Optokinetic technique for measuring infants' responses to color

Stuart Anstis, Patrick Cavanagh, Daphne Maurer, and Terri Lewis

Two motion tests will measure normal and defective responses to color in non-verbal infants. Moving gratings displayed on a computer-controlled TV monitor elicited optokinetic eye movements. The first test established three results. First, non-verbal infants can be successfully screened, the one baby known to be colorblind was readily identified. Second, the equiluminance point for red and green was shifted for protans, who needed more red light than normals to make an equiluminance match. Third, the relative contribution of R- and G-cones to the luminance pathways is already in place at the adult level within the first three months of life. The second test, run only on adults, correctly diagnosed deutans who were missed by the first test, and showed that opponent-color mechanisms contribute directly to motion for normal but not for color-deficient observers.

I. Introduction

It is easy to screen cooperative literate adults for color blindness with the standard Isihara and American Optical (AO) pseudoisochromatic plates. Normal people can read the numbers composed of red dots embedded in a background of green dots, using the hue discrimination which enables us (and other fruit-eating primates) to pick out ripe red fruit among green leaves. Color-defective individuals have poor hue discrimination and fail the test. Notice that in these tests luminance is a troublesome artifact which could permit cheating but is overcome by breaking the figures and background into dots and then randomizing the luminance of the dots.

These tests require the subject to read and speak, which rules out the testing of babies and other preverbal or nonverbal subjects. We have devised a pair of new tests for screening nonverbal populations such as animals and infants based on optokinetic eye movements. It is difficult to find out what a baby can see, since babies cannot respond to visual tests with words or button pushes as adults do. What other responses can babies make? Current test of babies' vision include preferential looking and evoked potentials. Preferential looking can be tedious and time-consuming, and evoked potentials require that electrodes be glued to the baby's head, a procedure that baby and mother may not tolerate well. Other methods of measuring color blindness in infants and animals are sometimes hard to use and generally require some form of discrimination training.[1,2]

One response babies can make is to move their eyes. In particular, when they view a moving full-field pattern their eyes show the classic ramplike waveform of optokinetic nystagmus, with linear slow phases in the same direction as the moving stimulus, interrupted by fast opposing saccades. Even newborns show optokinetic nystagmus.[3]

To ask a baby whether it sees a particular visual property, color, for example, we can convert color into a motion signal. The baby can communicate with us by one of the few means he has—by following the motion with his eyes. We drove eye movements with drifting gratings, and we devised a trick to convert the luminance of a colored pattern into motion, so that the baby's eye movements told us about the luminance of the colors. Essentially, a pattern of red and green stripes jumped across the screen of a computer-controlled TV, and it was arranged that to a normal eye these stripes appeared to jump to the left, but to a color blind eye they appeared to jump to the right. By observing the subject's eye movements we could assess some aspects of his color vision. Moving patterns of colored stripes have been used to evoke eye movements as a way of testing color responses in pigeons[4] and in man.[5] This paper reviews our progress so far in testing infant responses to color. Further details are published elsewhere.[6–10]

Consider two superimposed sinusoidal gratings drifting in opposite directions. It is well known that if they are of equal contrast they will sum to form a stationary counterphase flickering grating. However, if one grating, say, the leftward one, is higher in contrast, they sum to a counterphase grating plus an added drift to the left giving a net motion signal to the left.[11] Such gratings are defined by luminance; the direction of motion, left, right, or null, indicates the relative strengths (luminance contrasts) of the two gratings. We have generalized this technique so that we can evaluate the relative strength of stimuli along arbitrary dimensions with perceived direction of motion being the response. For example, two stimuli that differ in color can be equated for luminance. When two stimuli, one red and one green, drift in opposite directions, the perceived direction of motion will change as a function of their luminance contrast. We can use eye movements to determine the point of equality of the two stimuli along the dimension of luminance.

