# Time Course of Adaptation Along the RG Cardinal Axis

**Arthur G. Shapiro,[1]* Jennifer L. Beere,[1] Qasim Zaidi[2]**

[1] Department of Psychology, Bucknell University, Lewisburg, PA 17837

[2] SUNY College of Optometry, 100 East 24th Street, New York, NY 10010

Received 16 August 1999; accepted 26 February 2000

*Abstract: We examine how the RG cardinal mechanism adapts to a shift from one spatially uniform field to another. A probe-flash paradigm allowed the response to be estimated at an initial adaptation state, an end adaptation state, and four intermediate time conditions. The threshold curves were higher and flatter in the intermediate conditions than at the beginning and end of adaptation. The intermediate results cannot be explained by combinations of cone or opponent-level multiplicative and subtractive gain controls, and implicate higher-order adaptation processes.* © 2000 John Wiley & Sons, Inc. Col Res Appl, 26, S43–S47, 2001

*Key words: visual adaptation; visual sensitivity; color mechanisms; probe-flash; cardinal directions; higher-order mechamisms; temporal properties*

## INTRODUCTION

Shapiro and Zaidi[1] measured the effects of chromatic adaptation to lights along the cardinal directions of color space defined by Krauskopf et al.[2] In steady-state conditions, discrimination was best at the chromaticity of the adaptation field and worse at chromaticities away from the field along the cardinal line. For the RG cardinal axis, threshold curves for steady adaptation to the R, W, and G points appeared to be parallel-shifted versions of one another, a finding that is consistent with other reports in the literature.[3,4] Zaidi, Spehar, and DeBonet[5] showed that such results could be modeled by an early post-opponent high-pass temporal filter, a process equivalent to a subtractive gain control located after the combination of cone signals but before an invariant response nonlinearity.

In the current study, we measured the time course of adaptation to uniform backgrounds along the RG cardinal axis. The experiment was designed to determine (1) how long it takes the cardinal mechanisms to adjust their sensitivity to a new uniformly colored field; and (2) whether an early high-pass temporal filter, like that used to describe the steady adaptation data, is also sufficient to describe the intermediate changes in adaptation. We used a probe-flash technique[1,6–10] that allowed the response function to be estimated over an extended range of inputs. This technique enabled us to separate gain changes from changes in the response function. Other studies that have measured the time course of chromatic adaptation[11–14] have not examined changes in an extended response range.

## METHODS

### Specification of Colors

The line in Fig. 1(a) represents the RG cardinal axis, i.e., the constant S line of Derrington, Krauskopf, and Lennie.[15] This line is parallel to the L/(L + M) axis of MacLeod and Boynton.[16] The parentheses contain the values of the R, G, and W lights expressed in L/(L + M) cone units: W had a value of 0.657; R, of 0.696; and G, of 0.618. All lights had a photopic luminance of 50 cd/m$^2$. The scotopic contrast along this line was always below rod threshold.[17]

### Procedure

The experiment was designed to measure the sensitivity of the RG system as an observer's adaptation state shifts from one chromaticity to another. The conditions are shown in Figure 1(b). The observer began the experiment by fixating on a spot in the center of a steady field (10° square); the field was set to an initial adaptation chromaticity on the RG cardinal axis (R, W, or G). After 120 s, the field

* Correspondence to: Arthur Shapiro, Dept. of Psychology, Bucknell University, Lewisburg, PA 17837 (e-mail: shapiro@bucknell.edu)

