

# Adult brightness vs. luminance as models of infant photometry: Variability, biasability, and spectral characteristics for the two age groups favor the luminance model

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When infants fail to make chromatic discriminations, do the characteristics of their performance minima coincide more closely with the properties of adult luminance matches or heterochromatic brightness matches? In addition to their spectral properties, adult luminance matches are typically characterized by relatively small individual differences, whereas brightness matches are believed to be both more variable and more biasable. Two complementary experiments were carried out on adults and 8-week-old infant subjects. Both groups were tested with small ( $1.5^\circ$  to  $4^\circ$ ) red and blue test fields of varying luminances, embedded in a white surround. In adults, heterochromatic brightness matches were measured. Individual differences spanned about 0.5 log units, and brightness matches could be biased by as much as 0.8 log units by varying the range of test field luminances. In infants, the locations of performance minima were measured. Individual differences spanned less than 0.1 log units, the mean performance minima coincided with predictions based on  $V_{10}(\lambda)$ , and the location of the performance minimum was nearly unaffected by the range of test field luminances used. Thus by all three criteria, these data suggest that infants' performance minima are mediated by luminance rather than by brightness signals. To date there remains no evidence that the infant visual system computes a brightness signal.

Keywords: photometry, motion photometry, heterochromatic brightness matching, infant vision, infant color vision, infant photometry, bias effects in brightness matching, variability of brightness matches

## Introduction

Color vision can be defined as the capacity to discriminate among lights of different wavelength composition on the basis of the difference in wavelength composition alone. But to show that a subject such as a human infant is responding to a difference in wavelength composition, one must equate the two fields on the *intensive* - brightness or luminance - dimension. Since brightness and luminance are two distinct entities, and since infants' brightness or luminance equations are not necessarily the same as those of adults, special steps must be taken to assure intensive matches.

The distinction between brightness and luminance is well established in the adult vision literature (Ives, 1912a, 1912b; Wagner & Boynton, 1972; Wyszeki & Stiles, 1982; Lennie, Pokorny & Smith, 1993). In theoretical terms, luminance signals are thought to arise from a weighted sum of L- and M-cone-initiated signals at a very early stage of visual processing. Brightness signals, on the other hand, are thought to arise from a recombination of

luminance and chromatic signals at a much more central processing level.

In the 1970s, Peeples and Teller (1975) developed a rigorous experimental paradigm for demonstrating color vision in infants. In this paradigm, a test field of one wavelength composition is embedded in a surround of another. Each infant is tested with a series of luminances of the test field intended to span the credible range of intensive matches. Discrimination of the test field from the surround at *all* relative luminances, including by inference the infant's intensive match, implies that the infant has chromatic signals sufficient to mediate discrimination at the intensive match. In contrast, chromatic discrimination failures or weaknesses are revealed by U-shaped functions, with the infant's performance falling to or toward chance over a specific and relatively narrow range of test field luminances.

In the context of three-channel theories of color vision, a performance minimum in the Peeples and Teller paradigm occurs when signal failures occur in all three channels simultaneously under the conditions tested.

Signals in both of the chromatic channels must be either absent or too weak to mediate the discrimination, leaving only an intensitive channel operating. In addition, the particular combination of luminances of the test field and surround must be such as to null the signal in the intensitive - brightness or luminance - channel that the infant uses to mediate the discrimination. Thus, when performance minima occur, they can reveal the properties of the infant's intensitive channel.

The fundamental question addressed in this work is, when infants show performance minima in the [Peeples and Teller](#) paradigm, are these minima mediated by luminance matches or by brightness matches? We approach this question empirically by asking, do infants' performance minima share more closely the characteristics of adult luminance matches, or adult brightness matches?

## Luminance Versus Brightness Mediation Hypotheses

The simpler hypothesis is that infant performance minima arise at an early processing stage at which the intensitive channel is a luminance channel, and are mediated by an adultlike luminance mechanism such as Judd's modified  $V(\lambda)$  or  $V_{10}(\lambda)$ . If this option is correct, infants' performance minima should reveal spectral characteristics predictable from these standard luminance mechanisms. In addition, in adults luminance matches can be made with considerable precision, and individual differences are relatively small ([Ives, 1912a, 1912b](#); [Wyszecki & Stiles, 1982](#)). Thus, if the data are controlled by a luminance mechanism, individual differences in infants' performance minima should likewise be relatively small (cf. [Pereverzeva, Chien, Palmer, & Teller, 2002](#)).

The more complicated hypothesis is that infants' performance minima are imposed at a more central level, at which the intensitive channel is a brightness channel, and are mediated by adultlike heterochromatic brightness matches. In adults, heterochromatic brightness matches differ systematically from luminance matches, typically falling above  $V(\lambda)$  in the long-wavelength and (especially) the short-wavelength spectral region ([Ives, 1912a, 1912b](#); [Wagner & Boynton, 1972](#); [Wyszecki & Stiles, 1982](#); [Lennie, Pokorny & Smith, 1993](#)). Moreover, heterochromatic brightness matches show relatively large individual differences ([Ives, 1912a, 1912b](#); [Ikeda, Yaguchi, & Sagawa, 1982](#); [Wyszecki & Stiles, 1982](#)), and instabilities across days ([Walsh, 1958](#); [Wyszecki & Stiles, 1982](#)). Thus, if infants' performance minima are governed by adultlike heterochromatic brightness matches, these minima should reveal both a relatively elevated sensitivity with respect to  $V(\lambda)$  at long and (especially) short wavelengths, and considerable variability.

In addition to its other complexities, the brightness mediation hypothesis in its strongest form carries an internal contradiction. The problem is that brightness is

usually modeled as arising from the combination of luminance and chromatic signals. Thus, if the infant's chromatic signals were completely absent, no brightness signal could be computed. However, this problem can be overcome by assuming that infants have chromatic signals of sufficient magnitude to combine with a luminance signal to generate a brightness signal, but not of sufficient magnitude to mediate a chromatic discrimination under the conditions tested.

## Evidence From the Infant Color Vision Literature

Evidence from the infant color vision literature does not allow a definitive choice between the luminance and brightness mediation hypotheses. In early studies from our laboratory ([Peeples & Teller, 1975](#); [Teller, Peeples & Sekel, 1978](#); [Hamer, Alexander, & Teller, 1982](#); [Packer, Hartmann, & Teller, 1984](#); [Varner, Cook, Schneck, McDonald, & Teller, 1985](#)), infant performance minima were conceptualized in terms of brightness matches. In consequence, the luminances at infant performance minima were compared only to adult brightness matches measured in situ, and no detailed spectral calibrations were made. Many of the observed minima coincided reasonably well with the in situ adult brightness matches. However, especially for long wavelength stimuli, some of the minima fell above the adult brightness match points, suggesting the possibility of mediation by a luminance mechanism. In the final study of this series ([Clavdetscher, Brown, Ankrum, & Teller, 1988](#)), detailed calibrations were provided. However, in that study most of the infant performance minima coincided with the rod-based mechanism  $V'(\lambda)$ , suggesting that most of the luminances used were too low to engage photopic mechanisms.

