THE PERCEPTION OF CONTRAST AND COLOR BY THE HUMAN NEWBORN

By

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THE PERCEPTION OF CONTRAST AND COLOR BY THE HUMAN NEWBORN

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Abstract

This thesis investigated newborns' ability to detect contrast and to discriminate chromatic from achromatic stimulation. I studied newborns' sensitivity to contrast by taking advantage of their preference for patterned over unpatterned stimulation. Newborns (n=60) looked longer at checkerboards in which the checks contrasted by 11%, by 17%, by 23% and by 27% than at grey squares matched in mean luminance to the checkerboards, but showed no preference when tested with checks contrasting by 3% or 5%. In addition, the magnitude of their preferences increased as a function of increasing contrast. In order to examine contrast detection developmentally, 2-month-olds (n=24) were exposed to a series of contrasting checkerboards and the respective matching grey squares. The results showed that 2-month-olds demonstrated preferences for checkerboards with contrasts of 5%, of 11%, and of 23% but not of 3% over matching grey squares. However, 2-month-olds' preferences did not increase with increasing contrast. These results suggest that newborns and 2-month-olds are much more sensitive to contrast than previous studies had indicated.

In studies designed to test color perception, newborns were shown a series of colored-and-grey checkerboard patterns in which the difference in luminance between the color and the grey components was varied across a range centred at the luminance where adults would see the color and the grey as equally bright. It was assumed that with at least one of the patterns, newborns would not detect a brightness difference between the colored-and-grey checks. Therefore, newborns would be able to detect such a pattern only if they could detect its hue. In this case, newborns should show a preference for this pattern as well as all other checkerboards over the matched grey squares.

Newborns were shown six green-and-grey (n=60), six yellow-and-grey (n=60), six red-and-grey (n=60) and six blue-and-grey (n=60) checkerboards and the matching grey squares. The results showed that regardless of the difference in luminance between the chromatic and achromatic checks, newborns demonstrated that they differentiated grey from green, from red, and from yellow. However, when viewing blue-and-grey checkerboards, newborns did not show a preference for two of the patterns over their matching grey squares. Secondly, the pattern of newborns' preferences for these blue-and-grey checkerboards over the matched squares was very similar to what it had been when newborns were shown achromatic checkerboards in Experiment 2. This pattern suggests that only contrast information was present when newborns viewed these "blue"-and-grey checkerboards. A subsequent experiment with 1-month-olds revealed that infants at this age were able to differentiate the blue from the grey checks in the checkerboards.

These data constitute the first demonstration of color vision in newborns. They imply that newborns possess at least one functioning cone system and that at least some portion of the geniculostriate pathway may be operational. The data also suggest that there are limitations on newborns' color vision: Newborns appeared not to detect the short-wavelength hue. Moreover, the luminance at which their

preference for a blue-and-grey stimulus disappeared is consistent with previous reports that young infants see short-wavelength light as relatively brighter than do adults.

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THIS THESIS IS DEDICATED TO THE LOVING MEMORY OF MY MOTHER

HELGA (BRAMMANN) ADAMS

1934-1983

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Introduction

Color vision has been a focus of attention in a number of disciplines. However, little is known about the ontogeny of color vision. This paucity of knowledge has not resulted from a lack of interest since speculation about, and observations of, developmental trends in color vision have been made since the beginnings of experimental psychology (see Bornstein, 1978; Teller & Bornstein, 1983; and Werner & Wooten, 1979 for reviews). As we shall see in Chapter 1, it has resulted instead from a lack of adequate methods to test color vision.

The evaluation of newborns' color vision addresses a number of empirical and theoretical issues. At this point, it is not known whether the newborn perceives our chromatic environment in black-and-white, in full color, or in partial color. In addition, a study of color vision may provide information about the anatomical and physiological maturity of certain neural structures (Jacobs, 1976). For example, the process of converting physical wavelengths to neural signals relies upon a functioning cone system(s) in the retina. Beyond this level, chromatic signals are organized and transmitted along specific pathways through the lateral geniculate nucleus and finally to the visual areas of the occipital cortex (see DeValois, 1973; Hubel & Weisel, 1962; 1966). These structures are also responsible for other important visual functions such as form perception (De Valois, 1973). Given the anatomical data implying that certain portions of the nervous system such as retinal cones (Mann, 1933) and the visual cortex (DeCoursey, 1977) are immature in young infants, assessment of the state of newborns' color vision would be beneficial in helping to determine the degree to which these structures function.

The research presented in this thesis constitutes a behavioral evaluation on newborns' color vision. In addition to implications for neural development, these data also explore how color and contrast interact to determine young infants' visual preferences.

CHAPTER 1: Previous Findings on Infants' Chromatic Vision

a) Early Empirical Tests of Infants' Color Vision.

Infants' chromatic vision has been a topic of empirical concern for the past few centuries. Much of the early work was based on simple observations of infants' behavior in the presence of different colors. In his famous baby biography, Darwin (1877) noted that his son Doddy did not appear to respond differentially to different colors until his 49th day of life. However, Darwin did not control for the possibility that his son was responding on the basis of brightness and not hue differences between these stimuli. Several investigators in the early part of the 20th century realized this potential difficulty and attempted to control brightness by recording infants' responses to chromatic stimuli that adults perceived as equally bright.

Holden and Bosse (1900) presented 6- to 12-month-olds with six colored papers, each mounted on a grey background. The brightness of the background was judged by adults to be the same as the brightness of the hues. Holden and Bosse argued that if infants showed interest and grasped at any of the colored stimuli, this would indicate that they could discriminate the hue from its background. The results showed that only after the tenth month did infants grasp at all of the stimuli. Marsden (1903) examined the development of color sensitivity in his son by presenting him with a pair of "equally bright" colored balls and recording which of the pair the infant preferred to grasp. Marsden discovered that by the fourth month, his son showed definite preferences for certain hues. Marsden's son grasped mostly at yellow, followed by blue or red, white or green, black, and finally, brown. Using a similar procedure, McDougall (1908) found that 6-month-olds preferred red, green and blue stimuli over grey stimuli that adults judged to be as bright as the colors. McDougall concluded that these infants showed a well developed ability to detect the primary hues. This finding was essentially replicated in similar studies by Myers (1908) and Wooley (1909). However, the infant that Wooley tested detected all but a green stimulus. In a procedure incorporating reinforcement contingent upon the infant grasping at one member of a pair of colored stimuli, Valentine (1914) reported that an infant as young as 3 months showed evidence of detecting red, yellow, brown, blue and green stimuli that adults judged to be equally bright. In summary, many of these authors concluded that by 3 to 6 months, infants have the ability to detect most colors and secondly, appear to have developed color preferences.

Although the use of infants' grasping is convenient as a dependent measure, later researchers (see Bornstein, 1976; and Werner & Wooten, 1979 for reviews) argued that grasping is too variable and insensitive to be a reliable index of infants' color perception. This criticism stemmed from the fact that grasping is a perceptual-motor response which relies on very complex neural coordination. Thus, the onset of coordinated grasping rather than of color vision may have been what was actually measured in these studies. As a result, different techniques were sought in the hope of "tapping" color perception in younger infants.

One such technique is to catalog infants' overt behavior in the presence of different colors. Pratt, Nelson and Sun (1930) observed the entire repertoire of newborns' physical movements to colored light. Pratt et al. found that in several cases, the number of newborns' movements (e.g. number of head movements) depended upon what color infants viewed. However, Smith (1936), using what he termed "the immediate response" (i.e. bodily activity, rate of respiration, and crying), discovered that newborn males responded to no colored stimulation whereas newborn females responded to blue, green and yellow but not to red stimulation.

Although the multiple response methods employed in the Pratt et al. and Smith studies were useful in evaluating young infants' responses to color, like grasping, such measures are only indirect indicators of color perception. Chase (1937) devised a new method to study 2- to 10-week-olds' responses to color. In Chase's experiment, infants were required to visually track a colored stimulus which moved across a larger background field of a different color that adults judged to be the same brightness as the stimulus. He found that infants at all ages consistently tracked all of the stimuli, regardless of the color of the background. Spears (1964) measured the amount of time that 4-month-olds spent looking at each member of a pair of "equally bright" Munsell hues (1). On any given trial, infants viewed a grey patch and either a red, yellow or blue patch. The results indicated that, with all pairings, 4-month-olds spent more time looking at the chromatic than at the achromatic member of the pair. In a more recent study, Fagan (1974) exploited the fact that infants prefer to look at patterned over unpatterned stimulation. Fagan showed 4- to 6-month-olds a pair of stimuli, a checkerboard in which the checks (e.g. red and green) were constructed from equal-brightness Munsell papers and a solid colored square (e.g. red or green). Fagan tested infants with checkerboards composed of every possible combination of the four primary hues. Fagan argued that if infants saw the checkerboard as a pattern composed of two hues, they should prefer to look at it rather than at the plain square. The 4- to 6-month-olds showed a preference for all of the checkerboards over the single-hue squares. Based on these findings, Fagan concluded that color vision is well developed by 4 months of age.