Contract grant sponsor: NEI; Contract grant number: EY07556

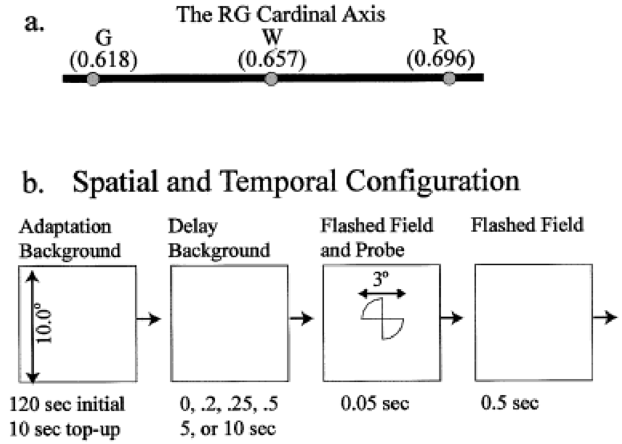


FIG. 1. (a) All lights in the study had a chromaticity along the RG cardinal axis. The units in parentheses are L/(L + M) cone units from MacLeod and Boynton.[16] (b) The spatial configuration and temporal sequence of the lights in the experiment.

switched to the second adaptation chromaticity (the delay background), which remained for a fixed delay time (0, 0.25, 0.5, 5.0 or 10.0 s). The chromaticity of the field was then changed to that of the flashed background, with a probe superimposed in the center. The probe remained for 0.05 s, and the flashed background remained for an additional 0.5 s. The observer was then presented with the initial adaptation chromaticity for a 10-s "top-up" adaptation period. We chose a duration for the probe and flash that would not disturb the adaptation state as we measured chromatic thresholds along the cardinal axis.

The probe was configured as two quadrants of a 3° disk. For all delay conditions, the flashed backgrounds were at the same points along the cardinal axis; threshold changes thus reflect differences only in observer adaptation. The observer's task was to identify the orientation of the probe (left oblique or right oblique) by pressing one of two buttons on a response box. Two interleaved staircases (constant step size) controlled the difference between the chromaticity of the probe and the chromaticity of the flashed background. The difference was decreased following three consecutive correct responses and increased following each incorrect response. A reversal occurred when there was a decrease in the difference following a series of increases or an increase following a series of decreases. The difference threshold was the mean of twelve such reversals.

### Apparatus and Calibration

Stimuli were displayed on a Tektronix 690SR color television monitor running at 120 interlaced frames per second. Images were generated with an ADAGE 3000 raster-based frame-buffer generator. The calibration procedure is discussed in detail in Zaidi, Shapiro, and Hood.[10]

### Observers

The data presented here are from one of the authors, AGS. Flicker photometry was used to set the equiluminance of the cardinal lines for the observer.

## RESULTS

Figure 2 shows the results for shifting the adaptation field from W to R. The field was set to W in the initial adaptation phase and R in the delay phase. Each panel represents a different delay time (0, 0.25, 0.5, 5.0, and 10.0 s). The

