
SHORT COMMUNICATION

A new technique for estimating chromatic isoluminance in humans and monkeys

AVI CHAUDHURI AND THOMAS D. ALBRIGHT

The Salk Institute for Biological Studies, La Jolla, CA

(RECEIVED June 15, 1990; ACCEPTED August 6, 1990)

Abstract

Current approaches to the problem of equating different colors for luminance (chromatic isoluminance) rely upon human reports of perceptual events that are reduced at some luminance ratio. In this report, a technique is described that evokes a vivid percept of motion of a textured pattern only at isoluminance. Furthermore, in both humans and monkeys, the moving stimulus produces a striking optokinetic response in the same direction as the perceived motion. If used in this manner, the technique can provide an estimate of chromatic isoluminance in a variety of species and be used to corroborate a human subjects' perceptual judgement.

Keywords: Equiluminance, Heterochromatic, Optokinetic nystagmus, Flicker, Motion

Introduction

The use of chromatic patterns that are equated for luminance has become increasingly popular in psychophysical and neurophysiological studies of visual processing (e.g. Livingstone & Hubel, 1987). Classical techniques for determining isoluminance require perceptual judgements on the minimization of a particular sensory parameter. In heterochromatic brightness matching, a reference light of fixed wavelength and luminance is presented adjacent to a comparison field of a different wavelength. The observer is required to adjust the luminance of the comparison field in order to minimize a brightness difference between the two (Walters & Wright, 1943; Ikeda & Shimozono, 1981). In heterochromatic flicker photometry, two coextensive fields of different wavelengths are alternated at frequencies greater than 10 Hz (Ives, 1912). Subjects are required to adjust the luminance of one of the components until the sensation of flicker is minimized and the field takes on the appearance of an intermediate color. In the minimally distinct border technique, subjects adjust the luminance of one field in order to reduce the contrast of a precisely juxtaposed border with a reference field of a different wavelength (Boynton & Kaiser, 1968).

Criterion responses that rely upon such perceptual judgements are susceptible to variability and imprecision. Moreover, although flicker discrimination paradigms have been used with some success in rhesus monkeys (Schiller et al., 1990), they are generally difficult to employ in nonhumans. Recently, a technique that produces a reflexive response has been used to esti-

mate isoluminance. The minimum motion technique (Anstis & Cavanagh, 1983; Cavanagh et al., 1987) yields perceived movement in one direction when the luminance ratio in a chromatic grating is less than 1.0 and movement in the opposite direction when that ratio is greater than 1.0. As expected, optokinetic (OKN), head, and body movements often follow the grating and the directional reversals have been used to estimate the isoluminant point in human infants (Anstis et al., 1987), rhesus monkeys (Logothetis & Charles, 1990), and fish (Anstis et al., 1990). Despite its apparent utility, like previous methods, the minimum motion technique relies on minimization of a perceptual (perceived motion) or reflexive response (OKN).

In this report, a new technique is introduced that has the converse property, that is, a striking percept of motion and concomitant optokinetic response is produced *only at chromatic isoluminance*. Small deviations from the isoluminant point in either direction eliminate the percept of motion. They also abolish the eye movements entirely and, in some cases, produce an optokinetic response in the opposite direction. Because the procedure evokes a reflexive response, it can be used in all animals that display OKN, without the need for any special training. Furthermore, the OKN responses provide an independent assessment of chromatic isoluminance that can be used to confirm values obtained with any of the classical paradigms. This work has appeared previously in abstract form (Chaudhuri, 1990).

Methods

The approach is a modified version of that used in heterochromatic flicker photometry. A two-color textured pattern is alternated at 30 Hz and translated in a particular direction. Su-

Reprints requests to: Avi Chaudhuri, The Salk Institute for Biological Studies, P.O. Box 85800, San Diego, CA 92186-5800, USA.

perimposed upon the chromatic pattern is a luminance-noise pattern composed of randomly placed black dots. At each alternation, the color contrast of the textured pattern is reversed and, along with the luminance-noise pattern, moved in a particular direction. When the two colors that compose the textured pattern are unequal in luminance, an overriding flicker sensation will mask the true movement of the entire pattern. In fact, a paradoxical percept of motion in the opposite direction is often reported. Prior studies have documented a phenomenon, called "reverse-phi," which is seen with luminance-contrast patterns that undergo contrast reversals as they are translated (Anstis & Rogers, 1975). At isoluminance, however, flicker in the dichromatic textured pattern is minimized and a striking veridical motion percept of the black dots emerges.