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Each of our two color tests consisted of a pair of superimposed gratings drifting in opposite directions. Our first test consisted of two oppositely drifting red/green gratings. It measured the luminosity ratio of red and green, exploiting the fact that red light looks dimmer to protans (red-defectives) than to normals. A difference in color luminosity produces a reversal in the direction of the stimulus motion,[6] while at equiluminance the motion disappears and is replaced by static flicker. Our second test consisted of a red/green grating drifting in one direction superimposed on a light yellow/dark yellow luminance grating drifting in the other direction. This test measured the strength of the motion signal carried by an equiluminous colored grating so that the strength of the opponent-color channel response was converted into reversals in motion direction. We find that in normals, but not in color defectives, there is a measurable input from the opponent-color channels into motion. We shall explain the design of each test in turn and then describe our results.

In a simplified model of the visual system [Fig. 1(a)], outputs from the **R, G,** and **B** cones are subtracted from each other to give opponent-color signals, and outputs from the **R** and **G** cones are added to give luminance signals. (The **B** cones are not thought to contribute to luminance.[12]) Thus the luminance of a stimulus is proportional to the sum of the cone signals, and its color is proportional to their ratio. In our first test, motion information was carried only by luminance and not by opponent-color signals [Fig. 1(a)], and the point of motion null indicated the equiluminant match of the two colors used, for example, red and green. We found that protans, having an abnormal **R** cone, required more red light than normals to achieve a match. Conversely, some (but not all) deutans, having an abnormal **G** cone, required more green light. In our second test, we examined the motion information that was carried by opponent-color stimuli [Fig. 1(b)], and we found that both protans and deutans have a reduced output from the opponent-color channel into the motion channel.

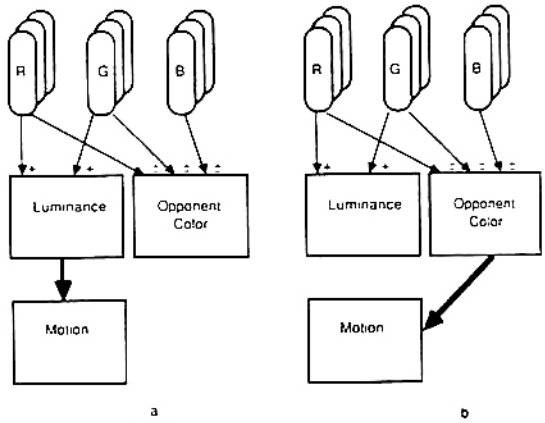

Fig. 1. Outputs of **R, G, B** cones are subtracted from each other in the opponent-color channel, and the outputs of the **R** and **G** cones are added in the luminance channel. (a) Our first moving test display [Figs. 2(c),(d)] stimulated only the luminance channel. Result: the equiluminance point was shifted for color defectives showing the luminance output for the red (green) stimulus was weak in protans (deutans). (b) Our second moving test display [Figs. 2(e), (f)] stimulated only the opponent-color channel. Results: the equivalent contrast (see text) of an equiluminous colored grating was 8% for normals but zero for protans and deutans. Thus the opponent-color channels contribute to motion in normals but not in color-defectives.

II. Test 1: Luminance-Based Minimum Motion Test

We measured the relative luminosity of red and green by observing the apparent motion[13,14] and the resulting optokinetic eye movements produced by a special computer-generated display. The direction of apparent movement in our display depended on whether the red stripes appeared lighter or darker than the green stripes.[7]

A novel patented technique for heterochromatic photometry has been based on opposed movements[15] [Figs. 2(a) and (b)]. To measure the luminance of an unknown red light two square-wave gratings were superimposed, an unknown red and black grating drifting to the right and a calibrated green and black grating drifting to the left. The luminance of the green grating was varied until no net motion was seen, and at this point the red and green were equiluminous. This technique[15] encounters one major problem: as red and green approach equiluminance the motion signal decreases, but the amount of counterphase luminance flicker increases and tends to mask the motion, leading to a loss of sensitivity and greater variance in equiluminance settings. We solved this problem by in effect filling in the black bars with colors. The black bars of the green grating were filled in with dark red bars, and the black bars of the red grating were filled in with dark green bars, giving the luminance profile shown at the top of Fig. 2(c).

