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A New Test of Luminous Efficiency for Babies

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We used the minimum motion method devised by Anstis and Cavanagh (1983) to measure the luminous efficiency of red and green and of yellow and blue for "normal" 1- to 3-month-old babies and for one 3-month-old boy destined to be color-deficient because of a deutan mother. Subjects watched a display which created apparent motion, the direction of which depended on the relative luminance of the colors. To determine the equiluminant points, we observed the optokinetic nystagmus elicited by the display as the relative luminance of the colors was varied. The equiluminant points of the normal mothers and their infants were similar to each other but different from those of the deutan mother and her son. Our new method demonstrates the early maturation of input from red and green cones into achromatic pathways. It can also be used to identify some color-deficient infants. Invest Ophthalmol Vis Sci 30:297–303, 1989

Although young infants do have some color vision, they differ from normal adult trichromats. Even newborns can discriminate some wavelengths from white,[1] and hence at least two receptor mechanisms must be functional at birth. Yet during the first 1 to 2 months of life, infants appear able to make chromatic discriminations only with large stimuli,[2,3] and even with large stimuli, have difficulty in making Rayleigh discriminations (discriminating a 589 nm yellow from a 650 nm red or from a 550 nm green) and apparently fail to make a number of other discriminations (the discrimination from white of 470 or 475 nm blue, of 538 or 561 nm yellow-green, or of a mid-purple, and the discrimination of a tritan pair, namely a 416 nm blue from a 547 nm green-yellow).[1–6] Although these studies make clear that young infants' color vision is limited, it is difficult to identify the cause of the limitation because their behavior does not match that of adults with any congenital color deficiency.

To investigate whether some of these limitations are caused by immature achromatic pathways, we examined babies' luminous efficiency. Luminous efficiency is known to reflect the ratio of the contributions of red versus green cones to the achromatic or non-opponent pathways. (Under most conditions, blue cones do not contribute to the achromatic pathways).[7] In adults, luminous efficiency is typically measured by flicker photometry, which produces a function relating sensitivity to wavelength known as V_λ. We have tested infants' luminous efficiency with a new method, called minimum motion, which in adults yields the same functions as flicker photometry.[8,9] The results should indicate whether red and green cones are present during early infancy and whether the balance of their inputs into the achromatic pathways is adult-like. That balance is abnormal in adults with color deficiencies. For example, red light looks dimmer to a protan than to a normal adult because the long-wavelength-sensitive ("red") cones contribute relatively less than normal to the achromatic pathways.

Two previous studies of infants have based measurements of sensitivity across the spectrum on the latency of the visually evoked response to light of different wavelength.[10,11] Both reports indicate that infants are relatively more sensitive to short-wavelength light than are adults. In contrast, a behavioral study of increment sensitivity found that adults' relative sensitivity across the spectrum was similar to that of the two infants tested.[12] It is difficult to draw conclusions about underlying mechanisms from these studies, not only because of the discrepant results, but also because, under some conditions, measurements made with either method (the visually evoked response or increment thresholds) appear to depend on activity in both the achromatic and chromatic pathways, and, therefore, not to be true measures of luminous efficiency.[13–15]

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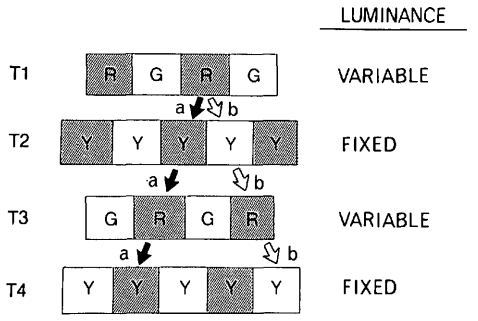

Fig. 1. Four colored gratings were exposed in a repeated sequence at times T1 through T4, on the screen of a computer-controlled TV. Positions of the gratings were superimposed, not displaced vertically as illustrated. Each grating was displaced sideways one-quarter cycle (half a bar width) from its predecessor. Direction of apparent motion, shown by the arrows, depends 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 into the dark yellow bars in the grating at time T2 (or T4). Conversely, when the red bars were lighter than the green bars, they appeared to jump rightward into the light yellow bars. To control against left-right response biases, the stimulus shown here was mirror-reversed left to right on half the trials. To test for yellow-blue responses, the bars were made yellow and blue at times T1 and T3, and light and dark gray at times T2 and T4.

