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Computer-Generated Screening Test for Colorblindness

Two new techniques that test color vision using motion stimuli have allowed us to exploit optokinetic nystagmus as a response measure. We are now able to screen for color-vision deficits in adults and in nonverbal infants by observing their eyes as they watch a computer-controlled TV display. It was shown that the relative contribution of red and green cones to the luminance channels is already in place within the first few months of life. Colorblind individuals could be readily identified; in our first test they made abnormal equiluminance matches between red and green, and in our second test their opponent-color pathways, unlike those of normal individuals, gave no measurable input into motion perception.

Introduction

There are at least two standard techniques for measuring colorblindness. For instance, the Ishihara and American Optical (AO) pseudoisochromatic plates rely upon the shifts in apparent hue seen by the colorblind. These allow for quick and convenient screening of cooperative human adults who can read. Measuring colorblindness in infants and animals is much more difficult and generally requires some form of discrimination training.[1]

We have devised two new tests of colorblindness that are based on moving stimuli. In the first test, a difference in color luminosity produces a reversal in the direction of the stimulus motion[2] while in the second, the strength of the opponent-color-channel response is converted into a reversal in motion direction. The significance of both these tests is that color vision is tested by a motion stimulus and we can therefore use the natural motion-tracking responses of the observer (optokinetic nystagmus) to diagnose colorblindness in nonverbal populations such as infants[3] and animals.

Luminance-Based Minimum-Motion Test

Colorblindness affects not only apparent hue but also apparent brightness. For instance, green light looks dimmer to a green-blind than to a normal eye. The relative luminosity of red and green measured with flicker photometry[4] gives three different distributions, one for normals, one for protans (red-weak) and one for deutans (green-weak), although the deutan distribution overlaps somewhat with that of the normals.[5,6]

Our minimum-motion technique gives results similar to those of the standard minimum-flicker technique[4] but is slightly easier to use. Results are also consistent with those from the Ishihara and AO plates.[2]

We measured the relative luminosity of red and green by observing the apparent motion,[7,8] 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.[9] A colored square-wave grating of vertical red and green stripes was presented briefly and then replaced by an overlapping grating of light

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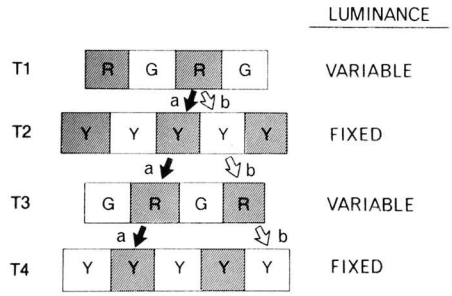

FIG. 1. Four coloured gratings were exposed in a repetitive sequence at times *T1* through *T4* on the screen of a computer-controlled T. V. Positions of the gratings were superimposed, not displaced vertically as illustrated. Each grating was displaced sideways by one-quarter cycle (half a bar width) from its predecessor. Direction of apparent motion, shown by the arrows, depended on the luminance. When the red bars were darker than the green bars, 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*) (a). Conversely, when the red bars were lighter than the green bars they appeared to jump rightward to the light yellow bars (b).

and dark yellow stripes displaced by half a bar width to the right (Fig. 1). Adding two more gratings produced a continuous four-stroke cycle, like a movie four frames long, which was displayed on a computer-controlled TV. Frames *T1* and *T3* were gratings of red and green stripes, and frames *T2* and *T4* were gratings of light and dark yellow stripes.

Subjects who viewed this stimulus reported apparent motion in a direction that depends on the relative luminance (not the hue) of the red and green stripes.[10] If the red stripes appear darker than the green stripes, the red stripes are seen as jumping to the left into the succeeding dark stripes (black arrows in Fig. 1). If the red stripes appear lighter than the green stripes, they are seen as jumping to the right into the succeeding light stripes (white arrows in Fig. 1). If the red and green stripes are of equal luminance, then no motion is seen.