We generalized this technique by devising a family of pairs of superimposed drifting gratings. Our gratings could be colored gratings of red and green bars or blue and yellow bars. Their luminance profiles could be sinusoidal or square wave, and they could either drift in real motion or shift abruptly in apparent motion, making jumps of one-quarter cycle (half of a bar width). But in every case the two gratings had the same spatial frequency and always moved in opposite directions. To understand what follows, remember that the summed output of any two gratings depends on the relative spatial phase of the two gratings. For example, Fig. 2(a) shows a red/black luminance grating superimposed on a green/black luminance grating. When they are in phase, with the red bars of the first grating exactly superimposed on the green bars of the second grating at times $T2$ and $T4$ in Fig. 2(a), they sum to a yellow/black luminance grating. When they are in antiphase, with the red bars of the first grating superimposed on the black bars of the second at times $T1$ and $T3$, they sum to a red/green grating.

A. Description of the Stimulus

We shall now describe test 1 in two ways, which sound different but are mathematically identical [see

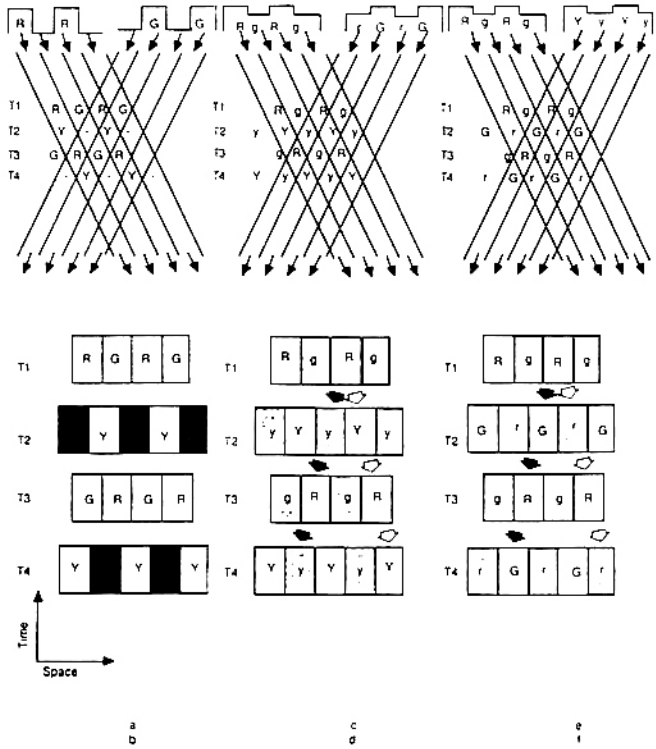

Fig. 2. Counterdrifting gratings used to study color responses. Time runs down the page. (a) A red/black grating drifting to the right superimposed on a green/black grating drifting to the left (Gregory, 1974). Luminance profiles of these two are shown at the extreme top. At times $T1$, $T3$ the green bars are exactly out of phase with the red bars, giving a combined grating of red and green bars. At times $T2$, $T4$ the red and green bars are exactly in phase and combine into a yellow/black grating. These four times are shown again in (b). (b) A special case of (a) in which the gratings jump in 90° phase steps. (c) Our test 1. Two red/green gratings drift in opposite directions, and red/green luminosity is varied (not shown) until perceived motion disappears at equiluminance. At times $T1$, $T3$ the gratings combine in phase into a single red/green grating, and at times $T2$, $T4$ they combine in antiphase into a single light yellow/dark yellow luminance grating. These four times are shown again in (d). (d) Combined grating exposed in a repetitive sequence at times $T1$ through $T4$. Positions of the gratings were superimposed, not displaced vertically as illustrated. Each grating was displaced sideways by one-quarter cycle (half a bar width) from its predecessor. Direction of apparent motion, shown by the arrows, depended on the luminance (not hue): (1) When the red bars were darker than the green bars (dark arrows), the dark red bars in the grating at time $T1$ (or $T3$) appeared to jump leftward to the dark yellow bars in the grating at time $T2$ (or $T4$). (2) Conversely when the red bars were lighter than the green bars (light arrows) they appeared to jump rightward to the light yellow bars. (e), (f) Our test 2. Red/green grating drifted to the right, and an adjustable luminance grating of light and dark yellow bars drifted to the left. At times $T1$, $T3$ these combined into light red and dark green bars and at times $T2$, $T4$ into dark red and light green bars. These four times are shown again in (f). (f) When the color-based rightward motion (light arrows) was stronger than the luminance-based leftward motion, red and green bars were seen moving to the right and changing in luminance. When luminance outweighed color, light and dark bars were seen moving to the left and changing in hue (dark arrows). The contrast setting of the yellow luminance grating at which no net motion was seen was defined as the "equivalent luminance contrast" of the red/green grating. This measures the strength of the motion signal produced by the colored grating. Normal subjects set the equivalent luminance contrast to 6–13%, but color defectives set it to zero, showing that they had zero output from opponent-color channels into motion.