The stimuli for these experiments were generated by a PC installed with a graphics coprocessor (Number Nine Computer Corp., Cambridge, MA) and displayed on a NEC Multisync high-resolution color monitor. Although a wide range of stimulus parameter values produced similar results, we found that certain values yielded stronger motion percepts, elicited better eye movements, and gave a narrower OKN tuning curve. The optimal stimulus parameter values with our system are as follows. The random-dot pattern had 6×6 pixel components which were randomly chosen to be either gray or green (Fig. 1a). Each pixel subtended about 3 min arc. The luminance of the gray components was set at 9.0 cd/m^2 ; the luminance of the green components was variable and under keyboard control by the experimenter. A standard photometer (United Detector Technology, Hawthorne, CA) was used to obtain luminance values in the patterns. Superimposed upon the chromatic-texture pattern was a luminance-noise pattern, composed of 2×2 pixel black dots and generated randomly with a spatial density of $1/16$ and the requirement that they not appear side by side.

The entire pattern, both chromatic-texture and luminance-noise components, was then moved upward by a displacement of 6 pixels at a frequency of 30 Hz (9 deg/s). With each displacement, a contrast reversal occurred in the chromatic-texture pattern so that all gray elements became green and all green ones became gray (Fig. 1b). The luminance-noise pattern remained unaffected by this process. Two human subjects and two rhesus monkeys (*Macaca mulatta*) viewed the stimulus through a tunnel (Length: 57 cm; diameter: 16 cm) placed against the monitor screen. This obscured all environmental

contours which could have interfered with the eye movements. The pattern viewed by all subjects was circular and had an area of 200 deg^2 . There was no fixation spot.

A brief consideration of the stimulus described above will reveal that its essential components consist of heterochromatic flicker superimposed upon a drifting luminance-textured pattern. We hypothesized that the motion of the luminance pattern would become maximally salient when the contrast reversal in the chromatic pattern does not mask its movement. This will occur at the heterochromatic flicker fusion point. Thus, motion should be perceived only at the point where the two colors in the display are perceived to be equally bright.

Eye movements were monitored by the technique of magnetic search-coil oculography (Robinson, 1963). In the human subjects, a search coil implanted within a soft annular contact lens (Skalar, Holland) was placed in the right eye, which had been anesthetized with Proparacaine HCl (0.5%) (see Collewyn et al., 1975 for details). The subjects viewed the stimuli binocularly through the tunnel at a distance of 57 cm with the aid of a chin rest and forehead support. In the monkeys, a search coil was surgically implanted under the conjunctiva (see Judge et al., 1980 for details). During the experiment, the monkeys sat in a specially constructed primate chair with their head held rigidly by a restraining pole attached to an acrylic skull cap. Synchronous demodulation of axis-specific frequency signals provided accurate estimates of both horizontal and vertical eye movements (CNC Engineering, Seattle, WA). The eye movements were obtained in 4-s epochs during which the subjects viewed the moving stimuli with a preset green/gray luminance ratio. A total of five such trials were collected for each luminance ratio. The oculographic traces were analyzed off-line at the end of the experiment in order to obtain eye-drift velocity.

Results and discussion

Figure 2 shows the OKN results for both human and monkey. Since we found similar results with all subjects, only one set of data from each species will be presented. Given a gray luminance of 9.0 cd/m^2 and a green luminance of 6.7 cd/m^2 , the human subjects displayed a significant downward OKN which was consistent with the "reverse-phi" motion they perceived at this luminance ratio. The monkeys, however, displayed only slight downward OKN in between a series of saccades over the

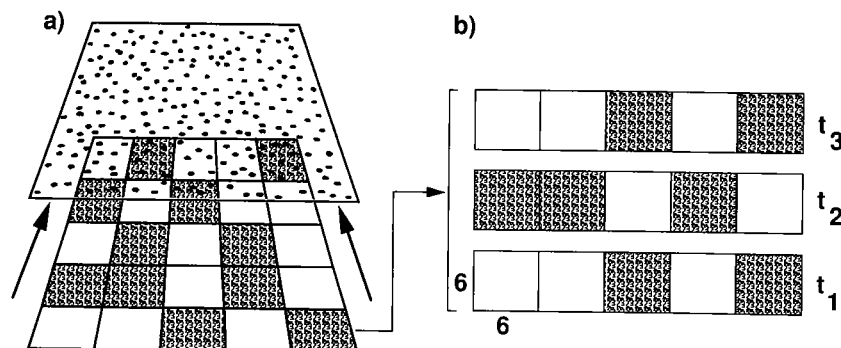


Fig. 1. Schematic depiction of the stimulus pattern used in this experiment. (a) A green/gray chromatic-texture pattern is first created with an element size of 6×6 pixels. Superimposed upon this are randomly placed black dots (2×2 pixels) with a spatial density of $1/16$. Both patterns are then moved upward, however, the chromatic pattern undergoes a contrast reversal with each displacement. (b) The color sequence for the bottom row in (a) is shown at three snapshots in time as it drifts upward. All green components (shaded) were interchanged with all the gray ones with each displacement.