Two standard photometric techniques have been modified to assess spectral sensitivity in infant subjects: a VEP-based version of flicker photometry ([Bieber, Volbrecht, & Werner, 1995](#)) and an eye-movement-based version of motion nulling ([Maurer, Lewis, Cavanagh & Anstis, 1989](#); [Teller & Lindsey, 1989](#); [Chien, Teller, & Palmer, 2000](#); [Pereverzeva et al., 2002](#)). In both kinds of studies, large test fields were used. In both cases, infant isoluminance values coincide closely with predictions based on  $V_{10}(\lambda)$ , except for an elevation at very short wavelengths that is probably due to reduced infant lens pigmentation ([Bieber et al., 1995](#)). In addition, individual infants' isoluminance values can be measured with precision, and individual differences among infants are small ([Pereverzeva et al., 2002](#)). Hence there is strong evidence that a functional  $V_{10}(\lambda)$ -like luminance signal exists in young infants, and is thus available to control the location of infant performance minima in the chromatic discrimination task. There remains no comparably strong evidence that the infant visual system computes a brightness signal.

In addition to its intrinsic interest, the question of luminance versus brightness signals is of some importance in relation to models of infant detection thresholds. For example, [Dobkins, Anderson & Kelly \(2001\)](#) explored the orientations of detection ellipses in the L-, M-cone contrast plane in 2- to 5-month-old infants and adults. The orientations of the group mean ellipses coincided closely with a spectral prediction based on  $V(\lambda)$  [which fell at 120° in the stimulus spaced used by [Dobkins et al. \(2001\)](#) (K. Dobkins, personal communication)]. These data are consistent with a model that assumes that infant detection thresholds are mediated by the joint action of adultlike luminance (L + M) and red-green chromatic (L - M) postreceptor channels. However, the potential agreement of the data with a brightness mediation hypothesis was not evaluated.

More generally, infants demonstrate large general losses of sensitivity; that is, their detection thresholds are elevated by a log unit or more with respect to those of adults ([Simons, 1993](#); [Dobkins et al., 2001](#)). Little evidence is available concerning the processing level at which these large sensitivity losses are imposed. It is certainly possible that the sensitivity losses come about at a stage at which the early chromatic code (L + M and L - M channels) remains in force. But since the final maturation of the visual system proceeds generally from more peripheral to more central levels, it is also conceivable that the infant's sensitivity losses are central rather than peripheral, and therefore could be mediated at a level at which a brightness rather than a luminance code is in force.

In sum, in our view the brightness mediation hypothesis is theoretically interesting, and has not yet been ruled out. In the early studies from our laboratory, infant performance minima coincided relatively well with adult in situ brightness matches, but no luminance calibrations were provided. More recent photometric and detection studies include precise luminance calibrations, but no brightness matches. A study is needed in which infant performance minima can be compared to in situ measures of both luminance and brightness, as well as to predictions based on adult standard luminosity curves; and in which the variability of the infant data can be compared to that of adults performing both brightness and luminance tasks.

Agreement of the data with the predictions of the brightness mediation hypothesis would have two important theoretical consequences. First, it would provide the first definitive evidence that the infant visual system computes a brightness signal, and second it would suggest that the infant's sensitivity losses are central as opposed to peripheral. Agreement with the predictions of the luminance mediation hypothesis would reconfirm the presence of a luminance signal, but in the absence of any evidence for a recoding of the intensive dimension to create a brightness signal, would provide little evidence

concerning the processing level at which the infant's sensitivity losses occur.

## Bias Effects

Finally, another possible approach to the question of luminance versus brightness mediation arises from the phenomenon of *bias effects*. We here define a bias effect as a change in the value of a psychophysically defined entity such as a threshold or point of subjective equality (PSE) that accompanies a change in task variables, or in the set of test stimuli used. This definition leaves open the options that bias effects can be due either to sensory variables such as light/dark, chromatic, or contrast adaptation (e.g. [Parker, Murphy & Schneider, 2002](#)), to decision variables such as shifts in the subject's psychophysical criterion ([Green & Swets, 1966](#)), or to a combination of both.

Many kinds of psychophysical biases have been defined ([Poulton, 1979](#)). Of particular interest here is the *centering bias*: subjects tend to center their psychometric functions around the center of the range of test stimuli used in the experiment ([Poulton, 1979](#); [Levison & Restle, 1968](#)). Different kinds of psychophysical measurements are differentially susceptible to bias effects. In particular, [Poulton \(1979, p. 777\)](#) argues "Responses that are closely linked to the stimuli by well-known rules are less easy to bias than responses that are only loosely related...." In other words, judgments for which there is a well-defined perceptual criterion are subject to minimal bias, whereas judgments for which there is no well-defined perceptual criterion will be particularly biasable.

Given these characteristics, the presence and magnitude of psychophysical bias effects may be useful in helping to decide between the luminance and brightness mediation hypotheses. This is so because the psychophysical operations that define luminance matches are based on readily recognizable criteria such as the minimization of perceived flicker, border distinctness, or motion. In contrast, observers probably have no clear or previously defined internal criterion to use in setting heterochromatic brightness matches. In consequence, it seems likely that heterochromatic brightness judgments are susceptible to relatively large bias effects, including a centering bias. We have, however, not been able to locate data on this point in the adult vision literature.

## Goals

This project had four goals. First and most broadly, the project was initially designed to search for evidence of a brightness signal in infant subjects. Second, we investigated the spectral characteristics, variability, and biasability of adult heterochromatic brightness matches, under conditions as similar as possible to those to be used with infants. Third, we investigated the spectral characteristics, variability, and biasability of infant

performance minima in the [Peeples and Teller \(1975\)](#) paradigm. And finally, we compared the infant and adult data for the purpose of differentiating between the luminance and brightness mediation hypotheses. In fact, the results favored the luminance mediation hypothesis, and our original goal of providing evidence for a brightness signal in infant subjects was not fulfilled.

## Methods

### General Methods: Apparatus and Stimuli

The apparatus consisted of a Sony GDM-FW900 color graphic display controlled by a Macintosh Power PC 7500, and calibrated with a Photo Research PR 650 spectroradiometer. The monitor had a peak luminance of  $63 \text{ cd/m}^2$  and a black level of  $0.1 \text{ cd/m}^2$ . The CIE chromaticity coordinates  $x$ ,  $y$  of the red, green and blue video phosphors were (.62, .34; .29, .61; and .15, .06) respectively. The color names red and blue are used to refer to test stimuli composed of the isolated red and blue phosphors.

The test stimuli were sharp-edged squares typically subtending a visual angle of  $2^\circ$ . In some experiments with infants,  $1.5^\circ$  and  $4^\circ$  stimuli were also used. At the test distance of 38 cm, the monitor screen subtended  $68 \times 42^\circ$ . The test stimuli were centered about  $10^\circ$  to the left or right of the center of the monitor. The luminances of the test stimuli ranged from  $1.3$  to  $19.7 \text{ cd/m}^2$  and from  $0.2$  to  $4.7 \text{ cd/m}^2$  for the red and blue test stimuli, respectively. The lower range of luminances was used with blue stimuli because of the limited maximum luminance of the blue phosphor.

A white surround with chromaticity coordinates (0.35, 0.35) filled the remainder of the screen. The luminance of the surround was  $9.4$  and  $2.4 \text{ cd/m}^2$  for the red and blue test stimuli, respectively. The monitor was further surrounded by a cardboard surface with chromaticity coordinates (0.34, 0.33), and luminance of  $0.42$  and  $0.12 \text{ cd/m}^2$  for the red and blue test stimuli, respectively.