Our new method uses a special computer-generated display to create apparent motion, the direction of which depends on whether stripes of one color are more or less luminous than stripes of the other color. When the two colors are equiluminous, then no motion is seen. Such a display elicits optokinetic eye movements in the direction of apparent movement and hence can be used with nonverbal subjects such as animals and babies. This technique has several advantages over previous methods. The response is based only on luminance and not on chroma, and hence, at least in adults, reflects only the relative contributions of red and green cones to the achromatic pathways. In addition, with this method the baby's equiluminant point is determined by a reversal of response (that is, following to the left versus following to the right), rather than by an absence of response. We used this method to compare the equiluminant points of normal mothers and their babies for red and green, and for yellow and blue. We also assessed the validity of the method by testing an infant boy destined to be color-deficient because his mother is a deutan.

Materials and Methods

Subjects

Normal mothers and their babies: We studied 38 "color-normal" mothers and their 1- to 3-month-old infants. All of the babies were full-term by maternal report (gestational age ≥ 38 weeks and birthweight ≥ 2500 g). We tested 22 mother-baby pairs with red-and-green stripes, and 16 with yellow-and-blue stripes. There were seven 1-month-olds (mean age = 31.6 days; range = 29–37 days; four tested with red/green; three with yellow/blue), 14 2-month-olds (mean age = 63.1 days; range = 56–70 days; eight tested with red/green; six with yellow/blue), and 17 3-month-olds (mean age = 90.0 days; range = 83–97 days; ten tested with red/green; seven with yellow/blue). There were 11 boys and 11 girls tested with red/green and six boys and ten girls tested with yellow/blue.

Deutan mother and her son: We also tested a deutan mother and her 3-month-old son. When tested with 25 Ishihara plates, the mother made 23 errors, including two omissions typical of a deutan; on the Hardy-Rand-Rittler, she missed all four red/green diagnostic plates and two of the three plates which indicate a medium red/green defect; and with an anomaloscope, she matched the yellow with a wide range of values which included abnormally high proportions of green. These results imply that she is a moderately severe deuteranomalous trichromat. Because this type of color defect is an X-linked recessive trait, she must have two defective X chromosomes, but not necessarily both leading to the expression of a deutan deficiency: one could be "protan" and one "deutan." Thus, her son is destined to be color-deficient but not necessarily a deutan.[16] The deutan mother and her son were tested with both red/green and yellow/blue stripes.

Control subjects: There were six control subjects: three of the investigators (aged 37–41 years) and three children (aged 5–16 years) who possess one emmetropic eye and one which had been rendered aphakic following surgery to remove a congenital (n = 1), developmental (n = 1), or traumatic cataract (n = 1). Control subjects made no errors on the Hardy-Rand-Rittler plates, and no more than two errors on the Ishihara plates.

Subjects were tested only after the procedure had been explained and a consent form had been signed by the subject himself, or in the case of babies, by a parent.

Display

The relative luminosity of the red and green for the babies was determined by observing the optokinetic eye movements elicited by apparent motion on a special computer-generated display. The direction of apparent movement depended on whether the red stripes appeared lighter or darker than the green stripes. 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 a bar width to the right, as shown in Figure 1. Adding two more gratings produced a continuous four-stroke cycle, like a movie four frames long, which was displayed on a Conrac (Covino, CA) high resolution video monitor controlled by a Grinnell (San Jose, CA) computer graphics system. Frames 1 and 3 were gratings of red and green stripes, and frames 2 and 4 were gratings of light and dark yellow stripes. The mean luminance was constant across frames. The yellow was composed of an equal mixture of the red and green from the red/green grating. This choice produced the least chromatic flicker when the two gratings were exchanged and hence minimized the possible masking of apparent motion by flicker.

Adults who view this display report apparent motion in a direction which depends on the relative luminance of the red and green stripes. If the red stripes appear darker than the green stripes, the red stripes are seen as jumping in one direction into the succeeding dark yellow stripes, for example to the left in Figure 1. If the red stripes appear lighter than the green stripes, they are seen as jumping in the other direction into the succeeding light yellow stripes, for example, to the right in Figure 1. If the red and green stripes appear equiluminous, then no motion is seen.

The relative luminosity of yellow and blue was determined in the same way, with gratings of yellow and blue bars which alternated with a grating of light gray and dark gray bars. (The "gray" was actually a bluish-gray composed of an equal mixture of the blue and yellow from the blue/yellow grating.)