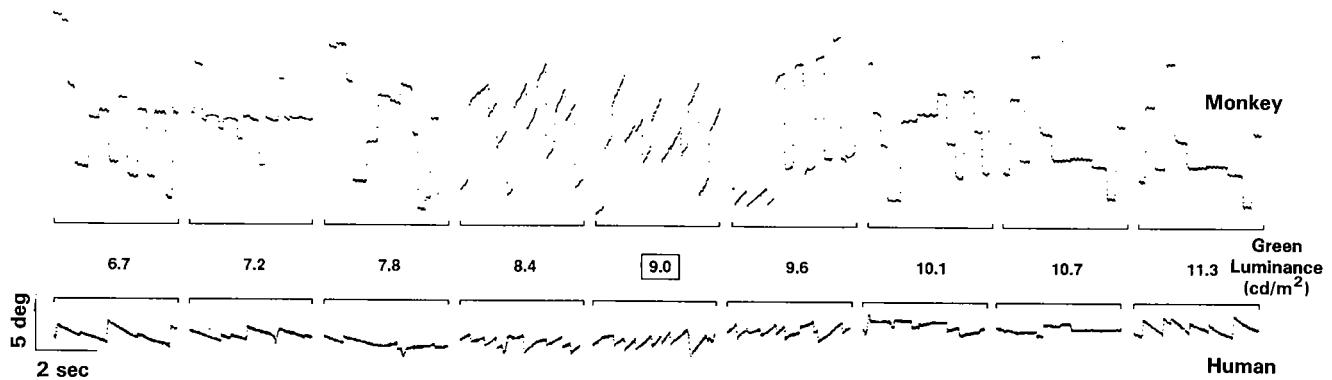


Fig. 2. Optokinetic eye movements generated by the dynamic flicker stimulus. The luminance of the gray components was maintained at 9.0 cd/m^2 (boxed) while the green luminance was varied from $6.7\text{--}11.3 \text{ cd/m}^2$, as indicated by the values placed between the eye movement traces. Each panel in this figure presents the eye movements for a 4-s epoch during which the luminance ratio was kept at a constant value. A striking upward OKN was seen in both humans and monkeys when green and gray luminances were matched.

stimulus field. As the luminance of the green components approached that of the fixed gray luminance (9.0 cd/m^2), a striking upward OKN emerged in both humans and monkeys. The human subjects reported seeing a vivid upward movement of the black dots at this point and that they were unable to suppress the concomitant upward eye drift. This suggests that the eye movements were not the exclusive product of tracking specific features (i.e. smooth pursuit) but rather the result of a reflexive response (OKN). Nevertheless, it can be assumed that some smooth pursuit was present in these eye movements since individual tokens were clearly seen to be moving at isoluminance. The monkeys, who were experimentally naive, shifted their gaze over all parts of the stimulus field. However, at each position, their eyes were driven upward by the stimulus. As the luminance of the green component was increased further, OKN gain declined for all subjects and became overtly negative for the human subjects (i.e. downward eye drift) at the highest luminance tested (11.3 cd/m^2).

From the oculographic traces, as in Fig. 2, OKN drift velocity was obtained by differentiating the slow-phase components with respect to time and neglecting the saccadic portions in each of the trials. OKN gain was then calculated as the ratio of eye velocity to pattern velocity (9 deg/s). As noted before, peak OKN velocity occurred at isoluminance with a rapid decline in gain on either side (Fig. 3). Three points about this tuning curve are noteworthy. First, the largest amplitude OKN occurred at the same point for both humans and monkeys indicating that similar chromatic mechanisms exist in the two species, as already noted in previous studies (DeValois et al., 1974). The reduced peak gain found with humans was most likely a consequence of the task since they were instructed to maintain gaze in the center and not to overtly track any moving targets. Second, at non-isoluminant ratios, the monkeys and especially the human subjects displayed negative OKN. As discussed before, this can be attributed to the phenomenon of "reverse-phi" which is known to occur with luminance-contrast displays that undergo contrast reversal as the pattern is displaced. Third, the stimulus used in this experiment is highly sensitive in that OKN was considerably reduced at small deviations from the isoluminant point and vanished entirely at 1.0 cd/m^2 above and below this point.