### Adult Landmarks

Several sets of predicted values for the infant performance minima were either calculated or measured on adult subjects in situ. The resulting landmarks are plotted on the upper abscissae of [Figures 1 and 2](#) and [Figures 4-6](#) below. Luminance matches were computed from published values for Judd's modified  $V(\lambda)$ ,  $V_{10}(\lambda)$  and  $V'(\lambda)$  ([Wyszecki & Stiles, 1982](#)), and are shown with single arrows labeled with these symbols. Adult motion nulls were determined as an in situ luminance measure, and are shown with the single arrows labeled AMN. Adult brightness matches were also determined in situ as

described in detail below, and the resulting brightness-based landmarks are shown with the double arrows labeled AB1, AB2, and AB3.

## Adult Experiments: Methods

### Overview

Two kinds of experiments were carried out on adult subjects. In the main experiments, we determined brightness matches between the test fields and the white monitor surround, and explored the biasing effects of varying the range of test field luminances. In the second kind of experiment, adult luminance matches were determined with a large field motion nulling technique. Since infant and adult motion nulls tested with standard video phosphors are virtually identical ([Pereverzeva et al, 2002](#)), the motion nulling data provide estimates of infant luminance matches in situ.

### Subjects

Adult subjects were laboratory personnel and graduate students at the University of Washington. All were between 24 and 35 years of age, had normal or corrected-to-normal vision, and were tested with untinted optical corrections as needed. None had a family history of color deficiency according to self-report. Their color vision was tested with Ishihara Color Plates, FM 100 Farnsworth-Munsell Color Test, and a modified Nagel anomaloscope, and all were found to be color normal. Written informed consent was obtained prior to testing.

A total of seven subjects were tested in the main experiment. Two (S.H.C. and U.H.) were tested with only the red stimulus set, two (I.Z. and D.H.) with only the blue stimulus set, and three (A.C., S.C., and E.H.) in both conditions, for a total of five subjects in each condition. A.C. is one of the authors.

### Stimuli

In the main brightness-matching experiment, the major independent variable was the range of log relative luminances of the test stimuli. These ranges are specified by the locations of their midpoints, with the value 0.0 denoting the  $V(\lambda)$  luminance match to the surround. Midpoint values from -0.6 to 0.1 were initially used for both red and blue test stimuli. The range of midpoints was later extended for blue test stimuli to allow the data to cross the identity line (see below). The luminances of the stimuli differed in steps of 0.05 log units (but see the ancillary experiments below). Typically, 11 stimuli were used (due to apparatus limitations, only 9 stimuli were used with the highest midpoints). The method of constant stimuli was used, and 20 trials per condition were collected (24 for the highest midpoints).

## Procedure

Adult subjects were seated 38 cm from the monitor. In mimicry of the infant experiments, a variety of black fixation targets (crosses, dumbbells, etc.) subtending about  $2^\circ \times 6^\circ$  were used, and adult subjects were instructed to fixate the fixation target between trials and foveate the test stimulus when it appeared. The subject's task was to report whether the test stimulus appeared brighter or dimmer than the surrounding white monitor screen. The timing of stimulus presentation was not controlled, but the test stimulus was usually present for about 2 s. After a judgment was made, the trial was terminated and a new trial was initiated, with an untimed inter-trial interval of about 2 s.

To begin the session, a midpoint was randomly selected, and the test stimuli appropriate to that midpoint were presented in random order. When the data set was completed, a second midpoint was randomly selected, and so on. Typically, the different midpoints were all tested within a single session. It is noteworthy that this single-session design was sufficient to reveal large bias effects. Day-to-day variability within individual subjects was not explored.

## Ancillary Brightness-Matching Experiments

Two sets of ancillary brightness-matching experiments were also carried out. In the first set, the effects of test field size and retinal location were explored. Two subjects from the main experiment (A.C. and S.C.) made complete sets of judgments using  $1^\circ$  and  $4^\circ$  red test stimuli. The same range of midpoints used in the main experiment was used in these control runs. The experiments were repeated at about  $10^\circ$  peripheral by having the subjects continue to fixate the center of the screen during test trials. Peripheral matches were also made with  $2^\circ$  blue test fields. Variations in the data due to these parameters were negligible, except that in general, judgments were more variable in peripheral viewing (data not shown).

The second set of ancillary brightness-matching experiments was undertaken because the stimuli used in the infant experiments differed in several details from those used in the main adult experiment. In particular, since infant psychometric functions are flatter, the stimulus spacing was coarser; and "black" and "easy" stimuli (which could in principle anchor the subject's criterion and influence the magnitude of bias effects) were included in the stimulus set. Therefore, the adult brightness-matching experiments were repeated with both red and blue test stimuli, using the exact stimulus sets used with infants. Five subjects were tested in addition to author M.P. The data were virtually identical to those seen in the main experiment with the same stimulus midpoint, and are not presented.

## Analysis

For each test stimulus midpoint, the data were scored by tabulating the percent "brighter" judgments as a function of the log relative luminance of the test field. Curves were fit to each data set by probit analysis. The luminance required for 50% "brighter" responses was taken as the point of subjective equality (PSE).

The PSEs for each subject varied with the midpoint of the stimulus set. When plotted against the log of test range midpoints, the PSEs could be fit reasonably well by straight lines. The data from each subject were characterized by the slope of the best-fitting line. In addition, the *identity line* - the line for which the PSE and the midpoint of the stimulus range are identical - was identified as an important landmark, and the *crossover point* - the stimulus luminance at which the best fitting line crossed the identity line - was characterized for each subject and for the group mean data.

## Motion Nulling Experiments

Finally, adult large-field luminance matches were characterized in situ by a constant mean motion nulling paradigm described in detail previously (Chien et al., 2000; Pereverzeva et al., 2002). Since the spatial and temporal characteristics of infant motion nulls have not been explored, we make no claim that these adult motion nulls are precise luminance matches for the small test fields used in the main experiment, but they nonetheless provide a useful in situ landmark.

Briefly, two 0.25 cpd sinusoidal grating components of differing space-average chromaticities were superimposed on a video screen and moved in opposite directions at a speed of  $24^\circ/\text{sec}$ . The gratings fully covered the test display, and subtended  $68^\circ \times 42^\circ$  at the viewing distance of 38 cm. The combined components had constant space-time-average CIE 1931 chromaticity coordinates of about 0.33, 0.33. The contrasts (not the luminances) of the two grating components were traded off against each other to determine each motion null. The method of constant stimuli was used.

For comparison to the red test stimuli used in the present experiments, isochromatic red/black (0.49, 0.34) versus blue-green/black (0.21, 0.33) grating components were used. The combined luminance was about  $10 \text{ cd/m}^2$ . These colors maximized the modulation of the red primary given our mean chromaticity. For comparison to the blue test stimuli, the components were isochromatic blue/black (0.28, 0.25) and yellow/black (0.44, 0.49) gratings with a combined luminance of about  $3 \text{ cd/m}^2$ . These colors maximized the modulation of the blue primary given our mean chromaticity.