The studies outlined in the past few pages reveal how methods of measuring infants' responses to color have become more sophisticated. Collectively, the majority of studies appear to show that infants, from birth, may show some sensitivity to at least the primary hues. However, despite the elegance of some of the response measures employed and the attempts to control brightness cues (e.g. the use of Munsell hues), these data have been criticized on a number of grounds (c.f. Bornstein, 1976; Werner & Wooten, 1979). The most serious of these is the use of colors in which the brightness has been matched by adults. Since young infants possess several relatively immature neural structures (Maurer, 1975) such as the retina (Abramov et al., 1982; Mann, 1933), young infants may perceive the brightness of hue quite differently than do adults. As we will see in the following section there is some good evidence to support this claim.

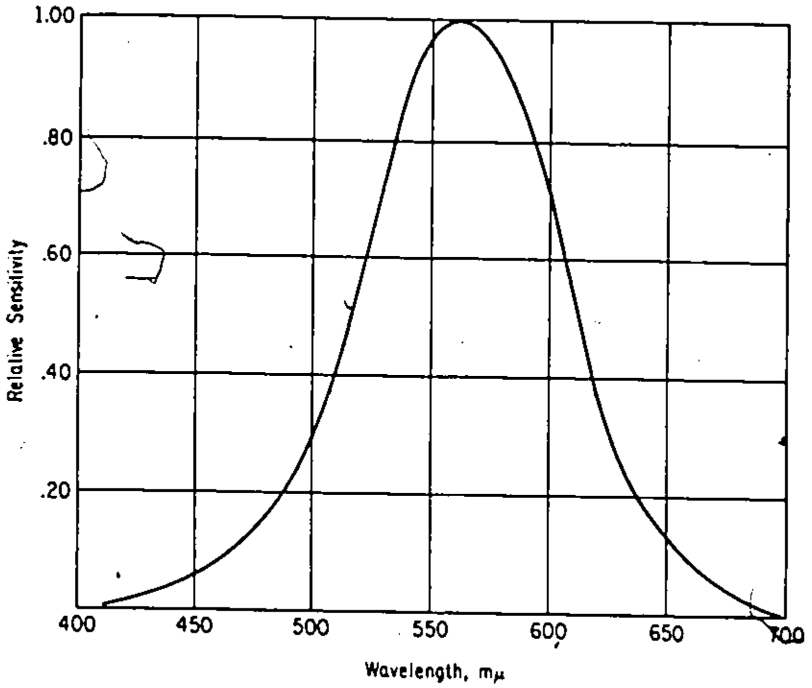
b) The Brightness Problem.

To demonstrate color vision in any species, it is necessary to be certain that the organism is responding differentially on the basis of perceived hue. This implies that the organism is not perceiving differences among hues by discriminating only the other components of color, brightness and saturation. Saturation is defined as the physical purity of the wavelength: The addition of other wavelengths or white or grey light to a single wavelength reduces its purity and thus, the color appears desaturated. Saturation poses little methodological problem in that it is a covariate of hue, i.e. the perception of saturation depends on the perception of hue. In addition, adults are relatively insensitive to variations in saturation (c.f. Hurvich, 1982), so it is reasonable to assume that infants are too. The control of brightness is more critical for two reasons. First, it is a component of color that can be perceived independently of hue. That is, an organism might discriminate one chromatic stimulus from another by merely noting that one is lighter or darker than the other. For example, when viewing a black-and-white photograph of a brightly colored scene, it is very easy for us to recognize objects by simply attending to the differences between the various shades of grey. Secondly, the human visual system is very sensitive to brightness differences (Graham, 1965). Given this fine sensitivity to brightness, studies of infants' color vision must take into account this potentially serious confound between brightness and hue.

The term used to describe how an organism's visual system responds to the luminance of different wavelengths is called spectral sensitivity. Teller and Bornstein (1983) argue that "although brightness and spectral sensitivity are not identical in adult vision (LeGrand, 1972), in practice one is a good predictor of the other; and, if infants' spectral sensitivity were known in a given situation, it might be used to provide a first approximation to infant brightness matches in that situation" (pg. 17). Figure 1 shows a typical adult spectral sensitivity function obtained under photopic (cone vision) conditions. Sensitivity is highest in the mid-spectral (green) region and decreases substantially with shorter (blue) or longer (red) wavelengths. Spectral sensitivity has been a good predictor of how adults perceive brightness since adults consistently report that they see a mid-spectral wavelength as brighter than either short or long wavelengths (Hurvich, 1982).

Some recent investigations have shown that infants' spectral sensitivity differs from adults' in some spectral regions. Peeples and Teller (1978) measured infants' and adults' photopic spectral sensitivity by finding the minimum amount of light necessary in order for 2-month-olds and adults to track a stimulus of a given hue moving over a white background field. Peeples and Teller found that infants' and adults' curves were relatively similar except at the spectral extremes (i.e. red and blue), regions where adults appeared more sensitive than 2-month-olds. Other studies have used the amplitude of the visually evoked cortical potential (VEP) to measure infants' spectral sensitivity. Dobson (1976) reported that after equating the peaks of infants' and adults' curves at 550nm, VEP amplitudes were similar at wavelengths that were 550nm or longer but infants showed less

Figure 1. Photopic spectral sensitivity (luminosity) curve of a standard adult eye. The ordinate is in units of sensitivity relative to the peak value, which is given the value of 1.00. The abscissa is in units of wavelength (millimicrons).


1.00
.80
.60
.40
.20
Relative Sensitivity
400
450
500
550
600
650
700
Wavelength, mμ

drop-off in sensitivity when tested with shorter wavelengths. Moscowitz-Cook (1979) also derived VEP spectral sensitivity curves for 3- to 22-week-old infants and adults. For wavelengths greater than 550nm, adults and infants generated curves that were virtually identical. However, infants again showed less of a drop-off in sensitivity with wavelengths less than 550nm. The general conclusion from studies examining infants' photopic spectral sensitivity is that infants and adults differ in their sensitivity to short-wavelengths (2). It is not clear what accounts for this difference. However, Werner (1982) has systematically examined the transmission properties of adults' and infants' eyes and found that because the lens pigment is less dense in infants' eyes, short-wavelength light is transmitted more readily to the receptors in infants' than in adults' eyes.

The finding that young infants' spectral sensitivity differs from adults' in certain spectral regions (most notably in the short-wavelengths) makes it inappropriate to estimate at what luminance infants might perceive two hues as equal in brightness with single values obtained from studies of hue matching in adults (3). As a result recent researchers have developed alternate methods to control for the potential confound of brightness and hue.

In their major review, Teller and Bornstein (1983) outlined two methods by which brightness can be controlled in studies of color vision. The first of these methods involves the unsystematic variation of luminance from trial to trial. In this procedure, "an approximation to the infant's brightness match (e.g. an adult's brightness match) is first set up between two chromatic stimuli, A and B. The relative luminances of the two stimuli are then varied unsystematically from trial to trial, over a wide range around the initial approximation of the infant's brightness match" (pg. 14). In some cases, the infant would perceive stimulus A as some degree lighter than stimulus B, in other cases, the infant would perceive A as darker. Then on any given trial, if the infant was responding only to the brightness of A or B, he would direct his visual behavior to the lighter or the darker of the two stimuli (depending upon his preference). If the baby responds consistently to one of the hues, one can conclude that he can differentiate A from B on the basis of hue. As Teller and Bornstein state, "consistent responding by the infant to one of the two chromatic stimuli, collapsed over all luminance pairings, cannot be carried out on the basis of brightness, and discrimination can therefore be attributed to the preservation of wavelength information" (pg. 14).

A second approach to the brightness problem is the systematic variation of luminance. In this case, "the infant is shown many trials of each of a series of several relative luminances of two chromatic stimuli, A and B, centred around the initial estimate of the infant's brightness match. Provided that the range of relative luminances used encompasses the infant's true brightness match, at least one of the relative-luminance pairings used will be likely to confront the infant with luminances of A and B which differ indiscriminably in brightness" (pg. 14). Therefore, if the infant chooses A or B consistently for all luminances, this implies that he can differentiate the two hues. If however, on one of the pairings in the series, the infant does not choose A or B consistently, this implies that he does not detect the color or brightness variation and hence, does not differentiate the hues.

These methods have been utilized with a number of response measures. It is to these experimental investigations that we now turn.

i) Experiments incorporating the unsystematic variation of luminance. The general goal of this type of experiment is to present the infant with a number of "examples" of a grey and of a hue of different luminances and subsequently analyze the data to see if his pattern of responding changes when color is present or not. In a study by Bornstein (1976), 3-month-olds viewed a blue-green stimulus for 12 consecutive trials. On each of these trials, the luminance of the blue-green stimulus was randomly selected from a range of values centred upon an adult brightness match for blue-green and white. Over the course of the 12 trials, infants gradually decreased the time that they spent looking at the stimulus. On trials 13 and 14, the stimulus was changed from blue-green to a white which equalled the average luminance of the series of blue-greens. Infants increased their looking time on these "white" trials. This implies that they "detected" the white as novel and therefore, Bornstein's data suggest that 3-month-olds are capable of discriminating blue-green from white. Also, the averaged looking times were about equal for all the different luminances of the blue-green. This suggests that infants were not responding favorably to one or a few of the luminance values in the series of blue-greens, and implies that under these experimental conditions infants' responses were influenced mostly by the hue of the stimulus and not its brightness.