Adult subjects used a joystick to adjust the relative luminance of red and green until no motion was seen. Our method was as reliable as minimum-flicker photometry,[4] and the direction of movement seen told the subject in which direction he should adjust the luminance. As a test for screening colorblind adults it was not as effective as the Ishihara and HRR pseudoisochromatic plates.[2] Although the test was able to identify all observers classified as protans (red-weak observers) by the Ishihara and HRR plates and even to identify the protans among those who were ambiguously classified by the Ishihara and HRR plates, there was a significant overlap between the distribution of equiluminance points on our test for the normals and deutans (green-weak observers). 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.[5,6]

For non-verbal subjects such as babies we exploited the optokinetic eye movements elicited by our display, which were in the direction of the apparent (perceived) movement.[2] We measured the luminous efficiency of red and green for 22 one- to three-month-old babies and for one three-month-old boy destined to be colorblind because of a deutan mother.

The infants sat on the mother's lap in front of a 64° × 64° display filled with 1° stripes, which had an equivalent speed of motion of 15°/sec. A hidden observer watched the baby's eyes and judged whether he 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. 2). Baseline 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.

The equiluminant points of normal mothers and their babies (Fig. 2, 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 standard error for normal mothers and their babies. For comparison, arrows at the bottom indicate mean values for adult protans and deutans.[11] There was complete overlap between the distributions for infants and for adults (Fig. 2, bottom).

In contrast, the son of the deutan mother showed an equiluminant point that fell outside the range of values observed in the other infants or in any normal adult we have ever tested. The shifts were in the direction expected for a

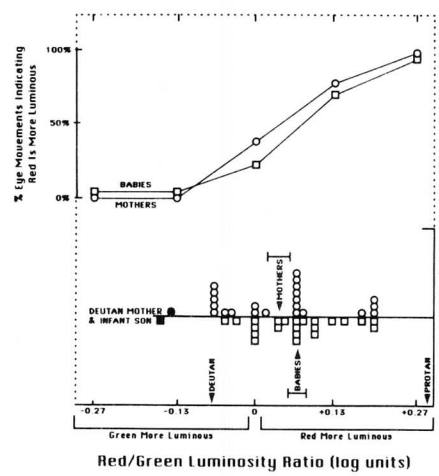

FIG. 2. Top. Equiluminance results for red *versus* green. Abscissa shows red–green luminosity ratio: positive values indicate relatively more red in the stimulus, negative values more green. Ordinate shows percent of trials per test on which subjects' eye movements corresponded to red more luminous. Data shown are the means of 22 mothers (○) and 22 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 standard error for normal mothers and their babies. For comparison, arrows at the bottom indicate mean values for adult protans and deutans.

deutan observer.[11] 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.[11]

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 1–3 months of age until adulthood. Because our method assesses the luminance, not the hue, of colored lights, we can draw no conclusions about opponent pathways (which signal hue, not luminance), nor, of course, can we say whether babies "see in color." In fact, our method bypasses the color channels, but it is sensitive to cone imbalances which presage defective color vision.

We have also used our luminance-based, minimum-motion test to evaluate the spatio-temporal properties of the contributions of the red-, green-, and blue-sensitive cones to the luminance channel.[12] Observers viewed a 2° field through a Powell five-element achromatizing lens and adjusted the relative luminance of the two colors being tested (red vs. green, red vs. blue, or green vs. blue) to achieve a motion null. We modified our stimulus to be sinusoidal, both spatially and temporally, and found that there was no significant spatial-frequency effect on the red vs. green equiluminance point, while there was an important temporal frequency effect. This suggested that equiluminance matches made at one temporal frequency will not hold at a different temporal frequency, that is, a match made by heterochromatic flicker photometry at 15 Hz will not be an acceptable match for a static image. Kelly[13] has made this same point using a different procedure.

