings (a chromatic patterned surround) or a uniform field [unpatterned surround; Fig. 1A]. The two fields were presented simultaneously to the left and right of a central fixation cross (Figs. 1B–1F). Each field had an inner dark diameter of 1 deg and an outer

diameter of 4 deg. Each ring thickness was 10 arcmin (spatial frequency 3 cpd). The center-to-center distance between the two circular fields was 7.6 deg.

Chromaticities were defined in a space representing relative excitation of the long (L), middle (M), and short (S) wavelength cones [22] using the Smith and Pokorny (1975) cone fundamentals [23]. The unit of the S axis in this space was normalized to $S/(L + M) = 1.00$ for equal-energy-spectrum (EES) “white”. The chromaticity of the unpatterned surround was EES ($L/(L + M) = 0.665$, $S/(L + M) = 1.0$) with a luminance of 5 cd/m². Each patterned surround had rings of two different chromaticities that differed along only the S-cone axis: the +S chromaticity was defined as $[L/(L + M), S/(L + M)] = [0.665, 1.70]$ and –S as $[0.665, 0.30]$. Both had a luminance of 5 cd/m². The background was black (metameric to EES “white”, <0.10 cd/m²), and the fixation cross was metameric to EES at 25 cd/m².

1. Quantification of Spatial Chromatic Induction from Patterned Surrounds (without Flash-Lag Effect)—

To measure the magnitude of chromatic induction without the flash-lag effect, the test ring within the chromatic patterned surround and the test ring within the unpatterned surround were both briefly pulsed (80 ms) to the left and right of the fixation cross (Fig. 1B). Three different conditions were tested: induction with –S contiguous contours (top left, Fig. 1A), induction with +S contiguous contours (top right, Fig. 1A), and an isomeric match with an unpatterned surround (bottom, Fig. 1A). Test rings within patterned surrounds were at a constant chromaticity $[L/(L + M), S/(L + M)] = [0.70, 1.0]$ at luminance 7 cd/m², and were compared to a ring in an unpatterned surround with $L/(L + M)$ fixed at 0.70, luminance at 7 cd/m², and an initial level of $S/(L + M)$ randomly selected from the range 0.73–1.25. The observer had three response alternatives: the test ring on the right appeared more orangish, less orangish (more pinkish/purplish), or a match to the ring on the left. After each response, the $S/(L + M)$ value of the pulsed test ring was shifted by 0.067 to converge on a match. The matching $S/(L + M)$ value was taken as the measurement.

2. Quantification of Flash-Lag Effect—

Experiments to measure the flash-lag effect compared a test ring that continuously changed in chromaticity over time to one that was briefly pulsed (Figs. 1C–1F). The changing stimulus varied in chromaticity over a temporal interval of 1.44 s; midway through this presentation, the pulsed stimulus was presented for 80 ms on the other side of the fixation cross (see Figs. 1C–1F). The chromaticity of the changing test ring varied along only the $S/(L + M)$ axis. The changing chromaticity could start at $[L/(L + M), S/(L + M)] = [0.70, 1.56]$ and go to $[0.70, 0.42]$ (referred to as “+S to –S”), or from $[0.70, 0.49]$ to $[0.70, 1.63]$ (“–S to +S”). In either case, the changing chromaticity was always $[0.70, 1.02]$ at the moment of the pulse. The luminance of both rings was fixed at 7cd/m². The chromaticity changed in $S/(L + M)$ in steps of 0.067 every 80 ms.

There were four different conditions (Figs. 1C–1F): (1) both the changing and pulsed stimuli had unpatterned surrounds (“Both Stimuli Not Patterned”), (2) the pulsed stimulus had a patterned surround and the changing stimulus an unpatterned surround (“Pulsed Stimulus Patterned”), (3) the changing stimulus had a patterned surround and the pulsed stimulus an unpatterned surround (“Changing Stimulus Patterned”), or (4) both the changing and pulsed

stimuli had patterned surrounds (“Both Stimuli Patterned”). If the pulsed stimulus had a patterned surround, both its test ring and patterned surround were pulsed in place of an unpatterned disc (Figs. 1D and 1F).