Oster (1975) adopted a different strategy in her study of 2-month-olds' color vision. Infants were presented with a pair of checkerboard-like 3 x 3 patterns. One pattern contained nine grey squares of various luminances whereas a second pattern was composed of eight grey squares plus one square that was either blue, yellow, green, or red. To adults, the luminance of the chromatic square was close to the average luminance within the nine greys. If 2-month-olds had not been able to perceive a particular hue, one would expect that infants would not respond any differently to this stimulus than to the other all-grey pattern. On the contrary, 2-month-olds looked longer at the patterns which contained the colored squares than at the pattern composed only of grey squares. These data suggest that infants were able to detect the color within all of the patterns. Oster therefore concluded that 2-month-olds can differentiate the primary hues from grey.

In another study, Schaller (1975) used a different technique to examine 2-month-olds' responses to red and green. Half of the infants were required to fixate the red member of the stimulus pair and upon doing so, were reinforced with an auditory stimulus. The other infants were required to fixate the green member of the pair. The luminance of each member of the pair was varied randomly from trial to trial over a large range (3.65 - 651 cd/m^2). Schaller argued that if infants were responding only to the brightness of the stimuli, they would not learn the contingency and most likely, would respond to the brighter or darker of the stimulus pair. Schaller found that 2-month-olds could be trained to consistently respond to the appropriate color and hence concluded that infants could differentiate red from green.

Thus, the data obtained from studies in which luminance was varied unsystematically have revealed that by 2 to 3 months of age, infants appear to detect many hues.

ii) Experiments incorporating the systematic variation of luminance. To the present day, the only data generated by this technique have been provided by Davida Teller and her colleagues. In their first study, Peeples and Teller (1975) examined 2-month-olds' discrimination of luminance as well as their ability to differentiate red from white. In the first phase of the experiment, 2-month-olds were shown an achromatic bar of some luminance on a white background of standard luminance. On every trial, an observer was required to guess on which side of the background the bar was actually located. The observer based these judgments on the infant's head and eye movements. Infants were said to be able to detect the contrast between a bar and its background if the observer guessed correctly the location of the bar on at least 75% of the trials. The results indicated that infants detected the bar when it differed from the background in luminance by more than .02 log units (a contrast of about 5%).

Armed with this information, Peeples and Teller then tested 2-month-olds' color vision. Their logic was quite simple: If infants were shown a colored (in this case, red) bar of some luminance on a white background of some luminance and, to the infant, the luminance contrast was 5% or less, the infant would be able to perceive the bar only if he could see its hue. However, Peeples and Teller could not predict the luminance at which 2-month-olds would not perceive a brightness difference between the bar and its background. As a result, they tested infants with a number of red bars of varying luminance selected from a range centred upon the luminance at which an adult would perceive the red and white as equally bright. Peeples and Teller assumed that when presented with at least one of the bars, 2-month-olds could not distinguish this bar from the background solely on the basis of brightness differences. To insure this, the difference in contrast between one bar/background pair and the next pair in the series was never more than 5%. Therefore, if infants showed evidence of detecting all of the red bars in the series, this would imply that they could perceive the hue in the bars. But if infants failed to detect at least one of the red bars in the series, this would imply that 2-month-olds did not detect the hue information in the stimulus.

Peeples and Teller showed 2-month-olds 12 different red bars, each of which contrasted with its background by some value. To an adult, six of the bars were lighter and six were darker than the background. Peeples and Teller found that 2-month-olds detected all of the red bars in the series. This pattern of results rules out the possibility that infants were responding only on the basis of brightness contrast between the red bar and its background. These data provide strong evidence that 2-month-olds possess some form of color vision.

Teller and her colleagues later used this technique to examine 2-month-olds' responses to other spectral hues. Teller, Peeples and Sekel (1978) presented infants with bars of blue, greenish blue, green, yellowish green, greenish yellow, yellow, orange, red, reddish purple,

purple and bluish purple on a white background. The luminance contrast between the bars and the background was varied in the same manner as in the Peeples and Teller (1975) study. The results indicated that infants detected blue, greenish blue, green, orange and red at all the contrast values. However, when infants were shown greenish yellow, yellowish green or purple bars of certain luminances on the white background, the observer's performance fell to chance. These luminances were very close to those at which adults would match the colors and the white. Teller et al. offer three explanations for 2-month-olds' apparent failure to detect these hues. The first is that 2-month-olds are color deficient and possess dichromatic neutral zones (4) similar to those apparent in color deficient adults. However, the spectral locations of color deficient adults' neutral zones and the locations where 2-month-olds failed to discriminate colored from white light are so dissimilar that it is unlikely that infants are typical dichromats. Another explanation offered by Teller et al. is that infants actually do have the capacity to detect these hues, but the hues appear desaturated and thus, may not provide a very compelling stimulus. Lastly, these authors propose that infants' apparent failure may have been due to attentional or motivational factors. It is quite possible that infants, like adults, can detect green-yellow hues but prefer to look at others. Therefore, over a series of trials, infants may have become somewhat "bored" with the green-yellow bars and stopped fixating them. Whatever the explanation, these data have revealed that 2-month-olds do not show the same sensitivity to all hues. Further experimentation is needed to determine whether 2-month-olds have some non-conventional color deficiency or whether infants perceive some hues as relatively desaturated or non-preferable.

The systematic variation of luminance has also been used to examine Rayleigh discriminations. A Rayleigh discrimination for a subject is obtained when he differentiates 535nm (green) and 670nm (red) light from a 589nm (yellow) light. Dichromacy is diagnosed if the subject fails to discriminate either the green (deuteranopia) or red (protanopia) lights from the yellow light. Hamer, Teller and Morris (1980) examined the ability of 2- and 3-month-olds to discriminate red and green of varying luminances from a yellow background. Again, the minimum change in contrast between the colored bars and the yellow background was determined by examining infants' sensitivity to contrast under these conditions. The logic of their study is as follows: If infants, like color deficient adults, failed to discriminate some of the red and/or green bars from the yellow background this would be strong evidence that infants have similar color vision deficits. Hamer et al. found that 3-month-olds easily discriminated the red and green bars from the yellow background at all contrasts. The same was true for the majority of 2-month-olds, although a few subjects did fail to discriminate some of the bars. In general, these infants, like adult protanopes, failed to differentiate some of the red bars from the yellow background.

We have observed in both the studies of Hamer et al. and of Teller et al. that the 2-month-old is certainly capable of detecting hue even when brightness cues have been minimized. These investigations have also revealed that infants' color vision may differ from that of normal adults.

Other studies have also noted limitations on infants' color vision. In follow-up studies to Hamer et al.'s investigation, Teller and her colleagues observed that when the chromatic stimulus was smaller (i.e. 2° x 2° as compared to 4° x 4° in the Hamer paper), 2-month-olds showed no evidence of discriminating green or red from yellow. As a result, Teller and Hartmann (1981) systematically examined the effect of the size of a chromatic stimulus on 1- and 3-month-olds' discrimination of hue. Three-month-olds were shown both 2° x 2° and 4° x 4° red stimuli of varying luminance on a yellow background. As expected, 3-month-olds showed evidence of detecting the red stimulus when it was 4° x 4°. However, when the red stimulus was reduced to 2° x 2°, infants appeared not to discriminate it from the yellow background. Nonetheless, individual differences were quite pronounced. When testing one particular infant, the observer was virtually always correct with stimulus sizes as small as 1° x 1°.

Teller and Hartmann also tested 1-month-olds' discrimination of a series of 4° x 4° and 8° x 8° red stimuli from a yellow background. These infants showed evidence of discriminating the two hues only when the red field was 8° x 8°. Initially, Teller and Hartmann could not explain why test field size affected infants' hue discrimination. However, upon examining some of the adult and infrahuman literature, they discovered that adult dichromats (Smith & Pokorny, 1977; Nagy & Boynton, 1979; and Gordon & Abramov, 1979) and cats (Loop, Bruce & Petulowski, 1979) show evidence of detecting wavelengths when the size of the stimuli was very large. This research suggests that dichromats, infants and cats may possess a relative scarcity of one or more of the three cone types (c.f. Hurvich, 1982) and thus a large chromatic field is required to activate a significant number of these cones.

To the present day, studies in which luminance has been varied systematically have provided the best evaluation of infants' color vision. In summary, these investigations have shown that by the age of 2 to 3 months, infants show definite sensitivity to most hues. In addition, infants as young as 1 month do show evidence of some hue discrimination. However, the color vision of infants who are two months of age or younger has a number of restrictions. These babies do not appear to discriminate either yellow-green or purple from white light. As mentioned this may be due to insufficient neural development, to variations in perceived saturation, or to color preferences. Secondly, the size of the color field must be large (i.e. at least 8° x 8° for 1-month-olds and at least 4° x 4° for 2-month-olds) for these infants to show evidence of discrimination.