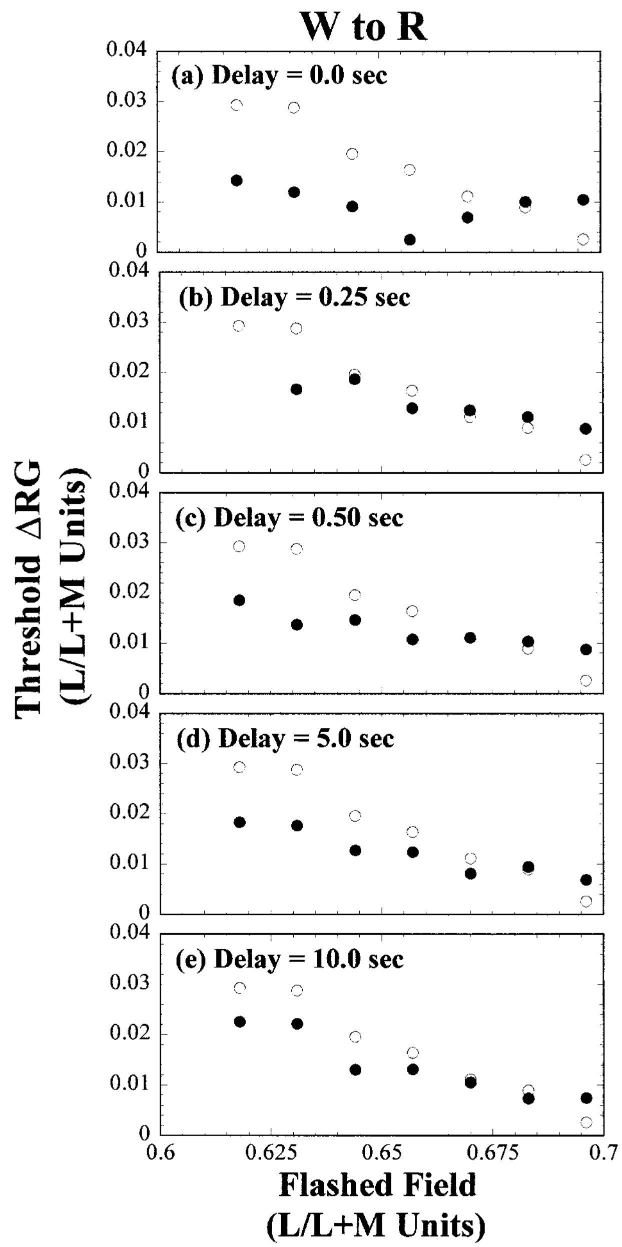


FIG. 2. The threshold curves for initial adaptation to W shifting to R. The difference thresholds are plotted versus the L/(L + M) excitation of the flashed background (filled symbols). Each panel shows the duration of the delay field. Open circles indicate the infinite delay condition, in which the observer adapts only to chromaticity R.

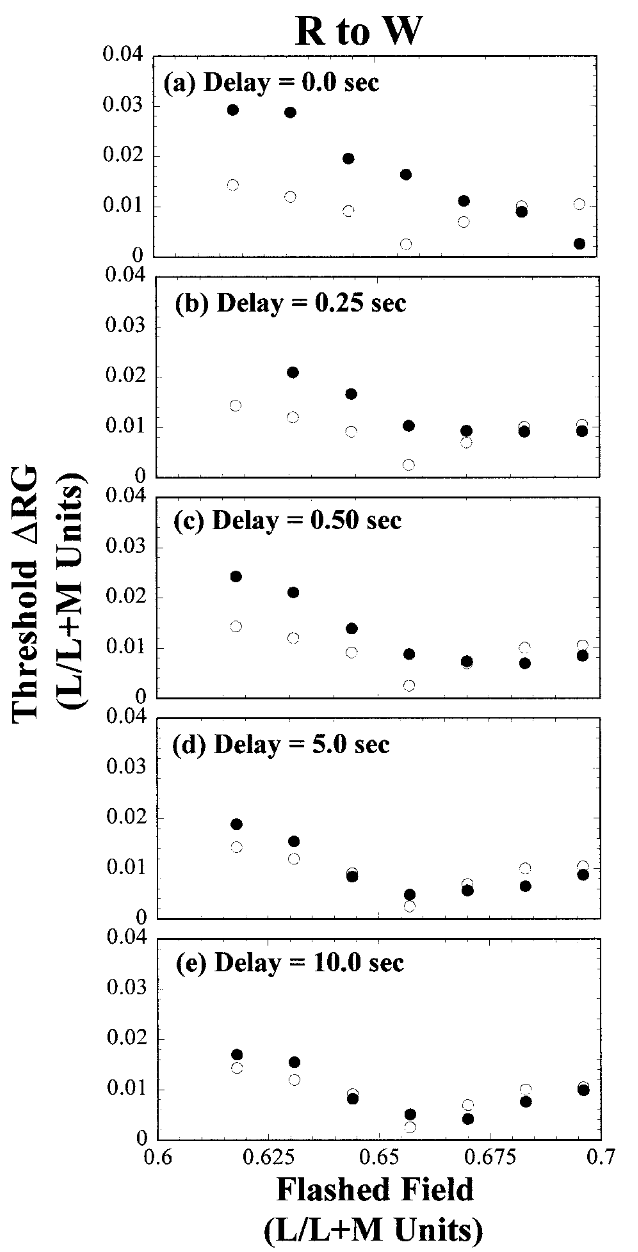


FIG. 3. Same as Fig. 2, except initial adaptation to R shifting to W. Open circles indicate the infinite delay condition in which the observer adapts only to chromaticity W.