Isoluminant patterns are commonly used to study the rela-

tive contributions of color- and luminance-based pathways in the processing of different visual attributes. Indeed, psychophysical evidence for functional differences between the two principal geniculostriate pathways, i.e. the magnocellular and parvocellular streams (DeYoe & Van Essen, 1988; Livingstone & Hubel, 1987), has been based largely on visual performance with chromatic isoluminant patterns. Similarly, the use of isoluminant patterns has gained importance in physiological studies of the primate visual system. Single-unit studies in the LGN (Kruger, 1979; Hicks et al., 1983), striate cortex (Gouras & Kruger, 1979; Lennie et al., 1990), and area MT (Saito et al., 1989), among others, have used isoluminant chromatic patterns. Recent studies in awake, behaving primates which attempt to correlate behavioral responses with underlying neural mechanisms have also used isoluminance paradigms in order to examine the contribution of color to various visual processes (Schiller et al., 1990; Logothetis et al., 1990; Dobkins & Albright, 1990). An accurate determination of isoluminance is therefore an essential part of any study which addresses the contribution of chromatic mechanisms to visual processing.

The technique described in this report offers a simple, sensitive, and reliable approach to estimating chromatic isoluminance. The nature of the display is such that with appropriate consideration of the stimulus parameters, large-amplitude optokinetic eye movements are observed only at isoluminance. Furthermore, because the stimulus is composed of random-dot patterns, drift rate is not constrained by any considerations of frame-to-frame correlations, as is the case with drifting gratings, thereby allowing free use of any pattern velocity capable of producing an OKN response. Although Logothetis and Charles (1990) have reported optokinetic eye movements with the minimum motion technique, we have been unable to obtain high-gain OKN in pilot studies with that method in monkeys that were not specifically trained to pursue stimulus features. It is reasonable to assume that the drifting gratings are less capable of driving the eyes and generating an OKN response given that such stimuli contain fewer contours and less luminance contrast than the chromatic-texture/luminance-noise pattern used here. Furthermore, by minimizing luminance flicker, the technique presented here maximizes perceived motion along with an associated oculomotor response. This distinguishes it from other techniques because the isoluminant point is posi-

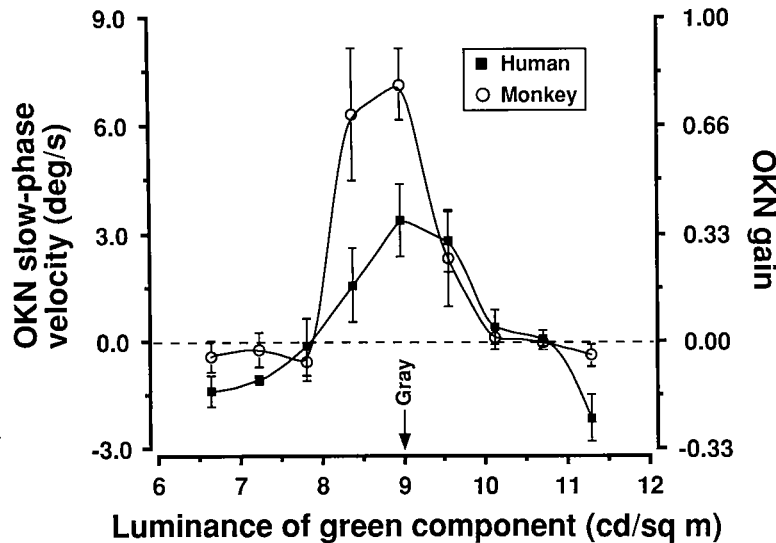


Fig. 3. Luminance tuning curves as obtained from OKN responses to drifting pattern (Fig. 2). A rapid symmetric decline in OKN was seen in both humans and monkeys at small deviations from the isoluminant point (arrow). At non-isoluminant settings, negative OKN was observed. Error bars represent standard deviations from five trials.

tively defined, whereas in other methodologies it is negatively defined. A detailed evaluation of this technique is under way and the results will appear in a forthcoming report.

Acknowledgments

We thank Gene Stoner and Karen Dobkins for help and advice during this study. We are especially grateful to Frederick Nahm and Gene Stoner for serving as subjects and participating in the search-coil experiments. This research was supported by NIH Grant EY07605 and a Sloan Foundation Research Fellowship to T.D. Albright.