However, these procedures have yet to be extended into the newborn period. As a result, we know little about the onset of color vision. The early studies examining newborns' detection of color did not adequately control for the possibility that infants were differentiating colored stimuli on the basis of brightness and hence allow no conclusions. The only modern data that exist have been obtained from three electrophysiological studies. Barnet, Lodge and Armington (1965) measured newborn electroretinograms (ERGs), which are recordings of the changes of the electrical activity in the retina of the eye. Barnet et al. found that when presented with orange light, newborns, like adults, display an early positive x-wave. This x-wave is thought to be indicative of photopic (cone) functioning (Adrian, 1945). In extending this finding, Lodge, Barnet, Shanks, and Newcomb (1969) recorded visually evoked potentials (VEPs) when newborns were shown orange and white light. VEPs are an index of underlying electrical activity in the cortex. Lodge et al. discovered that newborns show higher amplitude VEPs to orange than to white light, a finding that is again characteristic of photopic activity. In another VEP experiment, Fischel (1969) reported that newborns show higher amplitude VEPs to blue, green and red light than to white light. In addition, VEP amplitudes are different for every color. However, a number of problems exist in inferring that newborns show evidence of photopic activity. First, these studies used colored stimuli that adults judged to be of equal brightness. As has been pointed out many times in previous discussions, the differences between infants' and adults' spectral sensitivity make adult brightness matches inappropriate for infants. Since infants' and adults' photopic spectral sensitivity is different, newborns' responses may have been based on the detection of brightness variations between the colored stimuli. In addition, differential response patterns obtained from such gross electrophysiological methods, although suggestive, tell us little about what the infant actually sees. These techniques indicate that the presentation of a stimulus evokes some change in the underlying neural substrate. Whether this change is sufficient to allow the organism to perceive variation in the visual world will remain unknown until electrophysiological events can be correlated with actual behavior. Thus, if a newborn demonstrates behaviorally that he can differentiate a chromatic from an achromatic stimulus of equal brightness, this is much stronger evidence for the perception of color. This is precisely the focus of the research in this thesis.

In the following series of experiments, I have studied newborns' color vision by exploiting their preference for a pattern over a plain stimulus (c.f. Fagan, 1974; Fantz, 1963; Fantz, Ordy & Udelf, 1962). In the present studies, newborns were shown simple checkerboard patterns composed of colored (e.g. red) and grey checks and comparison all-grey squares. The luminance of this grey square equaled the average luminance of the checkerboards. If newborns could differentiate the colored from the grey checks, then the stimulus should look like a pattern and be preferred over the grey square. This of course sounds very similar to the logic of the previously described Fagan (1974) study. However, to test each color pair, Fagan used only one checkerboard made up of two colors which adults would perceive as equally bright. In the present studies, I have adopted the logic of Peeples and Teller (1975) and have systematically varied the luminance contrast between the colored and grey components of the checkerboard. If newborns were to show a preference for all checkerboards in the series over the respective grey squares, this would imply that newborns can differentiate the colored from the grey checks.

However, as demonstrated in the Peeples and Teller (1975) experiment, the systematic variation of luminance is a two-step process. One must first know how sensitive newborns are to luminance contrast.

In the subsequent color phase of these experiments, one then uses this contrast information to systematically vary the contrast within a series of colored and grey patterns.

The general plan of this thesis is as follows. In Chapter 2, I describe a pilot experiment that served to replicate the basic pattern preference phenomenon and to establish procedural parameters for subsequent investigations. In Chapter 3, I report a series of experiments that deal with newborns' sensitivity to contrast. Incorporating the findings of Chapter 3, in Chapter 4, I describe a series of experiments which analyze newborns' responses to the four primary hues, red, green, blue and yellow. In the final chapter I will discuss the implications of this work and suggest some possible mechanisms which underly the development of chromatic vision.

CHAPTER 2: General Methodology and Pilot Work

Experiment 1

The purpose of this experiment was to devise a method that would be useful for subsequent investigations of newborns' ability to detect contrast and to discriminate color. The requirements for such a method were that it be appropriate for the newborn period (i.e. not be too lengthy), and that it use behaviors within the newborn's repertoire. It is well known that newborns prefer to look at a pattern rather than at a homogeneous stimulus (Fantz, 1963; Fantz, Ordy & Udelf, 1963). Fantz and his colleagues employed a "stimulus choice" procedure in which the newborn was presented with a checkerboard and a plain square, one on the left and one on the right side of the stimulus field. In order to discover which of the stimuli the infant preferred, the observer's task was to record the amount of time that the infant spent looking at each stimulus. The results showed that infants looked longer at the checkerboard than at a plain stimulus.

In Fantz's experiments, an observer judged the length of a fixation by recording when the reflection of either of the stimuli fell near the centre of the infant's pupil. A problem with Fantz's general procedure is that young infants very often favor a particular side of the stimulus field regardless of its stimulus properties (c.f. Harris, 1973). To eliminate side biases, in the present study newborns were shown stimuli in a successive manner. In addition, due to the extreme response variability shown by a typical infant (c.f. Bornstein, 1978;

Salapatek & Banks, 1977), I chose to adopt an "infant control procedure" (Horowitz, Paden, Bhana & Self, 1972). This is a technique that deals effectively with such variability. In this method, the observer(s) records the length of the infant's first fixation on a stimulus. A trial ends when the infant looks away from the stimulus for some predetermined period of time (e.g. 2 seconds). As a result, the infant actually "controls" the length of each trial and there is no fixed trial length.

When starting this research, the applicability of an infant control procedure to a newborn population (5) was unknown. Nonetheless, for the reasons outlined above, I thought this procedure would be potentially very useful for the study of newborns' perceptual abilities.

In the first study, I attempted to replicate the finding that newborns prefer to look at a simple pattern rather than at a plain stimulus. Both the pattern and the plain stimulus were presented successively and newborns' looking times were measured by an infant control procedure. In addition, for the purposes of designing future experiments I was interested in the number of trials that newborns needed in order to show a preference for a patterned over a plain stimulus in addition to the number of trials that a newborn would remain alert in a typical session.

Method

Subjects

The subjects were 25 infants, 1- to 5-days-old ($\bar{x}$ = 3.2 days), at least 38 weeks gestation, at least 2500 grams at birth and selected from the McMaster University Medical Centre. An additional four newborns were tested but not included in the sample: three because they did not complete a single block of trials (fell asleep or were too fussy) and one because of low Spearman interobserver reliability (rho < .70).

Stimuli

The patterned stimulus was a high contrast (88%) black-and-white 2 x 2 checkerboard pattern. The plain stimulus was a 9 cd/m^2 homogeneous grey square which approximated the average luminance of the checkerboard pattern. When viewed from 40 cm, the stimuli were 16° x 16° and each check within the checkerboard was 8° x 8°.

Apparatus

The infant faced a vertical rear-projection screen (41 cm wide x 29 cm high or 54° x 38°) mounted in a black board. The stimuli, mounted in glass slides, were illuminated by white light and projected by a Kodak Carousel 600 projector. Small, 1 cm peep holes on each side of the screen permitted observers behind the screen to see the infant's eyes. The observers were equipped with switches that operated a shutter system mounted in front of the projector lens and with timers which allowed them to record infants' fixation times.

Procedure

An experimenter placed the baby in an infant seat inclined at 45°. The infant's eyes were approximately 40 cm from the centre of the screen. During each trial, two observers, one of whom was unaware of the actual stimulus, independently timed the length of the infant's first fixation on the stimulus by observing when the image of the stimulus fell over the centre of the infant's pupil. After both observers independently judged the baby to have looked away from the stimulus, a trial ended and the shutter in front of the projector lens was closed. The intertrial interval was approximately 10 seconds.

Each of the stimuli (the checkerboard and the grey square) was presented twice within a block of four trials in a predetermined ABBA or BAAB order. Order was counterbalanced across subjects. Blocks were repeated until the infant was no longer alert. The statistical analyses included only those infants who contributed one or more blocks of trials and for whom the interobserver reliability was > .70. For the 25 subjects in the final sample, the mean Spearman interobserver reliability coefficient was .93 (range = .70-1.00).

Results and Discussion

On the average, newborns completed 2.87 blocks (range = 0 - 7) and 11.48 trials (range = 1 - 28). The 25 newborns who met the requirements to be included in the final sample completed 3.16 blocks (range = 1 - 7) and 12.64 trials (range = 4 - 28). For each trial, I calculated the mean of the times recorded by the two observers. For each block of each subject, I computed the mean amount of time spent looking at the checkerboard and at the grey square. From these values, I computed the difference between the time the baby looked at the checkerboard and the time he looked at the square. Wilcoxon analysis for matched pairs was performed on all differences and revealed that newborns looked longer at the checkerboard than at the plain grey square, $T(25) = 18$, $p < .005$. Since newborns demonstrated a preference, this implies that they were able to detect the luminance difference between the black and the white checks in the checkerboard. This preference for a patterned over a plain stimulus supports the previous findings of Fagan (1974), Fantz (1963) and Fantz et al. (1963). In addition, an infant control procedure was successful in replicating this pattern preference.