Figs. 2(c),(d)]. Each decomposition reveals a different aspect of the test.

1. Two Countermoving Gratings [Fig. 2(c)]

A single grating of light red bars and dark green bars drifting to the right was superimposed on a single grating of dark red bars and light green bars that drifted to the left. This arrangement preserves the motion signal cue to equiluminance but nulls out the masking luminance flicker, greatly improving sensitivity.

As the two red/green gratings drifted in opposite directions over each other they moved in and out of spatial phase. At the instant $T1$ when the two gratings were in phase, with the red bars of the two gratings exactly in register, they summed to produce a combined grating of red and green bars. At the instant $T2$ when the two gratings were in antiphase, with the red bars of one grating in register with the green bars of the other grating, they summed to produce a combined grating of light and dark yellow bars. Subjects adjusted the relative luminosity of red and green (not shown in Fig. 2) until at equiluminance the perceived motion vanished.

The two component gratings could either drift in continuous real motion or make one-quarter cycle jumps in apparent motion. (One quarter of a spatial cycle is equal to half of a bar width.) The special case in which two square-wave gratings made such jumps can be redescribed as follows:

2. Four-stroke Cycle of a Single Grating [Fig. 2(d)]

A single jumping grating changed abruptly in color and luminance on each jump, being red/green at times $T1$, $T3$ when the two components were in spatial phase and being light yellow/dark yellow at times $T2$, $T4$ when the two components were in antiphase. [Note that the stimuli at times $T1$ through $T4$ in Fig. 2(d) are identical to the stimuli at times $T1$ through $T4$ in Fig. 2(c).] Thus a colored square-wave grating of vertical red and green stripes was presented briefly and then replaced by an overlapping grating of light and dark yellow stripes displaced by half of a bar width to the right [Fig. 2(d)]. Adding two more gratings produced a continuous four-stroke cycle, like a movie four frames long, which was displayed on a computer-controlled TV. Subjects who viewed this stimulus reported apparent motion in a direction that depended on the relative luminance (not the hue) of the red and green stripes.[13] If the red stripes appeared darker than the green stripes, the red stripes were seen as jumping to the left into the succeeding dark stripes

(black arrows in Fig. 2(d)). If the red stripes appeared lighter than the green stripes, they were seen as jumping to the right into the succeeding light stripes (white arrows in Fig. 2(d)). If the red and green stripes were of equal luminance, no motion was seen. Thus the direction of apparent movement depended on whether the red stripes were more or less luminous than the green stripes.