*Y*-axis shows the threshold chromaticity difference between the probe and flashed backgrounds expressed in ΔL/(L + M) units; the *X*-axis shows the flashed background expressed in L/(L + M) units. The filled circles represent the thresholds following the presentation of the R background in the delay phase; the open symbols represent the thresholds measured separately during steady adaptation to R (i.e., the threshold curve that should result when the delay is infinitely long). The curve designated by the open symbols is the same in each panel.

In the steady state condition (i.e., 0.0 s delay), the threshold is minimum at W and increases for flashed backgrounds on either side (as in Shapiro and Zaidi[1]). Each consecutive panel shows the shift towards R adaptation. The threshold curves are flatter in the 0.25 and 0.5 delay conditions. At the end of 10.0 s, the threshold curve is steeper but still shallower than in the infinite delay condition.

Figure 3 shows a similar set of figures for shifting the adaptation field from R to W. The filled circles are the thresholds following exposure to W for specified delay times; the open circles, the thresholds for infinite adaptation to W. At zero delay, thresholds are lowest at R and increase for the flashed backgrounds further away from R. As the delay times increase, the threshold curve approximates steady adaptation to W. The threshold curve on the R side of W flattens in the 0.25 and 0.5 s delay conditions before forming the "V" shape.

The high-pass temporal filter model predicts that the

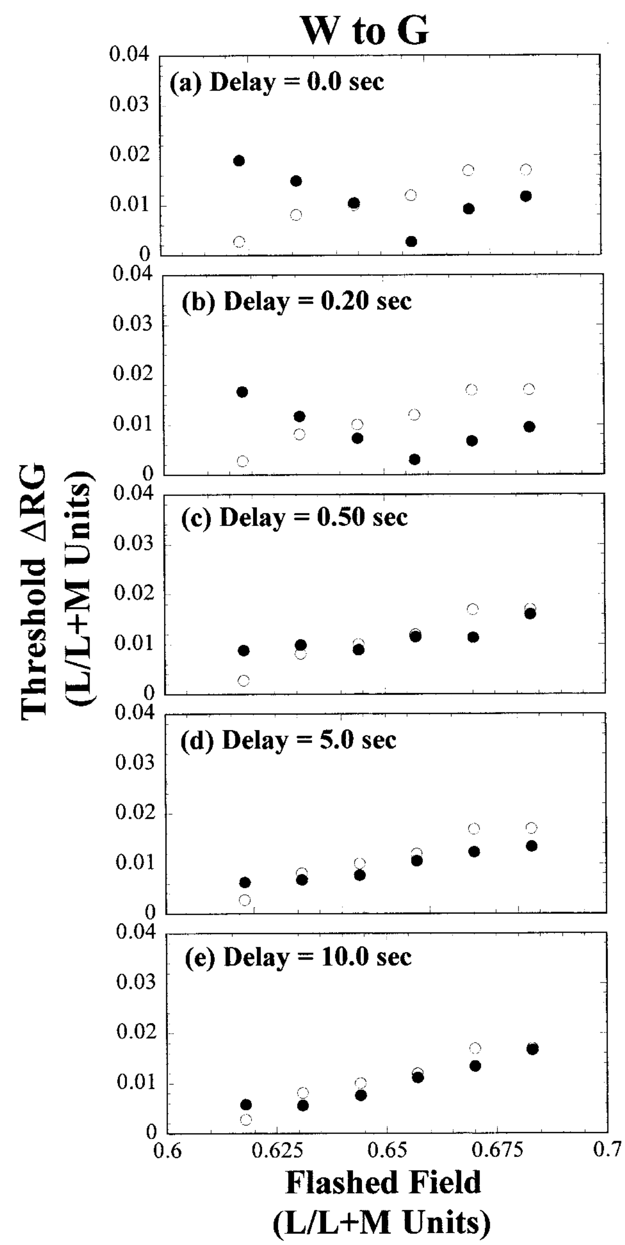


FIG. 4. Same as Fig. 2, except initial adaptation to W shifting to G. Open circles indicate the infinite delay condition in which the observer adapts only to chromaticity G.