Another question of interest was the number of stimulus presentations that were required in order for these 25 newborns to show a significant preference for the checkerboard. A cumulative blocks analysis was performed and revealed that newborns looked longer at the checkerboard in block 1 [T(25) = 47.5, $p < .005$], in blocks 1 and 2 combined [T(19) = 19, $p < .005$], and in blocks 1, 2, and 3 combined [T(16) = 34, $p < .005$]. Since only nine subjects completed four or more blocks, the analysis was not performed on more than three blocks. These data show that after just a single block (two presentations of the checkerboard and of the square), newborns demonstrated a clear preference for the pattern. Therefore, in subsequent experiments with this technique and a similar sample size, one can assume that one block per level of the independent variable is sufficient for newborns to demonstrate whether or not they show a preference for a 2 x 2 checkerboard over a grey square.

In summary, the results of this pilot study have replicated the finding of Fantz and his colleagues that newborns prefer patterned to plain stimulation. Secondly, an infant control procedure was successful in recording newborns' preferences. Therefore, with these tools in hand, we can now examine newborns' sensitivity to luminance contrast and to color.

CHAPTER 3: Experiments on Newborns' Contrast Detection

Experiments 2 and 2a

Since the plan of this thesis is to systematically vary luminance contrast in a test of newborns' color perception, it is very important to specify how sensitive newborns are to contrast. Luminance contrast is formally defined as the difference in luminance between the components of a stimulus, expressed as a percentage and calculated by the formula $\frac{L_1-L_2}{L_1+L_2}$ where L_i refers to the luminance of each component (see Fig. 2).

Two groups of investigators have already examined newborns' ability to detect variations in luminance contrast. Doris and his colleagues (Doris & Cooper, 1966; Doris, Casper & Poresky, 1967) studied newborns' optokinetic nystagmus (OKN) to a field of moving stripes, and found that newborns showed OKN only when the stripes contrasted by at least 35%. More recently, Atkinson, Braddick and French (1978) recorded newborns' visually evoked potentials (VEPs) to stripes of varying contrast and spatial frequency. They observed evoked potentials only when newborns were presented with stripes which contrasted by at least 50%. These studies suggest that newborns are very insensitive to contrast since under similar luminance conditions, adults detect contrasts smaller than 1% (Steinhardt, 1936).

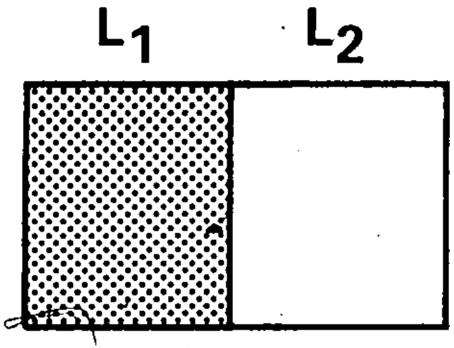
However, both OKN and evoked potentials are rather "peripheral" indices of sensitivity to luminance contrast, in that differential

Figure 2. Formula for calculating visual contrast: Given two luminances, L_1 and L_2, the contrast is simply the difference in luminance between L_1 and L_2 divided by the sum of their luminances.

CONTRAST FORMULA

$$\boxed{\frac{L_1 - L_2}{L_1 + L_2}}$$

WHERE L_i REFERS TO THE MEASURED LUMINANCE OF EACH STIMULUS COMPONENT



response patterns, although suggestive, tell us little about what the baby actually sees. In the studies reported below, I have used newborns' preferences for patterned over unpatterned stimulation to test their sensitivity to contrast. The patterned stimuli were a series of six 2 x 2 checkerboard patterns. Each of the checkerboards differed in the amount of contrast between the opposing checks. The plain stimuli were grey squares, each of which matched the mean luminance of one of the checkerboard patterns.

The logic of this experiment is again quite simple: If newborns show a preference for any checkerboard over its matched grey square, this implies that they saw the checkerboard as a pattern and thus detected the brightness differences between the checks.

Method

Subjects

The subjects were 60 infants, 1- to 5-days-old ($\bar{x}$ age = 3.2 days), at least 38 weeks gestational age and at least 2500 grams at birth. An additional 16 newborns were tested but not included in the sample, 12 because they did not contribute complete data and four because of low interobserver reliability (Spearman rho < .80). In Experiment 1, the criterion was .70. Since for most subjects in Experiment 1, the observers' reliability was greater than .80, I chose to adopt this new, more conservative criterion.

Stimuli

The stimuli were six 2 x 2 checkerboards in which the checks contrasted by either 27%, 23%, 17%, 11%, 5%, or 3% as measured by a Spectra Brightness Meter, Model UB (Photo Research Corporation). Each pattern was paired with its own plain grey square (composed of four equal-luminance quadrants) which matched the mean luminance of the checkerboard (range 3.6 to 4.5 cd/m^2). When viewed from 40 cm, the stimuli were 16° x 16° and each check within the checkerboard was 8° x 8°.

Apparatus

Most aspects of the experimental apparatus remained identical to those described in the pilot study. However, in this study, the stimuli were illuminated and projected by a Beseler Dicro 45MX II Color Computer system. This device offered the additional advantages of line voltage regulation, a light mixing chamber, steady luminous output over time and photosensitive detectors which provided continuous feedback on the chromatic characteristics of the transmitted light.

Procedure

The pilot data revealed that the average newborn contributed three blocks of four trials under an infant control procedure. In the present experiment, each newborn was shown three blocks of stimuli. Each of these blocks consisted of two presentations of one of three checkerboard stimuli and two presentations of the checkerboard's luminance-matched grey square. The thirty newborns in Group 1 viewed checkerboards in which the contrast was 3%, 17% and 27% and the matching grey squares. The thirty newborns in Group 2 viewed checkerboards in which the luminance contrast was 5%, 11% and 23% and their matching grey squares. Each of the stimulus pairs (a checkerboard and its control grey square) was presented twice within a block of four trials in a predetermined ABBA or BAAB order. Order was counterbalanced across subjects. The statistical analysis included only infants who contributed complete data (i.e. all three blocks) and for whom the interobserver reliability was > .80. For the 60 subjects in the final sample, the mean Spearman interobserver reliability coefficient was .94 (range = .82-1.00).