The mean luminance of the display was 20 cd/m^2 for red/green and 12 cd/m^2 for yellow/blue. The CIE x and y coordinates of the television phosphors, as measured by spectroradiometry, were 0.60, 0.35 for red; 0.29, 0.60 for green; and 0.15, 0.07 for blue (see Fig. 2). The CIE x and y coordinates of the yellow luminance gratings of the red/green condition and for the yellow bars of the yellow/blue condition were 0.46, 0.43, and the coordinates of the gray luminance grating in the yellow/blue condition were 0.20, 0.15.

Method

Each baby sat on the mother's lap 30 cm from a 64° × 64° display (37.5 cm) filled with vertical stripes 2° (1.05 cm) wide, which had an equivalent speed of motion of 15°/sec. An observer watched the baby's eyes through an aperture beside the screen and judged whether he followed to the left, to the right, or neither. The judgment "none" was given if the baby showed no (or no consistent) optokinetic nystagmus while watching the display for 60 sec. The observer and mother were not able to see the stimuli.

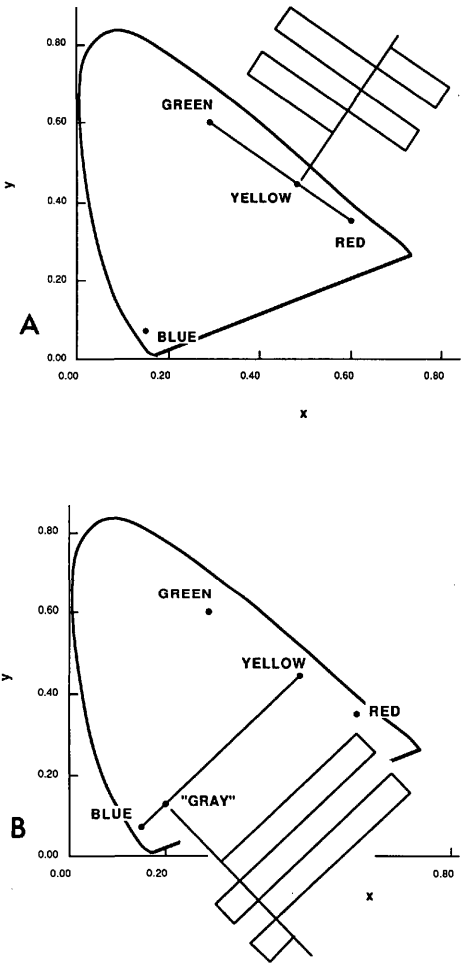

Fig. 2. (**A**) The bars of the red-green grating alternated between the red and green phosphor chromaticities while the yellow of the light yellow/dark yellow grating was produced by mixing red and green in the same luminance ratio as in the red/green grating. This ensured that the chromaticity of the light yellow/dark yellow grating always matched the mean chromaticity of the red/green grating, reducing chromatic flicker that might mask the perception of motion. The yellow point shown here is that of the mixture of red and green at photometric equiluminance. (**B**) The bars of the yellow/blue grating alternated between the blue phosphor and the mixture of red and green at photometric equiluminance while the yellow of the light gray/dark gray grating was produced by mixing blue and yellow in the same luminance ratio as in the yellow/blue grating. This ensured that the chromaticity of the light gray/dark gray grating always matched the mean chromaticity of the yellow/blue grating, reducing chromatic flicker that might mask the perception of motion. The "gray" (actually a bluish-gray) point shown here is that of the mixture of blue and yellow at photometric equiluminance.

Each test began with a practice grating of black-and-colored bars which gave a predictable direction of apparent motion and hence of eye movements. Data were collected only after the observer got four trials of this type in a row correct, a criterion usually met in the first four trials. We tested each baby with five luminosity ratios bracketing the normal adult equiluminance ratio (see Figs. 3, 4), and each of these ratios was presented twice in a randomized order. To control for any directional bias in the babies' eye movements, each stimulus was mirror-reversed so as to give leftward apparent motion during one presentation, and rightward apparent motion during the other. Whenever necessary, the observer switched the display from stripes to cartoons in order to attract the baby's attention. Twenty-one of the 38 babies completed the ten test trials a second time, and five babies completed a third set, in each case in a different random order.

Baseline adult settings were obtained from the normal mothers by the same procedure except that during each trial an observer first watched the eye movements and silently recorded a conclusion; the mother was then asked to write down the direction of motion she had seen. Each mother completed one run of the ten test trials.

Results

The equiluminant point for each subject was taken as the luminosity ratio at which OKN was observed equally often in the direction signifying red more luminous and in the direction signifying green more luminous. This was determined by interpolating between the two tested values that bracketed this 50% point. For these calculations, we used data from all test runs the baby had completed. Each of the 38 babies showed an orderly pattern of responding across the five luminosity ratios, with one, and only one, reversal of responding which identified an equiluminant point.