Six adult subjects (five for red stimuli and six for blue) were tested. In addition, two of the adult subjects (A.C. and S.C.) participated in two extra runs with the motion nulling technique. In these runs, the space-

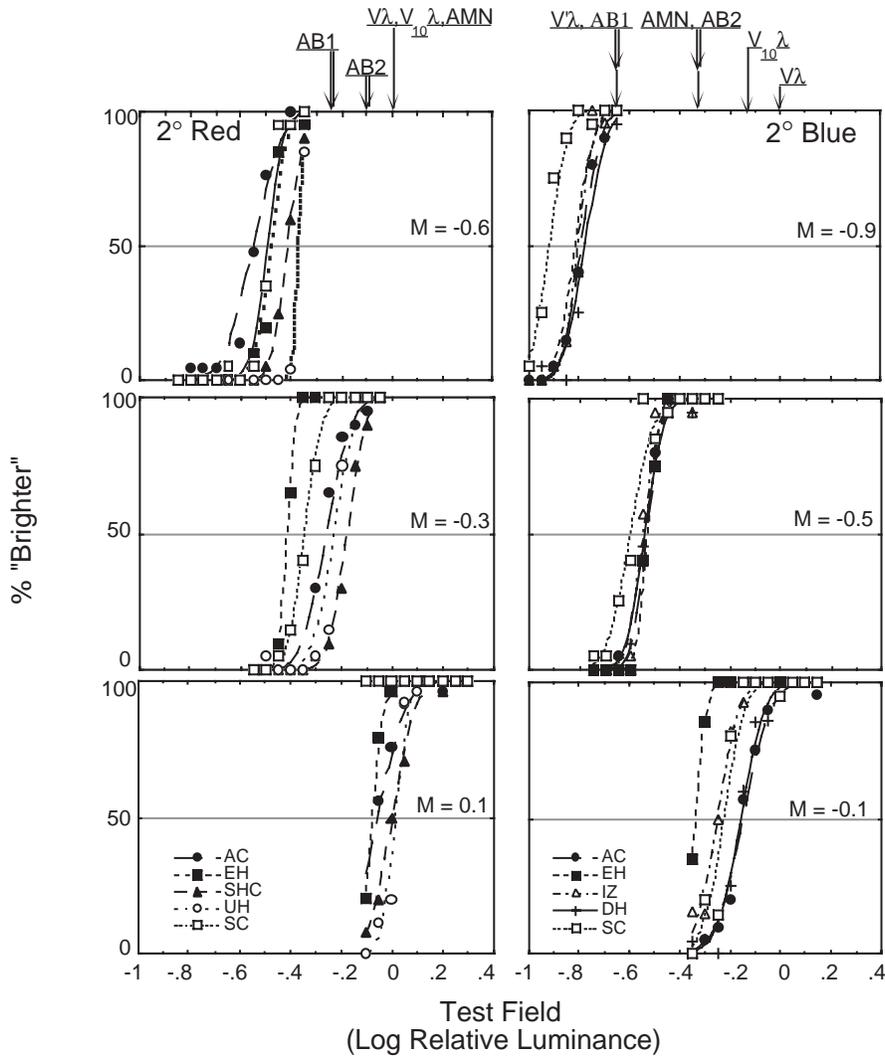


Figure 1. Psychometric functions for five adult subjects. The abscissae show the log relative luminances of the test field, with 0 indicating a  $V(\lambda)$ -based luminance match of the test field to the surround. The single arrows on the upper abscissae show various spectral landmarks based on luminance matches, including  $V(\lambda)$ ,  $V_{10}(\lambda)$ ,  $V'(\lambda)$ , and an in situ luminance match estimated from motion nulling (AMN). The double arrows show mean adult brightness matches, defined from the crossover points determined in the main adult experiment (AB1), and defined with test stimulus midpoints set to the same values used in infant testing (AB2). The ordinates show the percent of trials on which the subject judged the test field to be brighter than the surround. Data from red and blue test fields are shown in the left and right columns, respectively. The different panels show different values of the parameter  $M$ , the midpoint of the range of stimulus luminances used. The subjects' brightness judgments shift markedly with shifts in the midpoint, revealing large centering biases.

average luminances and chromaticities of the stimuli remained constant, but the range of luminance contrasts used was varied. The purpose of these runs was to see whether or not the motion null values were influenced by the range of luminance contrasts used; that is, to probe for potential bias effects caused by variations in stimulus midpoint in the motion nulling paradigm.

### Adult Experiments: Results Brightness Matching

Psychometric functions for brightness matches for all five subjects in the main experiment are shown in [Figure](#)

1. In each panel, the abscissae show the log relative luminances of the test stimuli. The ordinates show the percent of trials on which the stimulus was judged to look brighter than the surround. The parameter  $M$  specifies the midpoint of the range of test stimuli used. The six panels show data for red and blue stimuli, tested at each of three different test stimulus midpoints. PSEs are shown by the intersections of the curves fitted to the data with the horizontal line at 50% "brighter" judgments. The data show large centering biases at both individual and group levels. In all cases, the brightness match point shifts in concert with the midpoint of the stimulus range. Stimuli judged brighter than the surround on 100% of

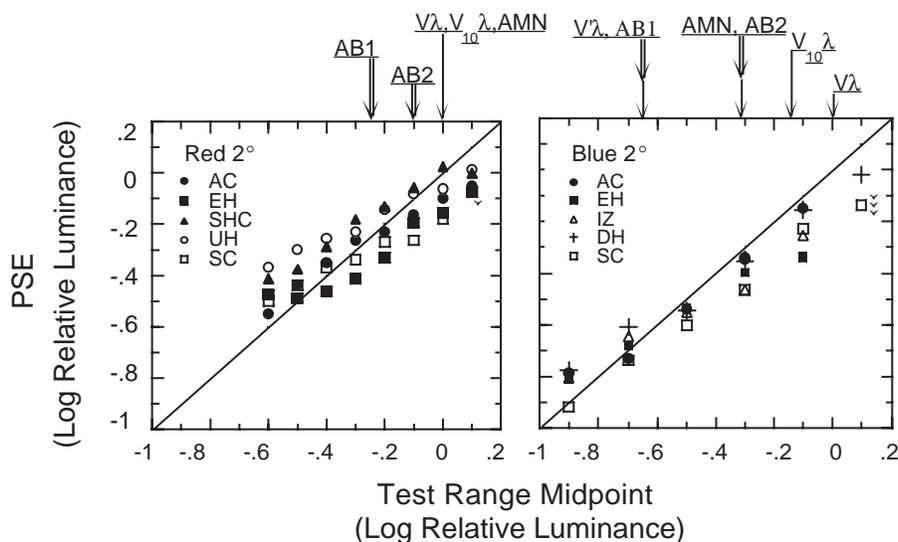


Figure 2. Points of subjective equality (PSE) for five adults. The abscissae show the midpoints of the ranges of test field luminances used. The ordinates show the PSE. Chevrons at the right of each graph show lower-bound estimates of PSE for subjects whose psychometric functions did not cross 50% at the highest test stimulus midpoint (0.1). For individual subjects, variations of PSE with stimulus midpoint show slopes of between 0.5 and 0.7 and 0.6 and 0.8 for red and blue stimuli, respectively. Crossover points vary among subjects over a range of 0.4 to 0.5 log units in each case.

trials with a low luminance midpoint (top panels) are judged dimmer than the surround on 100% of trials with a high luminance midpoint. For red test stimuli, a shift of midpoint of 0.7 log units shifts the mean PSE by a mean of about 0.4 log units; for blue test stimuli, a shift of midpoint of 0.8 log unit shifts the PSE by a mean of about 0.6 log units.