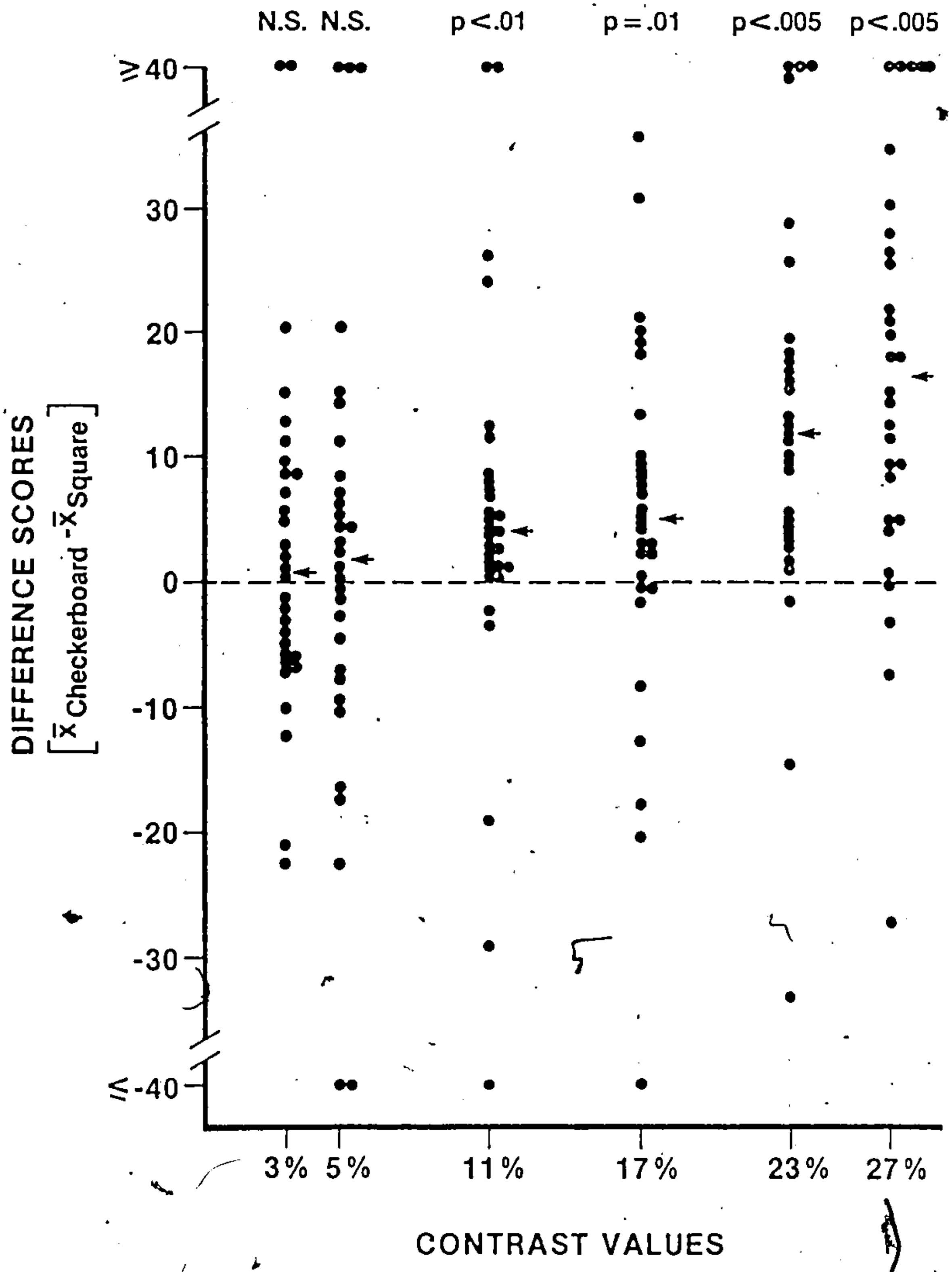
Results and Discussion

For each trial, I calculated the mean of the times recorded by the two observers. Then for each block of each subject, I computed the mean amount of time that the infant spent looking at each stimulus. From these values, I computed the difference between the time the baby looked at the checkerboard and the time he looked at the square. Thus, a positive score indicates that a newborn looked longer at the checkerboard than at the grey square, whereas a negative score indicates that he looked longer at the square. The results from Groups 1 and 2 are combined and summarized in Figure 3, which shows that most difference scores were positive for the checkerboards in which the contrast between the checks was 11% or greater.

A series of Wilcoxon analyses for matched pairs confirmed that newborns looked significantly longer at the patterns with checks contrasting by 27% [T(30) = 69, *p* < .005], by 23% [T(30) = 50, *p* < .005], by 17% [T(30) = 140, *p* < .01] and by 11% [T(30) = 117, *p* < .01] than at each of their respective matched grey squares. However, newborns did not show a preference for the checkerboard patterns in which the checks contrasted by 3% [T(30) = 240, n.s.] or by 5% [T(30) = 249, n.s.]. A second finding was that the magnitude of these difference scores appeared to increase with increasing contrast between the checks,

Figure 3. Distribution of the differences in looking time (mean looking time at the checkerboard minus the mean looking time at the square) at each contrast. Each dot represents the data from one newborn, and the arrows indicate the median difference score at each contrast. For the checkerboards in which the checks contrasted by 3% or 5%, newborns looked about equally long at both the patterns and the squares. However, with contrasts of 11% or greater most points lie above zero. This implies that newborns looked significantly longer at these checkerboards than at the luminance-matched grey squares.

NEWBORNS' DETECTION OF CONTRAST

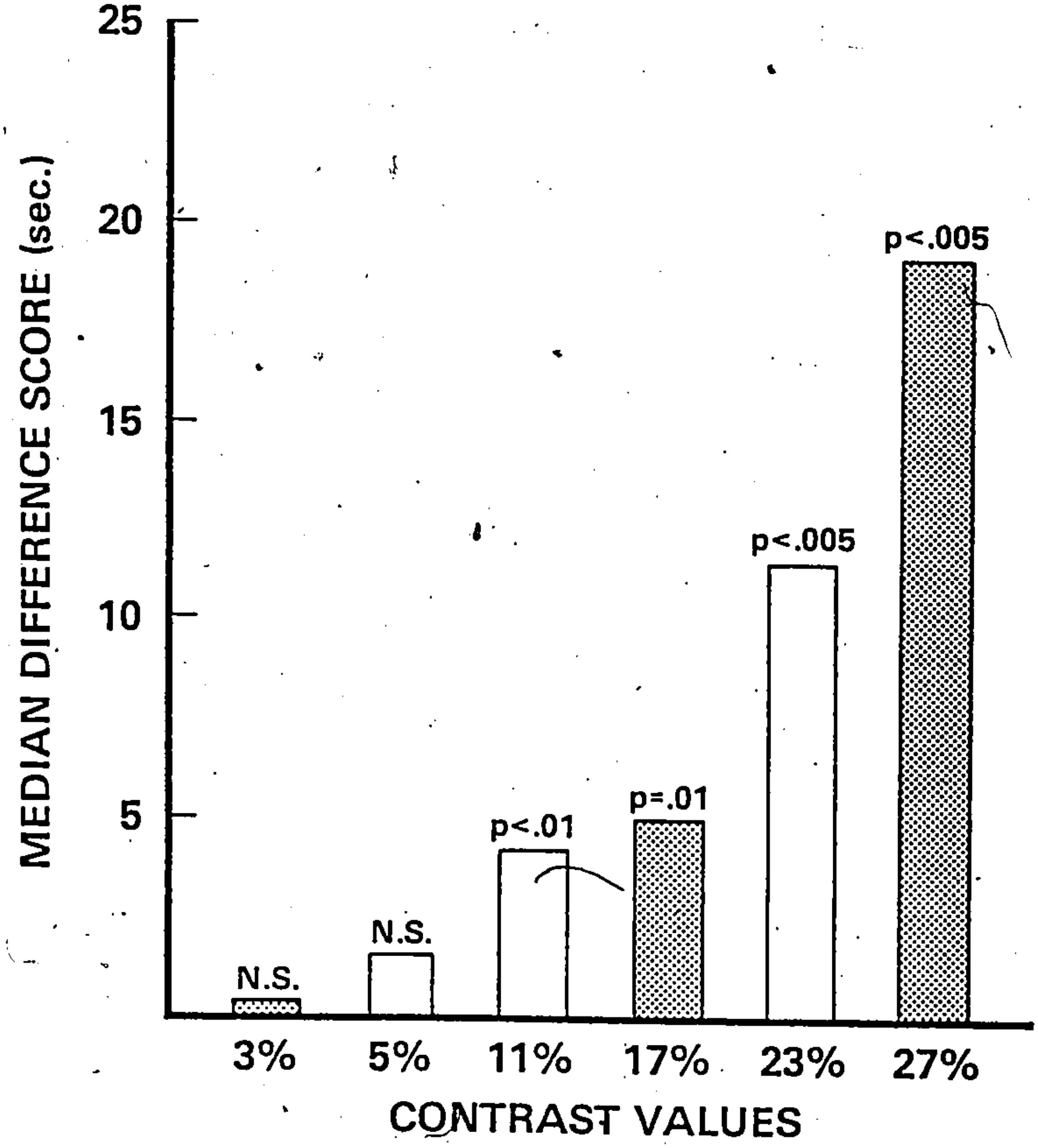


i.e. newborns' preferences were larger with the larger contrast. The median difference scores, represented as bars in Figure 4, demonstrate this pattern more clearly. This pattern is consistent with the common suggestion that large brightness differences (i.e. high contrast) are very appealing to the young infant (c.f. Fantz, 1963; Salapatek & Banks, 1977).

In summary, the results show that newborns are much more sensitive to contrast than the 35-50% limits estimated from previous reports measuring optokinetic nystagmus or evoked potentials. Newborns' apparent failure to respond to smaller contrasts in those studies may have been caused by the response variability which is very pronounced in measures of OKN and evoked potentials, or by the "peripheral" nature of these measures as indices of infants' vision. In addition, the evidence that newborns showed good sensitivity to contrast re-emphasizes the need for studies of color discrimination to demonstrate that newborns are responding to chromatic stimuli on the basis of hue and not brightness.

The manner in which newborns respond to varying degrees of contrast will be very important when interpreting the findings from the color studies. In these investigations of color vision, newborns are shown a colored-and-grey pattern and a luminance matched grey square. If newborns respond only on the basis of the brightness contrast and not the hue difference between the colored-and-grey checks, one would expect that they would generate a pattern of results very similar to those obtained in the present experiment.

Figure 4. Newborn's preferences for the checkerboards: Bars represent the median difference between looking time at the checkerboards and at the squares. White and specked bars differentiate the data obtained from the two groups of newborns.



NEWBORNS' CONTRAST DETECTION
(Combined Data)

Experiment 2a

Newborns' fine sensitivity to contrast is of obvious benefit in allowing them to distinguish objects in the visual environment. However, we know very little about how this ability develops. Thus, it would be valuable to evaluate how, and at what rate contrast detection develops during infancy. As a first step, I tested a group of 2-month-olds under experimental conditions identical to those used with newborns in Experiment 2.

In the literature, there are many discrepant reports on 2-month-olds' sensitivity to contrast (see Banks & Salapatek, 1981; and Salapatek, 1979, for reviews). For example, Doris et al. (1967) recorded 8-week-olds' optokinetic nystagmus responses to stripes of varying contrasts and observed OKN only when the stripes contrasted by more than about 17%. In contrast, Peeples and Teller (1975) examined the ability of 2-month-olds to detect a bar of light which contrasted with the background field by different amounts and found much greater sensitivity. Infants showed that they could detect the bar as long as it contrasted with its background by at least 3% (Weber Fraction = .05).