References

- ANSTIS, S.M. & CAVANAGH, P. (1983). A minimum motion technique for judging equiluminance. In *Colour Vision: Physiology and Psychophysics*, ed. MOLLON, J.D. & SHARPE, L.T., pp. 156–166. London: Academic Press.
- ANSTIS, S.M., CAVANAGH, P., MAURER, D. & LEWIS, T. (1987). Optokinetic technique for measuring infant's responses to color. *Applied Optics* **27**, 1510–1516.
- ANSTIS, S., MURASUGI, C. & CAVANAGH, P. (1990). Optomotor test for wavelength sensitivity in guppyfish. *Investigative Ophthalmology and Visual Science*, (ARVO Suppl.) **31**, 110.
- ANSTIS, S.M. & ROGERS, B.J. (1975). Illusory reversal of visual depth and movement during change of contrast. *Vision Research* **15**, 957–962.
- BOYNTON, R.M. & KAISER, P.K. (1968). Vision: the additivity law made to work for heterochromatic photometry with bipartite fields. *Science* **161**, 366–368.
- CAVANAGH, P., MACLEOD, D.I.A. & ANSTIS, S.M. (1987). Equiluminance: spatial and temporal factors and the contribution of blue-sensitive cones. *Journal of the Optical Society of America* **4A**, 1428–1438.
- CHAUDHURI, A. (1990). A new technique for determining isoluminance. *Society for Neuroscience Abstracts* **16**, 105.
- COLLEWIJN, H., VAN DER MARK, F. & JANSEN, T.C. (1975). Precise recording of human eye movements. *Vision Research* **15**, 447–450.
- DEVALOIS, R.L., MORGAN, H.C., POLSON, M.C., MEAD, W.R. & HULL, E.M. (1974). Psychophysical studies of monkey vision, I: Macaque luminosity and color vision tests. *Vision Research* **14**, 53–67.
- DEYOE, E.A. & VAN ESSEN, D.C. (1988). Concurrent processing streams in monkey visual cortex. *Trends in Neurosciences* **11**, 219–226.
- DOBKINS, K. & ALBRIGHT, T.D. (1990). Color facilitates motion correspondence in visual area MT. *Society for Neuroscience Abstracts* **16**, 1220.
- GOURAS, P. & KRUGER, J. (1979). Responses of cells in foveal visual cortex of the monkey to pure color contrast. *Journal of Neurophysiology* **42**, 850–860.
- HICKS, T.P., LEE, B.B. & VIDYASAGAR, T.R. (1983). The responses of cells in macaque lateral geniculate nucleus to sinusoidal gratings. *Journal of Physiology (London)* **337**, 183–200.
- IKEDA, M. & SHIMOZONO, H. (1981). Mesopic luminous-efficiency function. *Journal of the Optical Society of America* **71**, 280–284.
- IVES, H.E. (1912). On heterochromatic photometry. *Philosophical Magazine* **24**, 845–853.
- JUDGE, S.J., RICHMOND, B.J. & CHU, F.C. (1980). Implantation of magnetic search coils for measurement of eye position: an improved method. *Vision Research* **20**, 535–538.
- KRUGER, J. (1979). Responses to wavelength contrast in the afferent visual systems of the cat and rhesus monkey. *Vision Research* **19**, 1351–1358.
- LENNIE, P., KRAUSKOPF, J. & SCLAR, G. (1990). Chromatic mechanisms in striate cortex of macaque. *Journal of Neuroscience* **10**, 649–669.
- LIVINGSTONE, M.S. & HUBEL, D.H. (1987). Psychophysical evidence for separate channels for the perception of form, color, movement, and depth. *Journal of Neuroscience* **7**, 3416–3468.
- LOGOTHETIS, N.K. & CHARLES, E.R. (1990). The minimum motion technique applied to determine isoluminance in psychophysical experiments with monkeys. *Vision Research* **30**, 829–838.
- LOGOTHETIS, N.K., SCHILLER, P.H., CHARLES, E.R. & HURLBERT, A.C. (1990). Perceptual deficits and the activity of the color-opponent and broadband pathways at isoluminance. *Science* **247**, 214–217.
- ROBINSON, D.A. (1963). A method of measuring eye movement using a scleral search coil in a magnetic field. *IEEE Transactions (BME)* **10**, 137–145.
- SAITO, H., TANAKA, K., ISONO, H., YASUDA, M. & MIKAMI, A. (1989). Directionally selective response of cells in the middle temporal area (MT) of the macaque monkey to the movement of equiluminous opponent color stimuli. *Experimental Brain Research* **75**, 1–14.
- SCHILLER, P.H., LOGOTHETIS, N.K. & CHARLES, E.R. (1990). Functions of the color-opponent and broadband channels of the visual system. *Nature* **343**, 68–70.
- WALTERS, H.V. & WRIGHT, W.D. (1943). The spectral sensitivity of the fovea and extrafovea in the Purkinje range. *Proceedings of the Royal Society B* **131** (London) 340–361.