Brightness match values (PSEs) are shown as a function of midpoint in Figure 2. In this plot, if no centering bias occurs - if variations in the stimulus midpoint do not influence the PSE - the data from each subject would fall on a line with a slope of 0. Alternatively, if the centering bias were complete - if the PSE always coincided with the midpoint of the stimulus set - the data would fall on the identity line, with a slope of 1. In fact, straight lines fit to the data of individual subjects have slopes between 0.5 and 0.7 for the red stimuli, and between 0.6 and 0.8 for the blue stimuli, showing incomplete but marked and consistent centering biases.

Although all subjects show rather similar centering biases as determined by slopes, it is interesting to note that there are also individual differences in the vertical positions of the different data sets. That is, all subjects are similarly influenced by the range of stimuli used but reveal consistently different ranges of PSEs. In consequence, different subjects show different crossover points, ranging from about -0.5 to 0.0 log units for red test fields and -0.9 to -0.5 log units for blue. Both the between-subject variability and the biasability of the PSEs again suggest the absence of any natural perceptual criterion on which subjects can base brightness judgments.

Given the large bias effects shown in Figure 2, what criterion should be used in defining an unbiased adult brightness match for comparison to the infant performance minima? In the psychophysical literature on bias effects, an unbiased estimate occurs by definition when the PSE falls at the middle of the stimulus range (Poulton, 1979). Using this criterion, the unbiased brightness matches of the five adult subjects would be represented by their crossover points (see "Analysis" above), and the mean crossover point would provide an unbiased estimate of the mean adult brightness match. The mean crossover points from Figure 2 provide the adult brightness landmarks AB1 in Figures 1 and 2 and Figures 4-6.

A possible alternative choice of an adult brightness landmark is a brightness match taken with exactly the same stimulus set used with infant subjects. Landmarks based on this criterion are shown in the figures as the double arrows labeled AB2 and AB3 (see below). Although this alternative has some appeal, it is problematic because these brightness matches are likely to be biased toward the midpoint of the stimulus range.

Moreover, use of these brightness landmarks is particularly problematic to the interpretation of the main experiments undertaken on infants, in which the ranges of test stimuli are centered at or near adult luminance matches. If the same ranges of test stimuli are used for defining adult brightness matches, centering biases will inevitably move the adult brightness matches toward the luminance matches, and reduce or eliminate the differences between brightness and luminance landmarks.

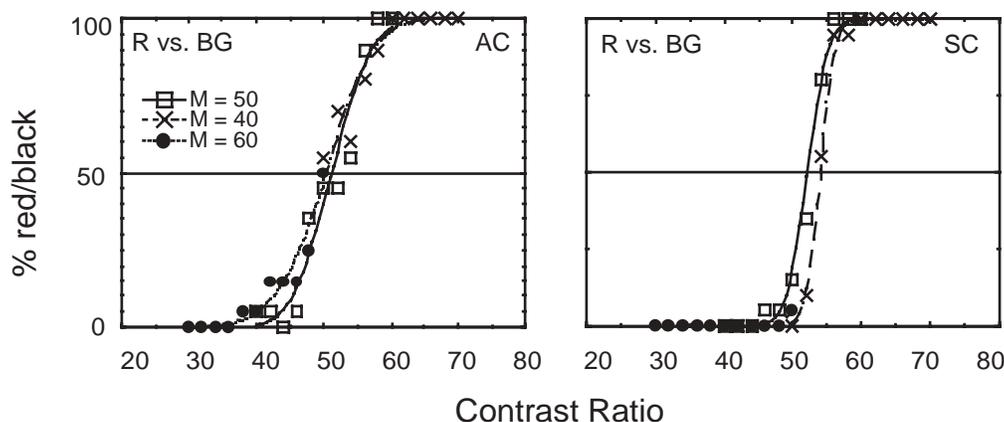


Figure 3. Motion nulling data for two subjects, determined with three different ranges of contrast ratios. The abscissae show the contrast ratio  $C_{red}/(C_{red} + C_{bluegreen})$  of the stimulus. The ordinates show %red/black, the percent of trials on which the subject judged that the stimulus moved in the direction of motion of the red/black stimulus. The value of the contrast ratio at which %red/black = 50 defines the motion null. The parameter  $M$  specifies the midpoint of the range of contrast ratios used. Shifts of the range of contrast ratios produced little or no change in the motion null value.

This problem will become apparent in the main infant experiments (Figure 5 below). It is eliminated in the infant bias experiment (Figure 6 below), in which the midpoint of the stimulus range used with infants is shifted away from the adult luminance matches.

## Motion Nulling

Finally, data from the bias experiment in the motion-nulling paradigm, measured with red/black versus blue-green/black stimuli, are shown in Figure 3. In this plot, the abscissae show the luminance contrast ratio  $C_{red}/(C_{red} + C_{bluegreen})$  of the stimulus (Chien et al., 2000; Pereverzeva et al., 2002). The ordinates show %red/black, the percent of trials on which the subject reports motion in the direction of the red/black stimulus component. The parameter  $M$  specifies the midpoint of contrasts for the red/black stimulus component. The three different symbols show the data for three different stimulus midpoints, 40%, 50%, and 60% contrast for the red/black component and 60%, 50%, and 40% contrast for the blue-green/black component, respectively. For these three stimulus ranges, the motion null values are 51%, 51%, and 50% for subject A.C., and >50%, 54%, and 55% for subject S.C. Clearly, the effect of contrast midpoint on the motion null values is negligible under our conditions.

The basic motion-nulling experiment ( $M = 50$ ) was also carried out on five subjects using both red/black versus blue-green/black and blue/black versus yellow/black gratings. The mean motion null values were  $51.6\% \pm 0.8\%$  for red stimuli and  $70.3\% \pm 1.5\%$  for blue (data not shown). These values coincide well with earlier data and with predictions from  $V_{10}(\lambda)$  (cf. Chien et al., 2000; Pereverzeva et al., 2002). They provide the adult motion-nulling landmarks AMN.

## Infant Experiments: Methods

### Overview

In the infant phase of the experiments, 8-week-old infants were tested with small, sharp-edged red and blue test fields of a series of log relative luminances, centered either to the left or the right of the center of the white surround.

For these experiments to succeed, it was necessary for the infants to show performance minima - weaknesses or failures of discrimination of the test field from the surround - within the luminance series, so that the spectral and other characteristics of the performance minima could be evaluated. Two features of the experiment were chosen to insure the presence of performance minima. First, because younger infants show performance minima more readily than older infants (Hamer et al., 1982; Clavadetscher et al., 1988), the experiment was performed on 8-week-old infants, the youngest test age currently feasible in our laboratory. Second, because infants show performance minima more readily with small than with large test fields (Packer et al., 1984), small test fields, subtending  $1.5^\circ$  to  $4^\circ$  of visual angle, were used. Performance minima were generated successfully by combining these features.

### Subjects

Infant subjects were 8 weeks old and recruited from the Infant Studies Subject Pool at the University of Washington. All infants were healthy according to parents' reports, had no known family history of color deficiency, and were born within 14 days of their due dates. Infants were tested for three to four 1-h sessions on separate days within the week of their 8-week birthday.