Several other studies have derived contrast sensitivity functions in 2-month-olds. Pirchio, Spinelli, Fiorentini and Maffai (1978) obtained measurable evoked potentials when infants were presented with sine waves contrasting by 29% or greater. Two investigations using preferential looking have found greater sensitivity to contrast. Atkinson, Braddick and Moar (1977) reported that 2-month-olds preferred a sine wave to a grey field when the sine wave had a contrast greater than about 18%. Banks and Salapatek (1978) found that 2-month-olds showed a preference even when the contrast of a sine wave was as small as about 8%. However, these values represent the "optimal" contrast sensitivities obtained with sine waves of 2 cycles per degree. With bigger stimulus components (like those used in the present study) both Atkinson et al. and Banks and Salapatek reported that 2-month-olds appeared to detect sine waves only when the contrast was 20% or greater, and Pirchio et al. found a cut-off as high as 47%.

Thus, the results obtained from observations of 2-month-olds' contrast detection have been extremely variable. Some studies (e.g. Peeples & Teller, 1975) have shown 2-month-olds to be very sensitive to variations in contrast whereas other investigators have found poor responsivity (e.g. Pirchio et al.). The range of the estimates (3%-47%) can probably be explained by differences in response measures, in luminance conditions, and in stimulus size. In order to study the development of contrast detection, I tested 2-month-olds with the same methods used in Experiment 2 to test newborns.

Method

Subjects

The subjects were 24 8- to 10-week-old infants ($\bar{x}$ age = 64 days) all of whom were at least 38 weeks gestational age and at least 2500g at birth. An additional five infants were tested but not included in the sample: three because they did not contribute complete data (fell asleep or were fussy) and two because of low interobserver reliability (Spearman rho < .80).

Procedure

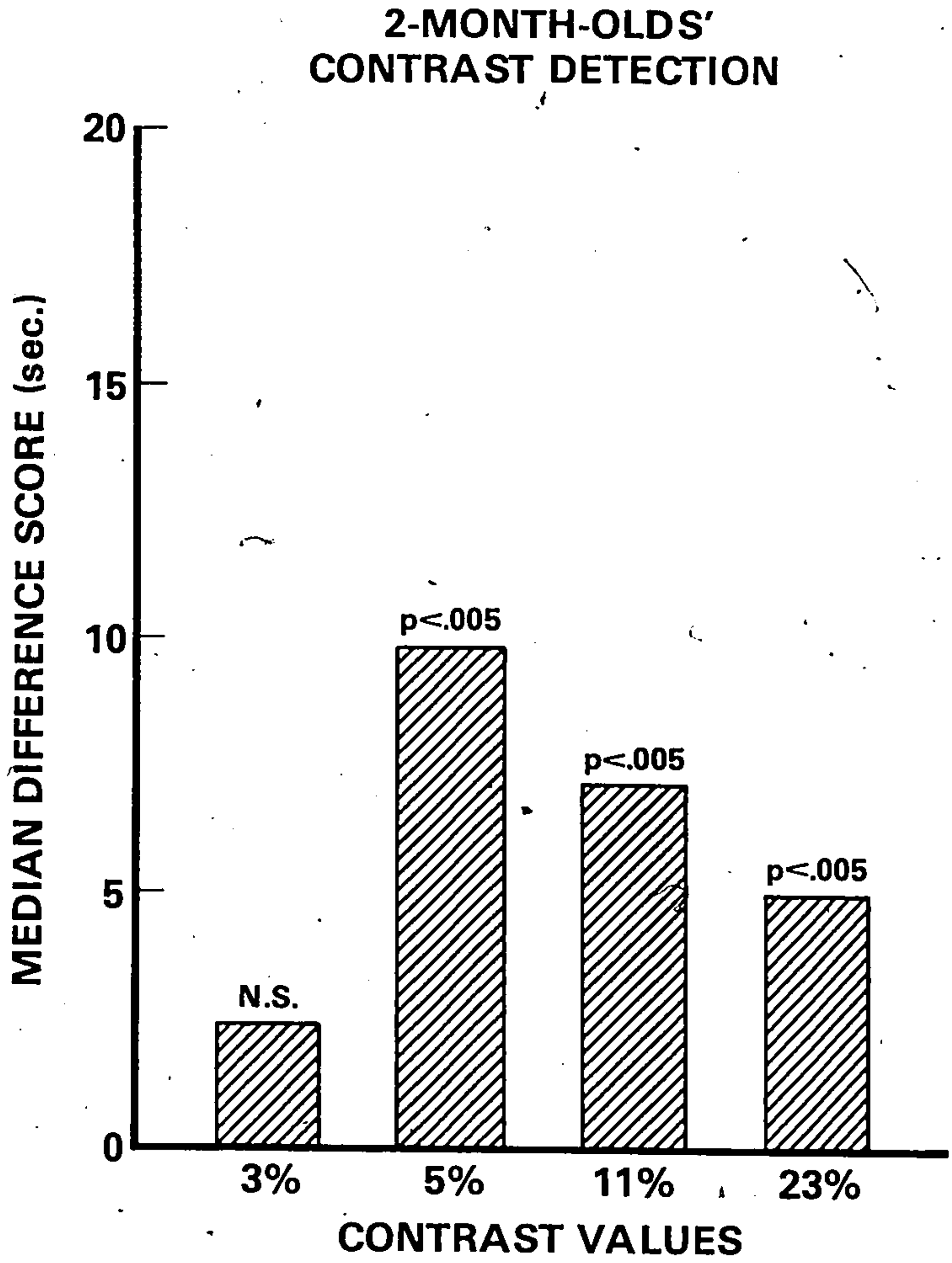
The apparatus was identical to that used with newborns in Experiment 2. In this study, however, 2-month-olds were shown the checkerboard patterns with checks contrasting by 3%, 5%, 11% and 23%. Each pattern was again paired with its own luminance-matched grey square. All other details remained identical to those outlined in Experiment 2. The statistical analysis included only those infants who contributed complete data for all four blocks of trials and for whom interobserver reliability was > .80. In the final sample, the mean Spearman interobserver reliability was .95 (Range = .89 - 1.00).

Results and Discussion

The data were reduced in the same way as in Experiment 2. Wilcoxon analyses of matched pairs revealed that 2-month-olds looked longer at the checkerboards containing contrasts of 23% [T(24) = 34, *p* < .005], of 11% [T(24) = 14, *p* < .005] and of 5% [T(24) = 54, *p* < .005] than at the matching grey squares. They showed no significant preference for the checkerboard with checks contrasting by 3% [T(24) = 104, n.s.]. These data are presented in Figure 5 where it can be seen that the pattern of results obtained from 2-month-olds is somewhat parabolic as opposed to the positively accelerating function generated by the newborns. In other words, as the degree of contrast between the checks increased, the magnitude of 2-month-olds' preferences did not appear to increase as it had so dramatically in newborns.

The results obtained in Experiment 2 show that 2-month-olds are very sensitive to brightness contrast: They can detect the contrast between shades of grey which differ by only 5%. The results are similar

Figure 5. 2-month-olds' preferences for the checkerboard: Bars represent the median difference between looking time at the checkerboards and at the squares.


2-MONTH-OLDS'
CONTRAST DETECTION
MEDIAN DIFFERENCE SCORE (sec.)
20
15
10
5
0
N.S.
p<.005
p<.005
p<.005
3%
5%
11%
23%
CONTRAST VALUES

to those of Peeples and Teller (1975) who found that 2-month-olds can detect contrasts as small as about 3%.

In comparing the data obtained from 2-month-olds (Experiment 2a) with those from newborns (Experiment 2), a number of phenomena emerge. Not surprisingly, 2-month-olds showed evidence of detecting contrasts that were smaller than those detected by newborns (i.e. 5% vs 11%). This represents a developmental change which should allow 2-month-olds to more easily distinguish objects and to see texture within objects. Doris et al. (1967) also reported that 2-month-olds showed a substantial improvement over newborns in the ability to see contrasts (from 35% to 17%). Secondly, the shapes of the functions obtained from newborns and 2-month-olds are strikingly different: 2-month-olds did not show increasing preferences with increasing contrast as newborns did. However, one must first test with a larger number of contrast values and check sizes in order to evaluate this trend more fully. A reason for this is that infants' preferences for check size change developmentally (Brennan, Ames & Moore, 1966). Since the check size (2° x 2°) used in these experiments was one most preferred by newborns (Brennan et al., 1966), it is difficult to evaluate the pattern of 2-month-olds' preferences. Perhaps with a more complex checkerboard (e.g. an 8° x 8°, Brennan et al.) 2-month-olds' preferences would vary with variations in contrast. Thus, these data have revealed that in addition to the fact that 2-month-olds are more sensitive to contrast than newborns, the manner in which these two age groups respond to various contrasts may also differ.