Equiluminance ratios involving blue varied strongly as a function of spatial frequency. More blue amplitude was required for a match at higher spatial frequencies, suggesting that the low sampling density of the blue cones was reducing the effectiveness of the stimulus amplitude. When we bleached the blue-sensitive cones, however, this spatial-frequency dependency remained and, in fact, the equiluminance matches were unaffected. We concluded that the blue-sensitive cones were not contributing to the luminance pathway, as had been previously argued by Eisner and MacLeod[14] but disputed by Drum.[15] We were able to identify the source of the spatial-frequency effect on the equiluminance matches involving blue as the inhomogeneity of the macular pigmentation within the 2° macula itself.

Opponent-Color Based Minimum-Motion Test

We devised a second test[16] to overcome the weakness of the first in separating deutans from normals. In this second test, an equiluminous color grating drifts to the right while a low-contrast luminance grating drifts to the left. Full details of the technique will be published later.

We have found that for normal observers the perceived direction of motion is to the right, i.e., the direction of the color grating, when the oppositely moving luminance grating has less than about 8% contrast. At about 8% contrast, the direction of motion is ambiguous, and for luminance

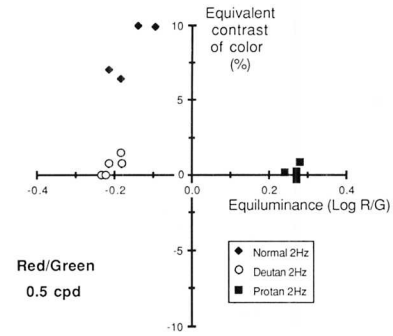

FIG. 3. Horizontal axis shows equiluminance settings derived from our second technique, while the vertical axis measures the effective luminance contrast of the same 10° colored stimulus at 2 Hz and 0.5 cpd.

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 equiluminous 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 contrast of the luminance grating to a motion null. This gave the *effective luminance contrast* of the color grating, which was 6–10% for the normals but near zero for the protans and deutans. Thus the opponent-colour channels gave a stronger input into motion perception for normal than for colorblind observers.

contrast of greater than 8% the leftward motion of the luminance grating is perceived and that of the color grating is invisible.

We consider this measure to be an indication of the *effective luminance contrast* of the color grating for the normal observer. The settings are easy to make and reliable. We have not yet tested this motion stimulus for its ability to drive optokinetic nystagmus but we feel that it will be able to do so, enabling us to make these measurements of effective luminance contrast of a color grating on nonverbal populations.

Of greatest interest, of course, was the effective luminance contrast that we would find for color gratings with protan and deutan observers. The results were very clear: All observers classified by the Ishihara plates as red–green defective, whether protan or deutan, had effective luminance contrast values near zero. In Fig. 3 we have plotted the effective luminance contrast of a 10° red–green stimulus at 2 Hz and 0.5 cpd against the equiluminance ratio for this same stimulus. We see three clear groups. The normals all have effective luminance contrasts of 6 to 10% while the protans and deutans have values around zero. In addition, the protans are easily distinguished from the deutans by the large differences in equiluminance point that was found by the previous technique.

This second test clearly identifies those deutans who may be missed by our first test and by many standard tests because their results overlap with those of the normal distribution.[5,6] In addition, it shows that in normal observers, but not in the colorblind, the opponent-color pathways provide a measurable input into motion perception.[17] We are

currently developing a version of this test for diagnosing infant color deficiencies.

Implementation

The tests we have described would be very difficult to present using optical methods, but lend themselves easily to computer-controlled video display. The limitation of the three phosphors commonly available in video monitors is not serious, as the color gamut available is sufficient for the needs of the two tests; monochromatic lights are not essential to their success.

The tests themselves are insensitive to moderate misalignment of the red, green, and blue color images on the monitor, and this is a significant advantage compared to tests such as the minimum border.[4]

The computer-graphics systems required are becoming increasingly affordable and, more important for infant research, increasingly portable. The tests can be implemented with acceptable measurement precision on an Amiga or an IBM PC with add-on graphics cards. The minimum requirements are at least four colors on screen at any one time and a color-lookup table with at least sixteen intensity levels for each of the red, green, and blue outputs.

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