All of these conditions were tested with the chromaticity changing from +S to −S (appearing pink to orange) or, in separate runs, from −S to +S (orange to pink). All patterned-surround conditions were tested with rings having +S contiguous contours (purple-appearing rings bordering the test ring) or −S contiguous contours (lime-appearing rings bordering test ring), which shifted the test ring appearance to more pinkish or orangish, respectively (Fig. 1A). When both the changing and pulsed rings had patterned surrounds (Fig. 1F), they had the same surrounding pattern on any given trial.

D. Procedure

Observers participated in the study on four separate days. Experiments were conducted in a dark room and typically took about 90 min each day. After pressing a button to initiate a trial, observers viewed a pair of test rings and then reported via a button press whether the ring on the right appeared more orangish, less orangish (more pinkish/purplish), or the two rings matched. Based on the subject’s response, the pulsed ring would change in chromaticity on the next trial along the S/(L + M) axis (step size 0.067) until a match was reported. All conditions were tested each day in a new randomized order.

On each day an observer completed four repetitions for every part of the study. In total there were 17 conditions: three chromatic induction matches without the flash-lag effect (+S contiguous contours, −S contiguous contours, isomeric match); two flash-lag conditions without spatial chromatic induction (“+S to −S”, and “−S to +S”); four flash-lag conditions with a patterned surround for only the pulsed test ring; four flash-lag conditions with a pattern surround for only the changing ring; and four flash-lag conditions with a patterned surround for both rings. The four flash-lag conditions crossed and counterbalanced (i) +S or −S contiguous contours with (ii) the chromaticity changing from either “+S to −S” or “−S to +S.”

3. RESULTS

A. Chromatic Induction without Flash-Lag Effect

Measurements were analyzed separately for each observer using the matches for each condition averaged across the four days. Figure 2 shows the results with both of the test rings briefly pulsed. This indicates the magnitude of chromatic induction from the patterned surrounds without any flash-lag effect. The horizontal black line shows the S/(L + M) value of the fixed test ring. As expected, isomeric matches are very close to this stimulus chromaticity for all three observers (circles, Fig. 2). If the contiguous contour of a patterned surround had the −S chromaticity (appearing “lime”), the matching ring in the unpatterned surround was shifted in chromaticity in the −S/(L + M) direction (minus symbols, Fig. 2). On the other hand, if the contiguous contour of a patterned surround had the +S chromaticity (appearing “purple”), the matching ring was shifted in the +S/(L + M) direction (plus symbols, Fig. 2). All three observers showed a significant shift in color appearance due to

induction from the patterned surrounds ($F(2, 9) = 256, 77$ and 65 for EL, AC, and LW, respectively; $p < 0.001$ for each observer). These results replicate previous findings [7,8].

B. Chromatic Flash-Lag Effect without Spatial Chromatic Induction

Measurements of the flash-lag effect with both rings within unpatterned surrounds (Fig. 1C) serve as a benchmark to compare later the flash-lag effect in conditions with patterned surrounds. The chromaticity of the pulsed ring required to match the continuously changing ring was shifted in the direction of the forward trajectory of the changing chromaticity for all observers (Fig. 3). Every observer showed a significant difference between changing the chromaticity from “+S to -S” compared to from “-S to +S” [$F(1, 6) = 144, 40$ and 23 for EL, AC, and LW, respectively; $p < 0.01$ for each observer]. This corroborates previous studies [20,21].

In the flash-lag experiments with a continuously changing ring, the results can be expressed as either shifts in chromaticity or “lag” times. The conversion from chromaticity to time (in milliseconds) requires multiplying the chromaticity shift by the factor $80/0.067$ because the chromaticity changed every 80 ms by 0.067 units along the S/(L + M) axis. The right ordinate in Figs. 3 and 4 is labeled in units of milliseconds of lag time.