B. Procedure

We have used test 1 to measure the relative luminosity of red and green and of blue and yellow in normal[7] and defective[6] adults and in infants.[8,9] It is well known that color blindness affects not only apparent hue but also apparent brightness. For example, red light looks dimmer to a red-defective than to a normal eye. The relative luminosity of red and green measured with flicker photometry[16] gives three different distributions, one for normals, one for protans, and one for deutans, and our minimum motion technique gives results in adults similar to the standard minimum-flicker technique[16] but is slightly easier to use. As a test for screening color blind adults it was not quite as effective as the Isihara and AO pseudoisochromatic plates.[6] Although the test was able to identify all observers classified as protans by the Isihara and AO plates and even to identify the protans among those who were ambiguously classified by the Isihara and AO plates, there was a significant overlap between the distribution of equiluminance points on our test for the normals and deutans. Clearly, several mild deutans would have been classified as normal on our test. This overlap of normal and deutan luminosity functions has been previously reported.[17,18] As we shall see, our second test dealt with this problem.

In our experiments with infants,[8,9] we measured the luminous efficiency of red vs green ($n = 22$) and of blue vs yellow ($n = 16$) for 1–3 month-old babies and of both color pairs for one 3-month-old boy destined to be color blind because of a deutan mother. The monitor phosphor was *P*22. CIE chromaticity coordinates were red $x = 0.68$, $y = 0.32$; green $x = 0.28$, $y = 0.60$.

Each infant sat on its mother's lap 30 cm in front of a 64 × 64° display filled with 1° stripes, which had an equivalent speed of motion of 15°/s. A hidden observer watched the baby's eyes and judged whether it followed to the left, to the right, or neither. The observer and mother could not see the stimuli. We tested each baby with five luminosity ratios bracketing the normal adult equiluminance ratio (see Fig. 3). Base line adult settings were obtained from the normal mothers by first observing their eye movements and then asking them to report the direction of motion they saw.

C. Results

The equiluminant points of normal mothers and their babies (Fig. 3, top) differed by an insignificant 4% or less, and we found no developmental changes or sex differences ($p > 0.1$ on all two-tailed t-tests). Arrows on the graph indicate the mean equiluminant point and S.E. for normal mothers and their babies. For comparison, arrows at the bottom indicate mean values for adult protans and deutans.[19] Babies and their mothers gave completely overlapping distributions (Fig. 3, bottom).

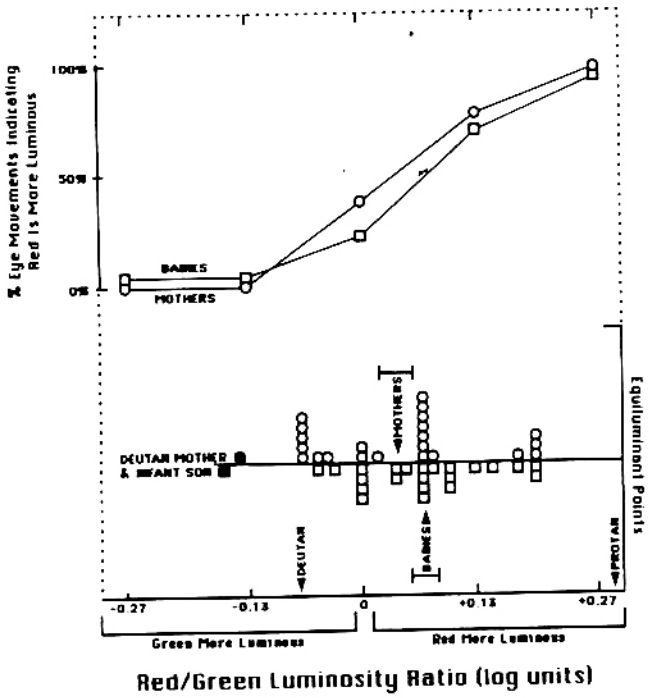

Fig. 3. Top. Equiluminance results for red vs green. Abscissa shows red/green luminosity ratio: positive values indicate relatively more red in the stimulus, negative values more green. Ordinate shows percent of trials per test on which subjects' eye movements corresponded to red more luminous. Data shown are the means of twenty-two mothers (○) and twenty-two babies (□). Bottom. Each symbol represents the equiluminant point for one subject. Data for the normal mothers (○) and the deutan mother (●) are shown above the line; data for the babies of the normal mothers (□) and the son of the deutan mother (■) are shown below the line. Arrows on the graph indicate the mean equiluminant point and S.E. for normal mothers and their babies. For comparison, arrows at the bottom indicate mean values for adult protans and deutans.