The sequence of ten test trials usually took 22 min (range 6 to 67 min) for the babies and 5 min for the mothers, and 38 out of 39 babies completed the sequence at least once. Reliability between runs was good: for the 21 babies who completed more than one run, the data were replicated on 92% of the repeated trials (range across babies = 70% to 100% of the repeated trials). In addition, the judged direction of the mothers' eye movements agreed on 99% of trials with their subjective reports of the direction of motion.

The results for red versus green are illustrated in Figure 3. The abscissa shows the luminosity ratio between the photometric luminances (log R/G) of the red and the green. Positive values indicate relatively more red in the stimulus, negative values relatively more green. The top half of the figure shows the percentage of trials per test on which the direction of subjects' eye movements corresponded to red more luminous. Data shown are the means for the 22 mothers and for their babies. Note the similarity between the curves for the mothers and the babies. The bottom half of Figure 3 shows the distribution of equiluminant points for red versus green. Each symbol represents the equiluminant point for one subject. Arrows on the graph indicate the mean equiluminant point and SE for normal mothers and for their babies. Note the complete overlap between the distributions for infants and for normal adults.

Figure 4 illustrates similar results for yellow versus blue. The data for two mothers with large refractive errors were excluded because control experiments (see below) indicated that such refractive errors could affect the equiluminant point for yellow/blue. Data shown are for the 16 babies and for the remaining 14 normal mothers. Note the similarity of the data for normal mothers and their babies in both parts of the figure.

For both red/green and yellow/blue, the distribution of equiluminant points for infants at each age and for adults overlapped completely. There were no sex differences and no obvious developmental changes, although the number of subjects at each age was too small to permit an adequate evaluation of any developmental changes ($P > 0.1$ on all two-tailed t-tests).

In contrast, the son of the deutan mother showed equiluminant points for both red/green and for yellow/blue which fell outside the range of values observed in the other infants or in any normal adult we have ever tested (see Figs. 3, 4). The shifts were in the direction expected for a deutan observer: at the baby's equiluminant point a normal observer would see the green (or blue) as more luminous than the red (or yellow). The equiluminant points for the deutan mother were also shifted in the expected direction, although like some previously tested deutans,[9] her results for red/green fell just inside the range of values we have observed in other normal subjects tested with this technique.

Control Experiments

Infants' luminous efficiency might differ from that of adults because cones contribute differently to the achromatic pathways, because clearer ocular media[17] and less dense macular pigmentation[18-19] filter light less before it reaches the cones, and/or because inaccurate accommodation[20] blurs the light. We ran control experiments to evaluate two of these non-neural interpretations. The data in each case were the subject's report of the direction of apparent motion.

To assess the effects of macular pigmentation, we compared measurements of the investigators made