C. Main Experiments: Predictions for Flash-Lag Effect with Patterned Surrounds

If a pattern surrounding the pulsed stimulus influences the flash-lag match, observers' matches will implicitly take account of the induction when setting a match. Similarly, if a patterned surround affects the color appearance of the changing chromaticity, then observers' match settings of the pulsed ring's chromaticity will reflect it. If patterned surrounds equally affect the changing and pulsed test rings, the net effect of patterned surrounds in the “Both Stimuli Patterned” condition should be zero, so these matches would be the same as in the “Both Stimuli Not Patterned” condition. On the other hand, if a patterned surround has no effect on the appearance of a changing chromaticity, then there should be no difference in the results for a changing chromaticity within a +S contiguous-contour patterned surround compared to a -S contiguous-contour patterned surround. These questions are taken up below.

D. Main Experiments: Flash-Lag Effect with Patterned Surrounds

The influences of patterned surrounds on the flash-lag effect are shown in Fig. 4. The horizontal dashed line represents the S/(L + M) value of the changing ring at the moment of the pulsed-ring presentation, and the horizontal solid black lines replot the flash-lag shifts with “Both Stimuli Not Patterned” (from Fig. 3). Plus and minus symbols in plots refer to +S and -S contiguous contours of the patterned surround, respectively.

For the “Pulsed Stimulus Patterned” condition (top row, Fig. 4), there is a large difference in the matching chromaticity, depending on whether the inducing pattern has +S or -S contiguous contours, for every observer. In this condition, +S contiguous contours required observers to reduce the S/(L + M) chromaticity for a match, while -S contiguous contours required the match chromaticities to increase in +S/(L + M). This is seen in the top row of Fig. 4 by the minus symbols consistently above the corresponding black line and the plus

symbols below it. The results for the “Pulsed Stimulus Patterned” condition, to a first-order approximation, are close to the sum of the baseline chromatic induction without the flash lag (Fig. 2) and the “Both Stimuli Not Patterned” (Fig. 3) baseline flash-lag effect (asterisks in top row of Fig. 4).

For the “Changing Stimulus Patterned” condition (middle row, Fig. 4) the shifts in the matches were in the opposite direction, as expected if the patterned surround shifted the changing ring’s appearance as it did the pulsed ring’s appearance in the top row (that is, plus symbols now above minus symbols, with the horizontal black lines between them). For +S contiguous contours, the matches were shifted in the +S/(L + M) direction, and for –S contiguous contours the matches were shifted in the –S/(L + M) direction. Thus, observers changed the chromaticity of the unpatterned pulsed ring in the direction of the hue shift induced into the changing test ring’s chromaticity. This shows that the perceived color of the changing test ring, and thus the flash-lag effect, is influenced by induced color shifts caused by the patterned surrounds. Further, this condition reveals consistent deviations between the measurements and the sum of the effects of a patterned surround alone from Fig. 2 (now surrounding the changing ring) and the baseline flash-lag effect alone from Fig. 3 (compare asterisks indicating the sum to plus and minus symbols representing measurements, middle row of Fig. 4). Each asterisk is farther from the corresponding black line than the measurement it predicts. Overall, the summing model (asterisks) gives larger values for the influence of the patterned surround than shown by any of the 12 measurements in the middle row of Fig. 4 (compare the distance to solid black line for asterisks versus plus and minus symbols; $p < 0.001$ by a two-tailed sign test).

In the “Both Stimuli Patterned” condition, with patterns surrounding both the pulsed and changing test rings, the differences between the +S and –S conditions are smaller than in the other conditions (bottom row, Fig. 4; plus and minus symbols closer to each other than in the other rows of Fig. 4). The summing model predicts no effect from the contiguous contours’ chromaticity (+S versus –S) because the patterned surround is identical for the changing and pulsed test rings; thus, two asterisks are shown side by side at the same value on each black line. While it is not surprising that the difference for every corresponding pair of +S and –S measurements is smaller in this condition (bottom row in Fig. 4) than in the other two conditions (top and middle rows in Fig. 4; $p < 0.005$ by a two-tailed binomial test), an important question is whether these differences in the “Both Stimuli Patterned” condition (bottom row) are non-zero. If so, the summing model (asterisks) would be invalidated because these results would show that the –S versus +S contiguous chromaticity alters the color shift. Note that all six comparisons between the –S versus +S conditions show a larger measurement for –S (all minus symbols above corresponding plus symbol in bottom row of Fig. 4; $p < 0.05$ by a two-tailed sign test), indicating the chromatic composition of a patterned surround affects the flash-lag measurements even when the identical pattern surrounds both of the test rings.