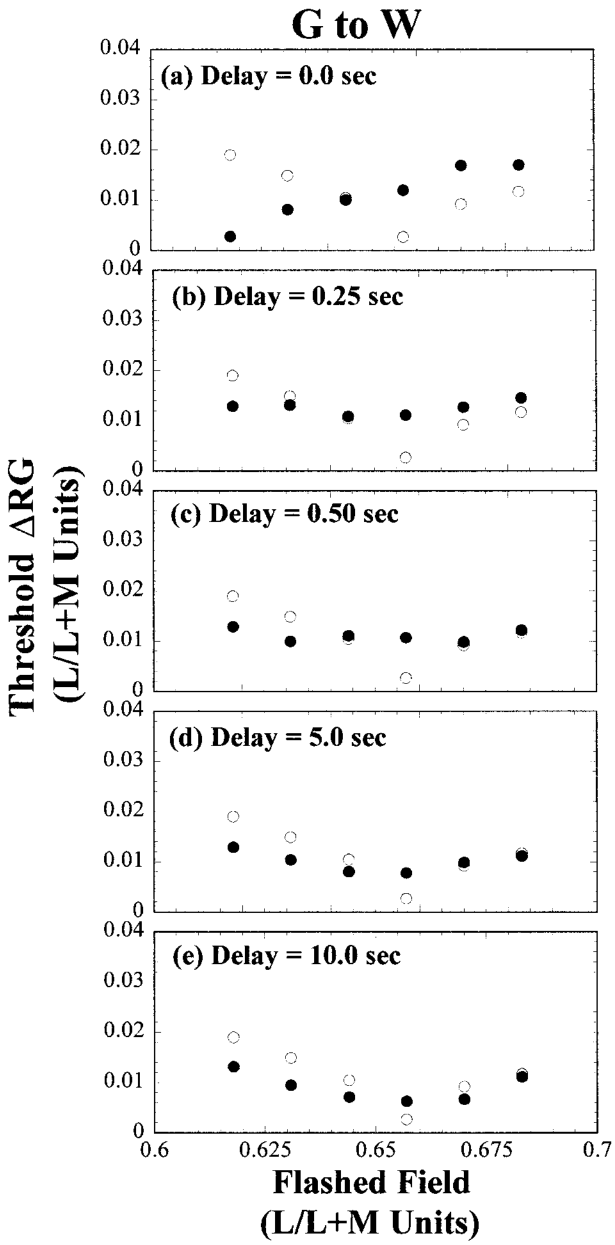


FIG. 5. Same as Fig. 2, except initial adaptation to G shifting to W. Open circles indicate the infinite delay condition in which the observer adapts only to chromaticity W.

intermediate threshold curves should be lateral translations of the steady state curve, with the location of the minimum threshold level shifted towards the new adaptation chromaticity. Figures 2 and 3 show that for the initial change, i.e., the 0.25 s delay condition, neither set of curves can be described by such a shift. A comparison of the figures shows that the initial change from R to W is less dramatic than the shift from W to R.

Figures 4 and 5 show the threshold shifts from W to G and G to W, respectively. The general conclusions are the same as for Figs. 2 and 3. In both sets of figures, there is a shift in minimum from the initial adaptation point to the second adaptation field. In each case, the threshold curve flattens before forming the minimum values found in the infinite delay conditions. Adaptation is not complete by the end of 10 s.

## DISCUSSION

In the steady-state conditions (open and closed symbols in the 0.0 s delay panels for Figs. 2–5), the threshold curves have the same minimum threshold value and rise with approximately the same slope. If one were to examine only these conditions, one might be misled into believing that chromatic adaptation along the RG cardinal axis could be explained purely by a high-pass temporal filter, or equivalently a subtractive gain control, interposed before the nonlinearity. However, in the intermediate delay conditions, the minimum threshold is elevated and the threshold curves are flattened, indicating the operation of an additional transient process. Shapiro and Zaidi[1] and Zaidi and Shapiro[18] showed that multiplicative gain-controls before or after the nonlinearity cannot flatten the slopes of the threshold curves, and are therefore ruled out as possible mechanisms. The flattened threshold curves seem similar to the curves following exposure to temporal modulation[1,18] and to spatial variation[19] along the RG axis. This flattening has been modeled by a change in the shape of the response function.