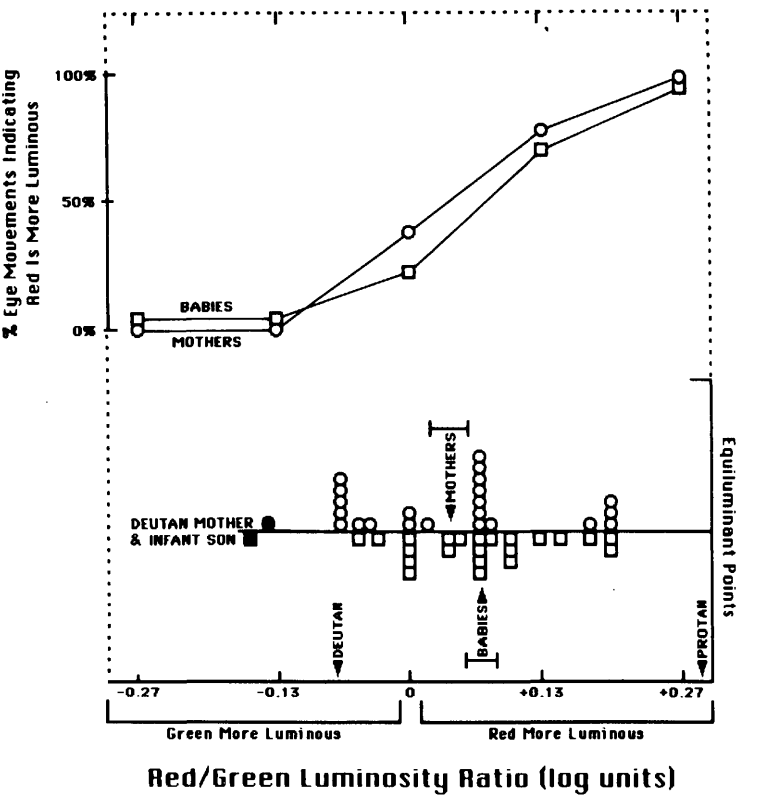

Fig. 3. Top: Equiluminance results for red versus green. Abscissa shows the $\log_{10}$ of the ratio of red and green photometric luminosities (R/G). Positive values indicate relatively more red in the stimulus, negative values more green. Ordinate shows percent of trials per test on which subjects' eye movements corresponded to red more luminous. Data shown are the means of 22 mothers (○) and 22 babies (□). **Bottom:** Distribution of equiluminant points. 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 SE for normal mothers and their babies. For comparison, arrows at the bottom indicate mean values for adult protans and deutans.[13]

with the normal display to measurements made while the subject was fixating the center of the display, the central 10° of which were blanked out so that only the peripheral retina was stimulated. The equiluminant points did not differ between these two conditions: for red versus green the difference in the three subjects tested ranged from 0.00 to 0.026 (log luminance ratio); for yellow versus blue the difference in the two subjects tested was −0.035 and −0.017. These results suggest that with such a large field (64°), macular pigmentation does not affect the results. They suggest, as well, that under these conditions, macular cones do not determine the equiluminant point.

To assess the influence of inaccurate accommodation and refractive errors, we tested the investigators under normal conditions and with +5D and +10D spherical lenses which, given a testing distance of ⅓ meter, would blur the display by about 2D and 7D, respectively. We also tested three aphakic subjects, who cannot accommodate, with the eye corrected progressively farther and farther away from the display. For red versus green, moderate misfocussings (focus 2 to 3D from the display) did not alter the response significantly in any of the five eyes tested: the change in the equiluminant point from the standard condition ranged from 0.00 to 0.026. Large misfocussings (focus 4 to 8D from the display) made little difference in four cases (change from the standard condition of 0.00 to 0.052) but in one aphakic eye the equiluminant point shifted by 0.145. In contrast for yellow versus blue, even moderate misfocussings (focus 2 to 3D from the display) altered the equiluminant point: it shifted by more than 0.087 in four of the five subjects tested. And with large misfocussings (4 to 8D) the equiluminant point shifted by more than 0.131 in four of the five subjects. Thus, moderate refractive errors appear to affect our yellow/blue measurements, but to have minimal effect on our red/green measurements. This may occur because chromatic abberation causes a greater difference in focus for yellow versus blue than for red versus green, a difference which becomes significant when the display is out of focus. Because of the results of this control experiment, we excluded one far-sighted mother (+4D) and one near-sighted mother