4. DISCUSSION

A. Influence of Patterned Surrounds on Pulsed and Changing Rings

The neural representation mediating the flash-lag effect for color depends on more than the changing stimulus chromaticity. It also incorporates induced perceptual hue shifts caused by a patterned chromatic surround. The clearest demonstration is the difference in the color of the changing ring depending on whether a patterned surround has contiguous contours with +S versus -S chromaticity (middle row, Fig. 4). If the flash-lag color depends on only the changing stimulus, not induced color shifts from a fixed surround, then a surrounding pattern would not alter the measurements. This is contrary to the results from every observer, thus demonstrating that flash-lag colors depend on color shifts induced from a surrounding region.

Corroborating evidence for this conclusion comes from a separate experimental condition with a patterned chromatic surround presented with both the changing ring, which is subject to a flash-lag hue shift, and a briefly pulsed comparison ring, which is not ("Both Stimuli Patterned" condition, bottom row of Fig. 4). Here the identical surround is presented with both the changing ring and the pulsed ring so any induced hue shift determined by the surround alone would be identical for both rings, thus nulling in the measurements any influence of adding the patterned surround. This predicts, therefore, that introducing identical patterned surrounds for both rings, regardless of whether the contiguous contours of the surround have chromaticity +S or -S, should not change the measurements. This too is rejected by the measurements. A patterned surround not only shifted hue percepts in this condition, but +S and -S contiguous contours shifted the hue in opposite directions (bottom row, Fig. 4). The influence of induced color shifts from a surround, therefore, cannot be attributed to a shift defined by only the surround itself. Note that this implicitly eliminates as an explanation optical spread light from the surround into the retinal area of the test rings at the moment the pulsed ring is presented because spread light from the identical patterned surrounds is equal for both test rings.

These points are readily seen by plotting the difference between the measurements with -S versus +S contiguous contours, while all other stimulus features are equal (Fig. 5). If there were no effect of the patterned surrounds, all of these plotted values would be at zero within measurement error. This was tested for each condition (horizontal axis) and each observer (in separate panels), averaging over the "+S to -S" and "-S to +S" runs and over the four days of replication. All three observers showed a significant difference from zero for the "Changing Stimulus Patterned" condition ($t(7) = -6.97, -10.4, \text{ and } -12.9$ for observers AC, EL, and LW, respectively; $p < 0.001$ for each observer, two-tailed). For the "Both Stimuli Patterned" condition, two of the three observers showed a significant difference from zero ($t(7) = 2.64$ and 4.37 for AC and LW; $p < 0.05$ and $p < 0.01$, respectively, two-tailed) while the difference for observer EL was in the same direction but marginal ($t(7) = 2.00, p < 0.09$, two-tailed).

Figure 5 shows also that a patterned surround induced a larger hue shift when presented with only the pulsed ring than with only the changing ring (leftmost bar larger in absolute value than the center bar, for every observer; $t(14) = 3.86, 3.94, \text{ and } 5.06$ for observers AC, EL,

and LW, respectively, so $p < 0.002$ for each observer, two-tailed). This is in accord with the Both (rightmost) bar in each panel of Fig. 5, the value of which is positive and so consistent with combining a larger induced hue shift from the pattern surrounding the pulsed ring than the changing ring.

In sum, the chromaticity of the flash-lag match is influenced by patterns surrounding both the pulsed and changing stimuli. The results of the experiments here differ from the flash lag with illusory motion, which is not susceptible to the perceived motion of the chopsticks illusion [13]. Also, studies of the tilt illusion and tilt aftereffect [18,19] report these illusions are independent of the flash-lag effect, while the current study shows that flash lag matches for color depend on induced hue shifts from a patterned surround, even when both the pulsed and the changing test ring are within an identical pattern. A speculative account for this difference between tilt/motion illusions and induced color may be processing at different stages of the visual hierarchy. This would be consistent with the percept of a rotating bar that changes chromaticity as it rotates: bar color and bar orientation retain their different flash-lag latencies, even when both features belong to the same object [21]. Another possible factor may be that the longer latency of the color flash lag allows extra time for context to contribute to the flash-lag color percept, compared to luminance-driven tilt/motion flash lags that have substantially shorter latencies.