Results for the son of the deutan mother were very different. His equiluminant point was strongly shifted in the deutan direction and lay outside the range of values observed in the other infants or in any normal adult we have ever tested. The equiluminant point for the deutan mother was also shifted in the expected direction, although like some previously tested deutans, her results just overlapped the normal range.[17]

The similarity between the data for normal adults and their babies suggests that the relative contributions of cones to the luminance channels are established very early and persist from 1 to 3 months of age until adulthood. Because our method assesses the luminance, not the hue, of colored lights, it tells us nothing about opponent pathways (which signal hue, not luminance), nor, of course, can we say whether babies "see in color." Although this test, unlike our second test, bypasses the color channels, it is sensitive to cone imbalances which presage defective color vision.

III. Color-Based Minimum Motion Test: Test 2

Test 2 consisted basically of an equiluminous red/green grating drifting in one direction, superimposed on a light yellow/dark yellow luminance grating drifting in the opposite direction. The purpose of the test was to measure the strength of the color response of the motion system. For normals, the motion of the color grating could be nulled by the opposing motion of the luminance grating when it had ~10% contrast; on the other hand, only 1% or less luminance contrast was required for (color defective) anomalous trichromat observers. This test was, therefore, able to discriminate both protans and deutans from normals.

A. Description of the Stimulus

This test, like test 1, can also be decomposed in different ways:

1. *Two Countermoving Gratings [Fig. 2(e)]*

Test 2 can be decomposed into an equiluminous red/green grating drifting in one direction, superimposed on a light yellow/dark yellow luminance grating drifting in the opposite direction. By adjusting the red/green luminosity ratio, the subject made the combined stimulus move in a left, right, or null direction, as described in Sec. III. B.

2. *Four-Stroke Cycle of a Single Grating*

In the special case where the spatial and temporal waveforms were square wave, the stimulus of Fig. 2(e) resembles the four-stroke cycle shown in Fig. 2(f). At time $T1$ a red/green grating is flashed up in which the red bars are lighter than the green. This is replaced at time $T2$ by a red/green grating, shifted one-quarter cycle (half a bar width) to the right. Now the red bars are darker than the green. (The brightness of the colors reverses because of the change in relative spatial phase between the two component gratings just described in the previous paragraph. The red bars of the red/green grating were in exact register with the light bars of the yellow luminance grating at time $T1$ but with the dark bars at time $T2$.)

Notice that the stimulus contains two opposed signals of potential motion. Luminance-based motion could be seen to the left from the light (red) bar at time $T1$ to the nearest light (green) bar at time $T2$. However, color-based motion could be seen to the right from the (light) red bar at time $T1$ to the nearest (dark) red bar at time $T2$. Adding two more frames at times $T3$ and $T4$ gives a continuous cycle of apparent motion which continues indefinitely. Thus the test pits luminance-based motion to the left against color-based motion to the right. This is quite different from test 1 [Fig. 2(d)], where the visible motion in either direction was luminance-based.

B. Procedure

If the two component gratings had both been luminance gratings drifting in opposite directions, the net direction of motion would depend on the relative contrast of the gratings. If the components have equal contrasts, neither direction is seen—counterphase flicker is seen instead. To measure the contrast of an unknown leftward grating we could adjust the contrast of a known calibrated grating that drifted to the right. The contrast setting that gave a motion null, let us say 10%, would, therefore, be equal to the contrast of the unknown grating. We used this technique to evaluate the contribution of an equiluminous colored grating to motion. We define the "equivalent luminance contrast" of the colored stimulus as the contrast of the moving yellow luminance grating that just nulls the motion of the colored grating.