Prior to testing, the parents were acquainted with the details of the experiment, and informed written consent was obtained.

A total of 96 infants provided useable data. Of these, 11 participated in a pilot experiment with 2° blue test fields; 85 participated in the main experiments: 12 and 21 with 2° and 4° red test fields, respectively, and 20 and 20 with 1.5° and 2° blue test fields, respectively. Finally, 12 infants were tested in an experiment with a shifted range of red test field luminances (the infant bias experiment, below).

Over all six data sets, a total of 39 infants from a total of 135 were excluded; 24 infants were excluded for failure to return or failure to complete the required minimum number of trials; 14 for performance of less than 80% on the easy trials (see below), and one for a suspected family history of color deficiency.

## Stimuli

Within each experiment, test fields were presented at a series of luminances. For the main experiment with red 2° and 4° test fields, 7 luminances were used, with the midpoint at a log relative luminance of 0.0 and a step size of 0.1 log units. For the pilot data carried out with blue 2° test fields, 7 luminances were used, with the midpoint at -0.1 and a step size of 0.1 log units, with one 0.3 log unit step at the high end of the range. For the main experiment with blue 1.5° (2°) test fields, 9 (9) luminances were used, with the midpoint at -0.2 (-0.3), and a step size of 0.1 (0.15) log units. In the infant bias experiment, carried out with red 4° test fields, 7 luminances were used, with the midpoint shifted to a log relative luminance of -0.3 and a step size of 0.1 log units.

A black stimulus with a luminance equal to the black level of the monitor was also included in each series. In addition, to establish that the infants were responsive to the display, presentations of *easystimuli* were randomly intermixed with the experimental trials. The easy stimulus in all conditions was an 8° x 8°, 1/2 cpd high-contrast stationary white/black grating. Data were excluded if the infant's performance on easy trials fell below 80%. For the subjects retained, the observer's mean performance on easy trials was 92%.

## Procedure

Infants were held in a vertical position 38 cm from the video monitor by an adult observer. Their eye movements and fixation behavior were observed via an auxiliary infrared video system. The observer could not see the stimulus, and no corneal reflection of the stimulus was visible on the auxiliary viewing system.

At the start of each trial, one of the set of six 2° x 6° black fixation targets was presented at the center of the screen. When the observer judged that the infant was fixating the fixation target, she initiated a test trial, and a

test stimulus appeared on either the left or the right side of the screen. The forced-choice preferential looking (FPL) technique was used for data collection (Teller, 1979). The observer's task was to observe the infant's eye movements and fixation behavior, and on that basis to make a forced-choice judgment of the location of the test stimulus on each trial. The duration of stimulus presentation was unlimited but a trial usually lasted for 2-5 s. The observer's judgment terminated the stimulus presentation. The inter-trial interval was not timed, but is judged to have been about 2 s. A mean of 348 trials per infant was obtained, for an average of about 40 trials per point on the U-shaped functions.

## Analysis

Each individual infant's data were fit with a U-shaped template derived from Weibull functions (Teller & Palmer, 1996), and the location of the performance minimum was estimated from the fitted function. For five of the 96 data sets, the estimated minima fell well outside the stimulus range. Three of these cases occurred for the blue 1.5° condition, and one each for the red 2° and blue 2° conditions. These data sets produced outliers in the estimated locations of performance minima. Means and SEs of the performance minima were calculated both with and without inclusion of these outliers for the three affected conditions.

A complication also arose in estimating the performance minimum in the bias experiment, because by design the stimulus range was shifted leftward with respect to the eventual position of the minimum. In consequence, the estimated minimum relies only on the reversal between the rightmost two data points which, by inspection of the error bars (Figure 6 below), do not differ reliably from each other. The fitting program estimated the minimum of the group average data at a log relative luminance of -0.05, but this value should be considered a lower-bound estimate for the reasons stated.

## Infant Experiments: Results

Individual data sets from 12 infant subjects tested in the main experiments are shown in Figure 4. Data collected with 2° and 4° red test fields and 1.5° and 2° blue test fields are shown in Figure 1A through 1D, respectively. In each panel, the abscissae show the log relative luminances of the test field, with 0.0 marking the  $V(\lambda)$  isoluminance match of the test stimulus to the white surround. The ordinates show the observer's percent correct in judging the location of the test field.

Data were selected for presentation in Figure 4 according to the following criteria. The data set for which the minimum coincided most closely with the mean minimum for all infants was chosen, followed by two other data sets whose minima deviated from this value by about  $\pm 1$  SD of the sample. Within these criteria, data

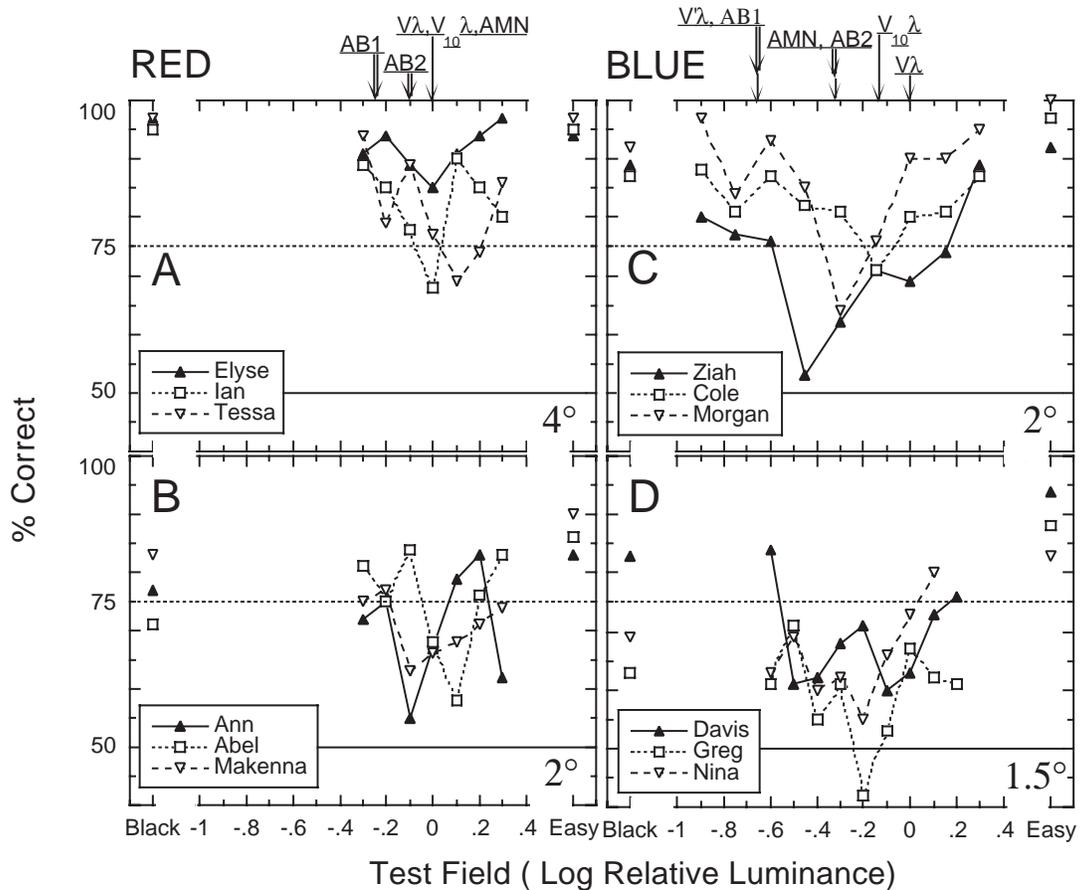


Figure 4. Individual data from 12 infant subjects. The abscissae show the log relative luminance of the test field. The ordinates show the observer's percent correct in a forced choice preferential looking (FPL) task. The data sets are selected to portray the overall quality and variability of the data.

were selected to convey an impression of the regularity and variability of the data.