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Fig. 1.

Experimental stimuli (schematic drawings, not precisely to scale). A, examples of spatial chromatic induction. The chromatic patterned surround at top left [top right] has contiguous rings bordering the test ring with $-S$ [$+S$] chromaticity (see text). At bottom, the test ring is within a uniform surround metameric to EES. Dashed lines demonstrate that all test rings have the same chromaticity, although their color appearances differ. Stimuli adapted from [7]. B, "Chromatic Induction Without Flash-Lag": both rings (one within a patterned and the other within a uniform unpatterned surround) were briefly pulsed. C, "Both Stimuli Not Patterned": both the changing and pulsed test rings had unpatterned surrounds (no spatial chromatic induction). D, "Pulsed Stimulus Patterned": the pulsed test ring had a patterned surround; the changing ring had an unpatterned surround. E, "Changing Stimulus Patterned": test ring changing in chromaticity had a patterned surround, the pulsed test ring had an unpatterned surround. F, "Both Stimuli Patterned": both the pulsed and changing test rings had patterned surrounds.

Fig. 2.

Spatial chromatic induction magnitude along the $S/(L + M)$ axis from patterned surrounds without the flash-lag effect (as in Fig. 1B); observers AC, EL, and LW, left to right). Plus [minus] symbols represent test rings with +S [-S] contiguous contours; circles represent isomeric matches. Error bars are ± 1 SEM. The black horizontal line shows the $S/(L + M)$ value of the fixed test ring.

Fig. 3.

Shift in color appearance along the S/(L + M) axis (left ordinate) with both the changing and pulsed rings on unpatterned surrounds. The right ordinate expresses the shift in terms of flash-lag duration (see text); the sign of lag duration always is positive, so the time on the right ordinate is positive on either side of zero. The circles [triangles] represent average matches with the ring changing from -S to +S (orange to purple) [+S to -S, purple to orange]. Error bars are ± 1 SEM. Horizontal line at 1.0 (left ordinate) shows the S/(L + M) value of the changing ring at the moment the pulsed ring was presented (thus equivalent to zero lag time on the right ordinate).

Fig. 4.

Shift in color appearance along the S/(L + M) axis (left ordinate) from flash-lag and also spatial chromatic induction (each column shows results for a different observer). Measurements are shown for the “Pulsed Stimulus Patterned” (top row), “Changing Stimulus Patterned” (middle row), and “Both Stimuli Patterned” (bottom row). The dashed horizontal line in each panel shows the S/(L + M) value of the changing test ring at the moment of the pulsed test ring (left ordinate), corresponding to a flash-lag duration of zero (right ordinate). The solid black lines in the left [right] half of each panel show the average match with unpatterned surrounds and the test ring changing from -S to +S [+S to -S], replotted from Fig. 3. The chromaticity of the contiguous contour is -S (minus symbols in plots) or +S (plus symbols in plots). The left [right] part of each panel is with the changing chromaticity from -S to +S [+S to -S], as indicated on the horizontal axis. Error bars show ± 1 SEM. Asterisks represent a sum of the individual shifts from the patterned surround alone and the flash-lag effect alone (see text).

Fig. 5.

Average difference in color shift caused by $-S$ versus $+S$ contiguous contours in patterned surrounds for flash-lag matches for the three main experimental conditions (“Pulsed Stimulus Patterned,” “Changing Stimulus Patterned,” and “Both Stimuli Patterned,” horizontal axis). Results for each observer are in a separate panel. Error bars are ± 1 SEM across the four repeated days and $+S$ to $-S$ and $-S$ to $+S$ directions of chromatic change. Asterisks indicate whether each value is different from zero (*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$).