We used the stimulus shown in Fig. 2(e). We fixed the contrast of the leftward moving yellow luminance grating at 10% and varied the red to green luminance balance of the rightward moving colored grating through a range that must include equiluminance. [In Fig. 2(e) red is shown as more luminous than green, and the change in red/green luminosity ratio is not shown.] Conceptually we were putting a rightward moving luminance grating on top of the colored grating and observing the points at which this combined stimulus just nulled the motion of the luminance grating. If color makes no contribution to motion, it is as if it were not there at all, and these two oppositely moving luminance gratings would have to have equal contrasts for their motions to cancel. On the other hand, if the color is making a contribution, say 8%, only 2% imbalance of red and green (the rightward luminance grating) is necessary to cancel the opposing motion. So from the known 10% leftward luminance contrast and the measured 2% red vs green contrast at the null point, we derive the equivalent luminance contrast of the colored grating to be 8%. In fact, the null luminance is measured twice, once when red is more luminous than green by say 2% and again when green is more luminous than red, also by 2%. Halfway between these null points is the equiluminance point that we were seeking, and from the separation between the two null points we derive the equivalent luminance contrast. When red is much lighter than green, as shown in Fig. 2(e), the red/green grating has a high luminance contrast of more than 10% added in to it, which swamps the yellow grating so light red and dark green bars are seen moving to the right and varying in luminance as they move. As the green luminance is gradually increased, bringing red and green to equiluminance, the effective contrast of the red/green grating falls below 10% and is overcome by the yellow grating; thus the motion reverses its direction, and light and dark bars are seen moving to the left and changing in hue as they move. Finally, as the green is lightened further until it is much lighter than the red, luminance contrast of more than 10% is added to the colored grating, and the motion reverses once more, so dark red and light green bars are seen moving to the right and changing in luminance as they move. Whereas the stimulus of test 1 reversed direction once, at equiluminance, this new stimulus reverses direction twice, once on either side of equiluminance. The spread between these two reversal points indicates the strength of the color contribu-

tion to motion: the closer they are, the stronger the color contribution.

C. Results

We found[10] that in color-normal adults the motion of the red/green grating had an equivalent luminance contrast of ~10% for 0.5-cycle/deg gratings moving at 2 Hz (Fig. 4). We also ran the test for blue/yellow gratings and obtained an equivalent luminance contrast of 4%. For these stimuli we used a 2° fixation bull's-eye to cover the macular area of yellow pigment.

The results were very different for anomalous trichromat observers (four protans and five deutans). Unlike the normals, these color deficient observers showed little or no contribution of color to motion for red/green gratings, either for deutans or protans. These red/green gratings were not invisible to the observers. They could still see them, although not so well as color-normal observers could. More surprisingly, these color deficient observers also showed little or no contribution of the blue/yellow stimuli to motion, even though they could discriminate these colors almost as well as normals. This suggests that part of the visual loss in our protans and deutans may have been not a loss of output from the **R**, **G**, and **B** cones into the opponent-color channels but from the opponent-color into the motion channels.

Figure 4 shows that the equivalent luminance contrast measure allowed a clear separation of normals from color deficient observers. When we also included the equiluminance settings of these observers on the x axis, we can separate these color deficient observers into deutans and protans. Note that neither measure alone could separate all three groups. The combination of the two measures in Fig. 4 is reminiscent of the analysis of chemicals by 2-D paper chromatography, in which two different solvents are applied to the paper at right angles.

We finish by summarizing the differences between test 1 and test 2. First, the displays differed. It is confusing (although true) that our test 1 can be decomposed in two ways: either into two red/green gratings moving in opposite directions or into a four-stroke cycle with two red/green and two light yellow/dark yellow gratings. On the other hand, our test 2 could be decomposed either into two gratings moving in opposite directions, one being red/green and the other being light yellow/dark yellow, or into a four-stroke cycle of light red/dark green and dark red/light green gratings. Neither decomposition is more fundamental.