The results of this study show that higher-level adaptation mechanisms may be required to explain the results of even simple adaptation experiments involving a sharp chromatic transition between two spatially uniform fields. To separate early and higher-order processing stages, we are presently measuring observer thresholds following exposure to two types of stimuli — a uniform background and a spatially and temporally complex background.

## ACKNOWLEDGMENTS

Portions of this work were presented previously at ARVO.[20] This work was partially supported by NEI grant EY07556 to Q. Zaidi.

1. Shapiro AG, Zaidi Q. The effects of prolonged temporal modulation on the differential response of color mechanisms. Vision Res 1992; 32:2065–2075.
2. Krauskopf J, Williams DR, Heeley DW. Cardinal directions of color space. Vision Res 1982;22:1123–1131.
3. Krauskopf J, Gegenfurtner K. Color discrimination and adaptation. Vision Res 1992;32:2165–2175.
4. Yeh T, Pokorny J, Smith VC. Chromatic discrimination with variation in chromaticity and luminance: data and theory. Vision Res 1993;33: 1835–1845.
5. Zaidi Q, Spehar B, DeBonet J. Color constancy in variegated scenes: role of low-level mechanisms in discounting illumination changes. J Opt Soc Am A 1997;14:2608–2621.
6. Geisler WS. Adaptation, afterimages and cone saturation. Vision Res 1978;18:279–289.
7. Geisler WS. Evidence for the equivalent-background hypothesis in cones. Vision Res 1979;19:799–805.
8. Hood DC. Psychophysical and physiological tests of proposed mechanisms of light adaptation. In: Armington J, Krauskopf J, Wooten B, editors. Visual psychophysics: its physiological basis. New York: Academic; 1978.
9. Hayhoe MM, Benimoff NI, Hood DC. The time-course of multiplica-

tive and subtractive adaptation process. Vision Res 1987;27:1981–1996.
10. Zaidi Q, Shapiro A, Hood D. The effect of adaptation on the differential sensitivity of the S-cone color system. Vision Res 1992;32: 1297–1318.
11. Fairchild MD, Lennie P. Chromatic adaptation to natural and incandescent illuminants. Vision Res 1992;32:2077–2085.
12. Hayhoe MM, Levin ME, Koshel RJ. Subtractive processes in light adaptation. Vision Res 1992;32:323–333.
13. Shevell SK. The time course of chromatic adaptation to non-uniform fields. In: International Color Vision Society. Gottingen, Germany. 1999.
14. Rinner O, Gegenfurtner KR. Time course of adaptation for color discrimination and appearance. Investig Ophthalmol Suppl 1999;40:750.
15. Derrington AM, Krauskopf J, Lennie P. Chromatic mechanisms in lateral geniculate nucleus of macaque. J Physiol (Lond) 1984;357: 241–265.
16. MacLeod DIA, Boynton RM. Chromaticity diagram showing cone excitation by stimuli of equal luminance. J Opt Soc Am 1979;69: 1183–1186.
17. Shapiro AG, Pokorny J, Smith VC. Cone-rod receptor spaces with illustrations that use CRT phosphor and light-emitting-diode spectra. J Opt Soc Am A 1996;13:2319–2328.
18. Zaidi Q, Shapiro AG. Adaptive orthogonalization of opponent-color signals. Biol Cybern 1993;69:415–428.
19. Zaidi Q, Spehar B, DeBonet J. Adaptation to textured chromatic fields. J Opt Soc Am A Opt Image Sci Vis 1998;15:23–32.
20. Shapiro AG, Zaidi Q, Hood D. Adaptation in the red-green (L-M) color system. Investig Ophthalmol Suppl 1990;31:262.