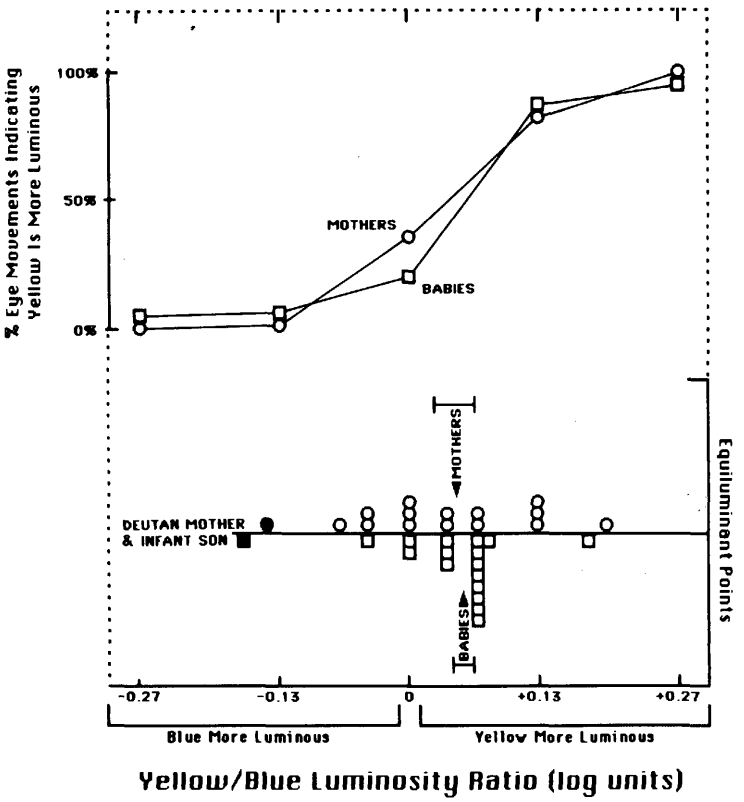

Fig. 4. Top: Equiluminance results for yellow/blue. Abscissa shows $\log_{10}$ of the ratio of yellow and blue photometric luminances (Y/B). Positive values indicate relatively more yellow in the stimulus, negative values more blue. Ordinate shows percent of trials per test on which subjects' eye movements corresponded to yellow more luminous. Other details as in Figure 3. Data are the means of 14 mothers (O) and 16 babies (■). **Bottom:** Distribution of equiluminant points for yellow/blue for normal mothers (O), their babies (□), the deutan mother (●), and her son (■). Other details as in Figure 3.

(−7D) from the results for yellow/blue. Misfocussing of the display is unlikely to have affected the yellow/blue results for the babies since 1- to 3-month-olds focus within 1.5D of a stimulus which is 30 cm away even though many are moderately hyperopic.[20,21]

Discussion

This new method is an effective test of luminous efficiency in babies: all but one of the 39 babies finished the ten-trial test; all of them showed one, and only one, reversal of response which defined an equiluminant point; and repeated testing yielded similar results across runs. In addition, control experiments indicated that non-neural factors (filtering of the light by macular pigmentation and, in the case of red versus green, inaccurate focussing) are likely to have only a minimal effect on the equiluminant point. Finally, the predictably deviant results from the son of the deutan mother indicate that the method is valid for identifying some color deficiencies in infants.

We found similar luminous efficiency in babies and in adults for red versus green and for blue versus yellow. The similar equiluminant points imply similarity between babies and adults in the ratio of inputs from red cones and from green cones to the achromatic pathways. As is apparent in Figure 1, the direction in which the bars appear to move is determined only by differences in luminance (not hue), and hence, by the contribution of cones to the achromatic pathways only. Under most conditions including those similar to ours, short-wavelength-sensitive ("blue") cones seem not to contribute significantly to the achromatic pathways.[7] Therefore, the results for both red/green and for yellow/blue will depend only on the relative contribution of red and green cones to the achromatic pathways. Consequently, if babies' luminous efficiency is similar to that of adults for red/green, then it would be expected to be similar for blue/yellow. A comparison of Figures 3 and 4 shows that was the case. This is further evidence that, in our set-up, non-neural factors, like any undetected refractive errors in the babies, have negligible effect on the location of the equiluminant point. Had such refractive errors been important, they would have shifted the babies' distribution of equiluminant

points for yellow/blue away from that for the mothers. Thus, our findings indicate that in early infancy, both red and green cones are functional and connected to the achromatic pathways. Moreover, the ratio of the contributions of red and green cones to the achromatic pathways is the same as in normal adult trichromats, at least for cones in the peripheral retina.

In contrast to our results, previous studies based on visually evoked responses have found that babies are relatively more sensitive than adults to short-wavelength light.[10,11] One explanation is that, unlike our method, visually evoked responses can be affected by activity in the chromatic, or opponent, pathways,[13] and that the chromatic pathways are immature during early infancy. An alternative possibility is that babies differ from adults in the contribution of macular cones to the achromatic pathways, and that those differences affect visually evoked responses but not our method. Control experiments indicated that with our method and a large display, macular cones did not determine the equiluminant point. Thus, our results demonstrate that when tested with a procedure which measures the luminous efficiency of the peripheral retina, babies' luminous efficiency resembles that of adults. Similarly, studies using visually evoked potentials have found that infants' sensitivity curves resemble those for the adult's parafovea, but not those for the adult's fovea.

We can draw no conclusions from our results about the absolute maturity of red and green cones or about opponent chromatic pathways (which signal hue, not luminance). Nor can we tell whether babies "see in color"; our test bypasses the opponent chromatic pathways but is sensitive to cone imbalances which presage defective color vision. But our results do rule out some models of the deficiencies reviewed in the introduction: the limitations on infants' color vision during the first 1 to 2 months cannot be caused by an absence of red or of green cones or by abnormalities in the achromatic pathways. Rather the limitations must reflect deficiencies in blue cones, in macular cones, in the input of cones to the opponent chromatic pathways, and/or in the preservation of information in those chromatic pathways.

Key words: color vision, luminous efficiency, infant vision, color blindness, heterochromatic photometry

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