For each individual data set, the luminance value at the performance minimum was derived by fitting a U-shaped function. The variability of performance minima across infants was relatively small. With outliers excluded, for the 2° and 4° red test fields, the mean performance minima occurred at log relative luminances of  $0.02 \pm 0.03$  and  $-0.01 \pm 0.02$ , respectively. For the blue pilot data, the minimum occurred at  $-0.14 \pm 0.04$ . For 1.5° and 2° blue test fields, the minima occurred at  $-0.23 \pm 0.02$  and  $-0.24 \pm 0.03$ , respectively. When the outliers are included, values for the 2° red test field changed to  $0.06 \pm 0.05$ ; for the 1.5° blue test field to  $-0.29 \pm 0.04$ ; and for the 2° blue test field to  $-0.20 \pm 0.05$ .

The group mean data for the five main data sets of the experiment are shown in Figure 5. Figure 5A and 5B show data for red and blue test fields, respectively. Vertical bars around the data points show SEs of the mean percentages. The group mean performance minima, derived from fitting U-shaped functions to the group average data, occurred at log relative luminances of 0.06, 0.04, -0.08, -0.28, and -0.26 for the red 2°, red 4°, blue 2°

pilot, blue 1.5°, and blue 2° conditions respectively. The means and SEs for the individual infants' data, with outliers excluded, are also shown at the bottom of Figure 5. These means and SEs can be used to compare the infants' performance minima to the various landmarks shown on the upper abscissa.

For red test fields, both the average of individual minima and the group minima coincide well with  $V(\lambda)$ ,  $V_{10}(\lambda)$ , and the adult in situ motion null AMN. The average deviation - the difference between the infant performance minimum averaged across conditions and the adult landmarks - was +0.02 log units.

Comparisons to brightness matches are more complex. For reasons discussed above, the adult brightness matches AB2, taken with the same stimulus set used in infants, differ from the luminance-based values by only about 0.1 log units. Therefore, by this criterion the locations of the infant minima alone do not discriminate convincingly among the predictions based on luminance versus brightness matches. However, compared to the crossover point criterion AB1, the average deviation is +0.3 log units, and the fit to AB1 can be rejected on statistical grounds ( $p < .01$  for both the 2° and 4° data

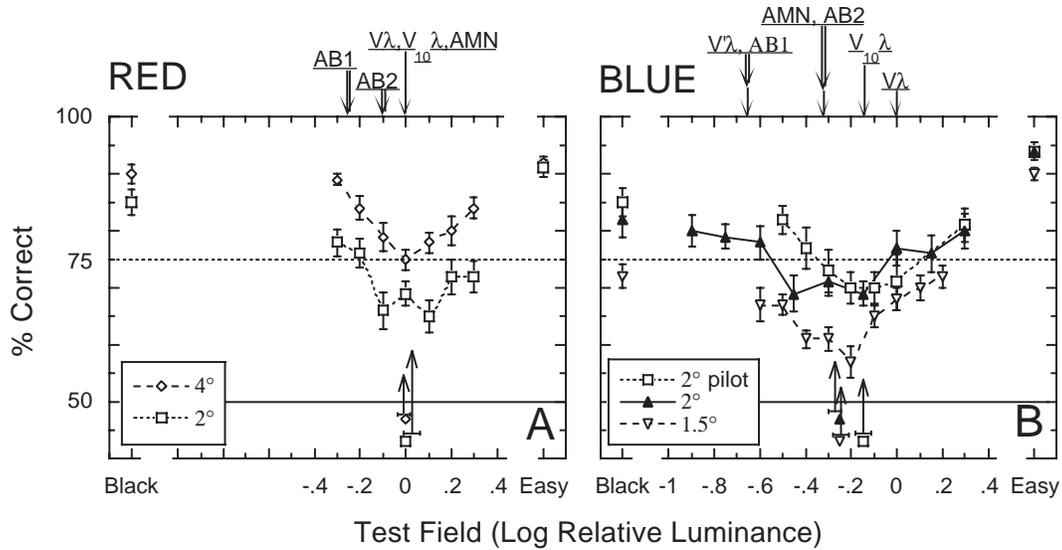


Figure 5. Group mean data from infants. Axes as in Figure 4. Vertical error bars show SEs of the mean percentages. The arrows and short horizontal lines at the bottom of each graph show the means and SEs of the performance minima. For red test fields, the infants' minima coincide well with the luminance-based landmarks  $V(\lambda)$  and  $V_{10}(\lambda)$ , and the adult in situ motion null AMN. For blue test fields, the infants' performance minima coincide better with  $V_{10}(\lambda)$  and AMN than with  $V(\lambda)$ . The landmark AB1, the unbiased adult brightness match, can be rejected in both cases. See text for discussion of the landmark AB2.

sets). The limited variability of the infant performance minima is also consistent with expectations based on luminance matches.

For blue test fields, the performance minima are displaced leftward from  $V(\lambda)$ , and fall near the predictions from  $V_{10}(\lambda)$  and the adult in situ motion null AMN. The similarity to  $V_{10}(\lambda)$  rather than  $V(\lambda)$ , even for small test fields, presumably occurs because of the reduced density of macular pigment in infants (Bieber et al, 1995). The average deviations were -0.2 for  $V(\lambda)$ , -0.1 for  $V_{10}(\lambda)$ , and +0.1 for AMN.

Comparisons to adult brightness matches remain more complex. Using the AB2 criterion, the average deviation is +0.1, and the data do not discriminate between luminance-based and brightness-based options. However, compared to the crossover point criterion AB1, the average deviation is +0.4, and the fit to AB1 can again be rejected on statistical grounds ( $p < .001$  for all three comparisons). Again, the limited variability of the infant minima is also consistent with expectations based on luminance matches.

Finally, the results of the infant bias experiment, measured with red test fields, are shown in Figure 6. In this experiment, the midpoint of the stimulus range was shifted to a log relative luminance of -0.3 log units, 0.3 log units below the midpoint used in the main infant experiments. For adult brightness matches, the landmark labeled AB3 on the upper abscissa indicates the adult PSE for this test stimulus midpoint. A shift of midpoint of this magnitude caused a shift of about 0.2 log units in the mean adult PSE defined by brightness matching, as shown by the difference between the landmarks AB2 (Figure 5) and AB3.