Second, the purposes and results of the two tests differ. Test 1 was a minimum-motion test of heterochromatic photometry which yielded the same equiluminance points as flicker photometry.[16] It showed, as other tests do, shifted equiluminance points for color-blind observers whether they were adults or babies. Test 2 also measured the equiluminance point, but it did something else as well, which other tests do not do: it found an input from opponent-color into motion for normals but not for color defective observers. Since, like test 1 it is motion-based, it should also be suitable for evaluating colour vision in babies and in other preverbal or nonverbal populations using optokinetic nystagmus.

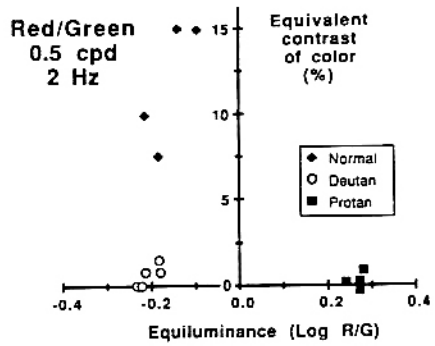

Fig. 4. Horizontal axis shows equiluminance settings derived from our second technique, while the vertical axis measures the effective luminance contrast of the same colored stimulus. Horizontal axis: To find an equiluminance match, protans (■) needed much more red than normals (♦), while deutans (○) needed slightly more green. Vertical axis: a red/green grating drifting to the right was superimposed on a low-contrast luminance grating that drifted to the left. Normal, protan, and deutan observers adjusted the red/green luminosity ratio to achieve a motion null. From this an effective luminance contrast of the color grating was derived which was 6–13% for the normals but near zero for the protans and deutans. Thus the opponent-color channels gave a stronger input into motion perception for normal than for color-defective observers.

Table I. Summary of Stimuli Used

Test	Drifting components	Subjects run	Tests for	Four-stroke cycle components
1	$R/G\rightarrow$ $+R/G\leftarrow$	Babies[16,17] and adults[6,8]	Equiluminance point of R&G	R/G $+Y/y$
2	$R/G\rightarrow$ $+Y/y\leftarrow$	Adults[10]	Equivalent contrast = Strength of opponent-color input into motion and equiluminance point	R/G $+R/G$

Table I summarizes the stimuli we have used. We omit the variations produced by real vs apparent motion and by square vs sinusoidal luminance profiles in space and time.

IV. Conclusions

Our first motion test is luminance-based and has shown the following:

(1) Nonverbal populations such as babies can be successfully tested.

(2) The equiluminance point for red and green is shifted for color defectives. Protans need more red light and deutans more green light to make an equiluminance match.

(3) Our one case provides encouraging evidence that individual color-blind babies can be readily identified.

(4) The relative contribution of **R** and **G** cones to the luminance pathways is already in place at the adult level within the first 3 months of life.

Our second motion test is color based and has shown that:

(5) Deutans who are missed by the first test are correctly diagnosed by the second test.

(6) Opponent-color mechanisms contribute directly to motion for normals but not for color-deficient observers.

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INFRARED SYSTEMS DEVELOPED TO TEST GALLIUM ARSENIDE WAFERS

Detecting flaws in gallium arsenide (GaAs) semiconductor materials should be easier with two polarized infrared light systems developed by NBS Semiconductor Electronics Division researchers. Both are nondestructive methods wafer manufacturers can use to screen materials before marketing. One system can examine an entire wafer, while the other employs a 75- to 600-X microscope to view isolated wafer portions. Both systems allow digital storage of images and the use of false-color graphics to represent wafer characteristics such as variations in the transmitted infrared intensity, which could indicate potential problems. GaAs wafer applications in high-speed electronic and optoelectronic devices are growing rapidly, but production of the near-perfect GaAs crystals needed for optimum performance is not as advanced as with the older silicon technology. The two NBS systems can aid in production control by pinpointing wafer flaws and inhomogeneities. Bureau researchers are using the infrared techniques in-house, but will also assist industries in setting up their own systems.