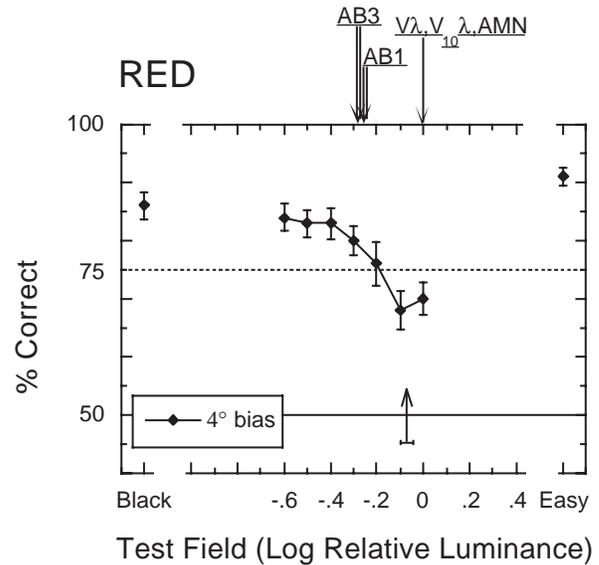


Figure 6. The infant bias experiment. Axes, error bars, arrows, and short horizontal lines as in Figure 5. The midpoint of the test stimulus range was set to a log relative luminance of -0.3. The landmark AB3 shows the adult brightness match taken with the same stimulus midpoint used in generating the infant data. The infants' performance minimum remains near the luminance-based landmarks  $V(\lambda)$ ,  $V_{10}(\lambda)$ , and AMN. The brightness-based landmarks AB1 and AB3 can be rejected.

The infant performance minima tell a different story. The location of the infant performance minimum shifted little if at all, remaining near the  $V(\lambda)$ ,  $V_{10}(\lambda)$  and adult motion null landmarks, with deviations of +0.2 from

both the AB1 and AB3 landmarks. Moreover, the true value of the performance minimum probably lies to the right of the measured value (see “Methods”), increasing its agreement with these landmarks and with the original data taken with red test fields (Figure 5). In any case, neither the AB1 nor the AB3 landmark provides an adequate fit to the data ( $p < .05$  for AB1,  $p < .01$  for AB3).

In summary, the absence of any substantial bias effect in the infant data, like the minimal variability of the data and the agreement of the performance minima with luminance-based landmarks, favors the luminance as opposed to the brightness mediation hypothesis.

## Discussion

The results of our experiments can be discussed from two perspectives: the variability and unexpectedly large biasability of adult brightness judgments and the mediation of infant performance minima by luminance versus brightness signals.

### Variability and Biasability of Adult Brightness Judgments

It is widely believed that, compared to luminance matches, brightness matches are both more variable among subjects and more biasable within subjects. However, our search of the vision literature revealed little systematic evidence on these points. Moreover, the stimulus configuration used for infant testing in the Peeples and Teller (1975) paradigm - a chromatic stimulus embedded in a white surround - is nonstandard for adult brightness-matching experiments. We were therefore drawn into a systematic study of the individual differences and biasability of adult heterochromatic brightness judgments made under the stimulus conditions used for testing infants.

We found that in a sample of five adult subjects, mean brightness matches as defined by crossover points varied by as much as 0.5 log units, and shifts in the midpoint of the stimulus range yielded bias effects of as much as 0.8 log units. We thus confirm the belief that adult heterochromatic brightness matches are highly variable among subjects and susceptible to a very large centering bias. As discussed in the “Introduction,” it is likely that judgments for which there is no readily recognized perceptual criterion will be particularly biasable, and the less definable the criterion, the more biasable the data may be. Our data are thus consistent with the speculation that subjects have little in the way of an internal perceptual criterion on which to base brightness judgments.

Two general comments about bias effects are in order. First, the effects of test stimulus range on the values of PSEs have seldom been studied in the vision context. Given the magnitude of the bias effects we have

stumbled upon here, it would seem prudent to investigate bias effects in other contexts, especially in the case of suprathreshold perceptual phenomena for which clear internal criteria are not obviously available.

Second, as stated in the “Introduction,” we have adopted a broad definition of bias effects (cf. Poulton, 1979), using the term to include all kinds of cases in which the PSE varies with the range of test stimuli used. This choice of terminology leaves open the more sophisticated question of whether the observed bias effects are caused by decision processes such as criterion shifts (Green & Swets, 1966) or by sensory processes such as light/dark, chromatic and/or contrast adaptation (cf. Parker et al., 2002).

Similarly, we recognize that the bias experiments we have carried out with brightness matching and with motion nulling are not identical in kind. In particular, in the brightness-matching experiments, the mean luminance of the set of test stimuli varies with the midpoint, allowing the possibility that sensory as well as decision processes could influence the measured PSEs. In the motion nulling experiments, the space-average luminance and chromaticity of the stimulus set remains constant, greatly reducing the potential influence of sensory factors. Experiments probing a variety of potential causes of the observed bias effects are in progress in our laboratory.

### Are Infant Performance Minima Mediated by Luminance or Brightness Signals?

In this work, three criteria were posed for deciding whether infants’ performance minima are mediated by luminance matches or by brightness matches. If a luminance signal governs the infant’s looking behavior, then the minima should coincide with predictions from one of the standard adult luminance mechanisms such as  $V(\lambda)$  or  $V_{10}(\lambda)$ ; individual differences should be small; and the performance minima should not be biasable by shifts in the midpoint of the stimulus range. On the other hand, if a brightness signal governs the infant’s looking behavior, then the minima should coincide with adult brightness matches; individual differences should be large; and the performance minima should be biasable.

We found that at least under the present conditions, infants’ performance minima coincide much better with  $V_{10}(\lambda)$  than with adult unbiased brightness matches defined by crossover points. Moreover, the low variability and minimal biasability of the infant performance minima clearly favor control by a luminance rather than a brightness signal.

## Conclusions

We (Peeples & Teller, 1975) initially characterized the task of detecting a chromatic field in a white surround when the chromatic channels are too immature to control behavior as a task for a brightness system. However, this work suggests that at least under the conditions used, infant performance minima occur at isoluminance rather than isobrightness values. It thus helps to establish the validity of a luminance- rather than brightness-centered perspective for infant chromatic discrimination work.

It has sometimes been suggested that, because infant and adult isoluminance values are similar, systematic variations of relative luminances like those used in the Peeples and Teller paradigm are unnecessary; that is, that an infant's performance at the adult isoluminance value is a sufficient characterization of the infant's color vision capacities. We have previously contributed support to this line of reasoning by showing that individual differences in infant isoluminance values are small, and have provided a detailed evaluation of this argument (Pereverzeva et al, 2002).

There remain no data that demonstrate the presence of a brightness signal in infants, and the possibility of mediation of infant performance by a brightness rather than a luminance signal may seem unlikely. We do, however, state a final caution. There could still be combinations of stimuli, perceptual tasks, and paradigms in which infants use brightness rather than luminance as the intensive dimension in their responses to chromatic stimuli. In such instances, the exclusive use of isoluminant stimuli could lead one astray in studies of infant color vision.

## Acknowledgments

This work was supported by National Institutes of Health Grant EY 04470 to D.T. M.P. was supported by Vision Training Grant EY 07031. We thank Susan Chang for infant testing, John Palmer, Sarina Chien, Joel Pokorny and Vivianne Smith for important discussions, and Karen Dobkins for calculation of the  $V(\lambda)$  axis for the Dobkins et al. manuscript. Commercial Relationships: None.

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