CHAPTER 4: Experiments on Newborns' Color Vision

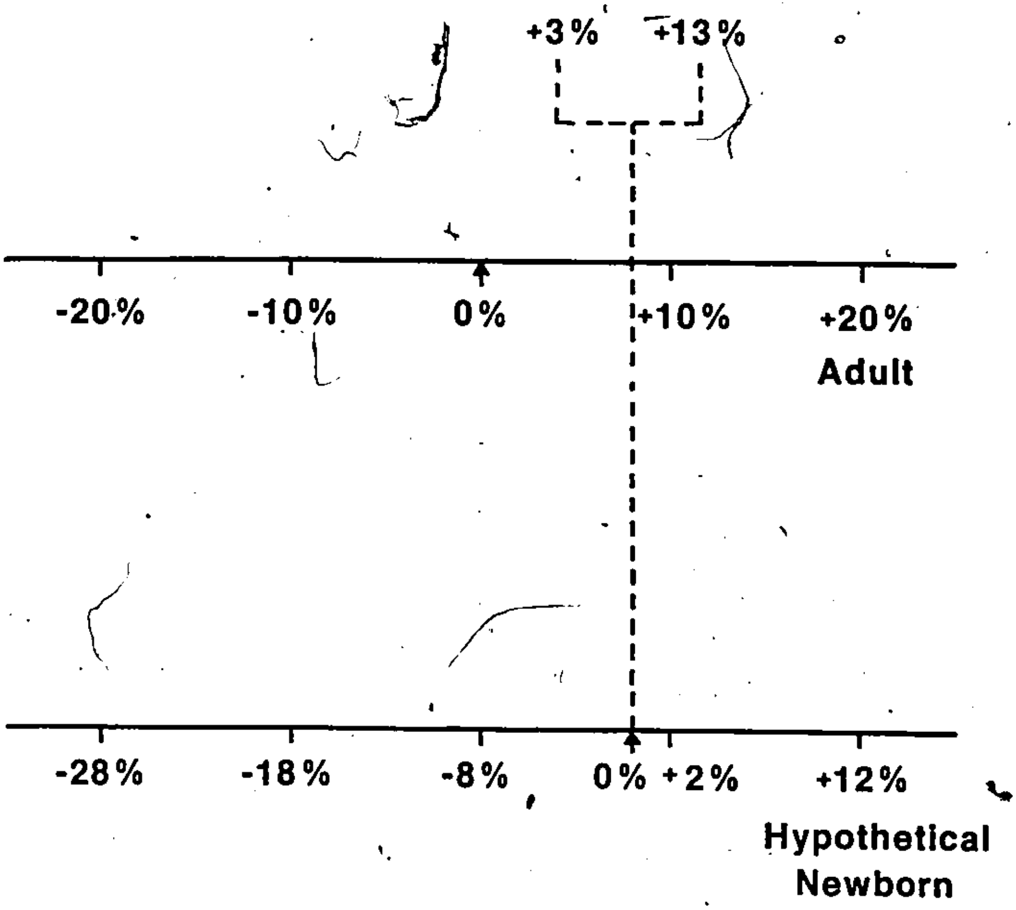
Experiments 3, 4, 5, 6, and 6a

In this series of investigations, I examined newborns' ability to detect the four primary hues, green, yellow, red and blue. In order to test their color perception, newborns were shown a series of colored (e.g. green-and-grey checkerboard patterns). Within each of the patterns, the contrast between the grey and the colored checks was varied across a large range centred around the point where studies of infants' spectral sensitivity suggested that the luminance of the color and the grey would be equal. To adults, in some of the checkerboards, the grey checks were of higher luminance than the colored checks (i.e. patterns designated as +), in other stimuli, the grey checks were of lower luminance than the colored checks (i.e. patterns designated as -).

These studies have incorporated the same logic as the Peeples and Teller (1975) experiment. In their first experiment, Peeples and Teller varied the contrast between an achromatic bar and a white background and found a contrast at which 2-month-olds failed to show evidence of detecting the bar. To test infants' color perception Peeples and Teller then varied the luminance difference between a series of red bars and a white background in steps of this size in order to be sure that 2-month-olds would not detect any difference in brightness between at least one of the bars and its background. Although Peeples and Teller could not predict at which luminance(s) infants would see red and grey as equally bright, it was assumed that with at least one of the red bars, 2-month-olds would not be able to detect a brightness difference between the bar and its background.

Peeples and Teller's strategy has been adopted for the present studies of newborns' color vision. In Experiment 2, newborns demonstrated that they did not show a preference for an achromatic checkerboard over a matching grey square if the contrast between the checks was 5% or less. In a test of color vision, I wanted to be sure that within at least one of the patterns, newborns would not detect any brightness difference between the colored and grey checks. The range of contrasts of the stimuli was large enough (about -25% to about +25%) to insure that one such checkerboard would be included. In addition, the contrast between the colored and grey checks was spaced by a maximum of 10%. As a result, at least one checkerboard was always within 5% of the point where newborns would not show a preference for a checkerboard over its matched grey square if they could not detect the hue and were responding solely on the basis of brightness contrast. To illustrate this, Figure 6 shows how an adult and a newborn might perceive a series of checkerboard stimuli. In the top portion of the figure, five stimuli are represented as they would appear to the "average" adult. The arrow (at 0%) illustrates a stimulus in which adults would perceive the color and the grey as equally bright. In the lower portion of the figure, these stimuli are represented as they would appear to a hypothetical newborn. The infant would perceive the color and grey as equally bright at a point which for adults would represent an 8% contrast. Therefore, since we know from Experiment 2 that newborns do not show a preference for a checkerboard over a plain grey square if its luminance contrast is

Figure 6. This figure represents how a series of grey-and-colored contrasting stimuli may appear to an adult and to a newborn (see text for a more detailed explanation).


+3%
+13%
-20%
-10%
0%
+10%
+20%
Adult
-28%
-18%
-8%
0%
+2%
+12%
Hypothetical Newborn

5% or less, a color deficient infant should not show a preference for the checkerboard if its contrast is between +3% and +13%.

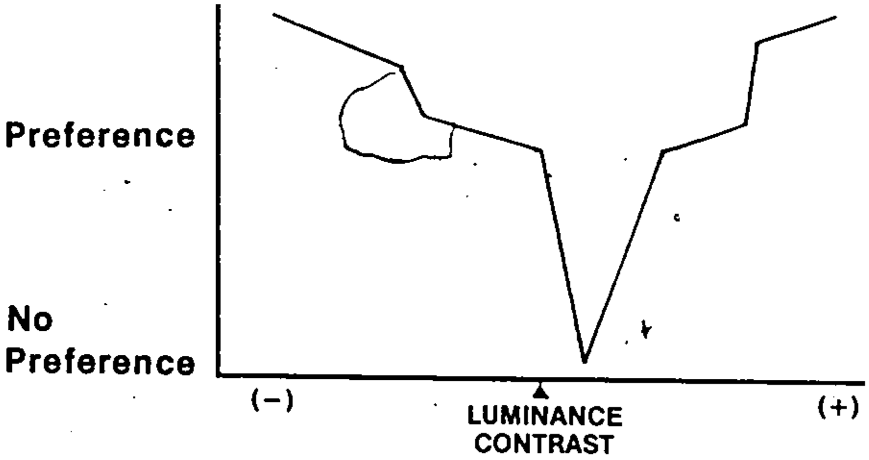
Part a of Figure 7 represents an expected pattern of results that would be obtained if newborns could not detect the hue in the checkerboard. As can be observed, newborns would not show a preference for one of the checkerboards (i.e. one in which the contrast is $< 5\%$). However, newborns should show increasing preferences for those checkerboards in which the brightness difference differs the most from the checkerboard for which they showed no preference. This is based on the pattern of results from Experiment 2 in which newborns viewed checkerboards of varying shades of grey.

The other two patterns of results shown in Figure 7 illustrate trends that would be expected if newborns differentiate the colored from grey checks within the checkerboards. In both cases, newborns perceive all of the stimuli as colored-and-grey checkerboards and thus show preferences for them over their respective matched grey squares. In some checkerboards, newborns detect both a hue and brightness difference between the checks, in others, they detect only a hue difference.

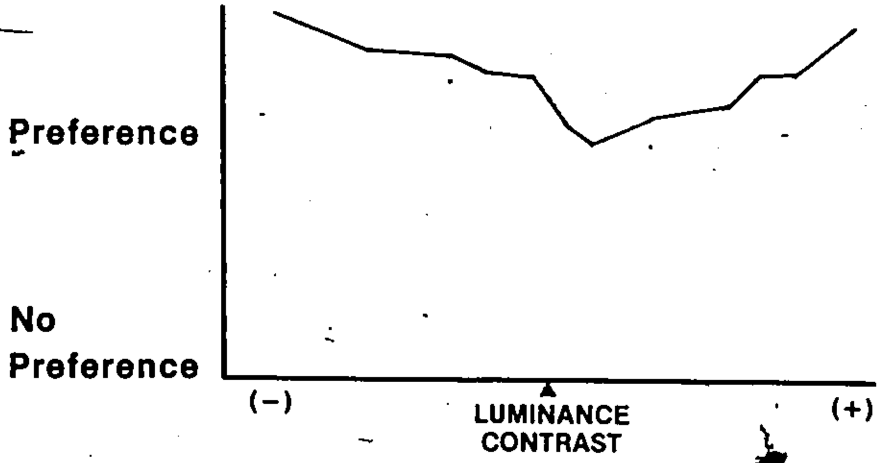
Part b shows a pattern of results that would be expected if newborns can discriminate a hue from grey at all contrasts but in addition, newborns' preference for a checkerboard increases as a function of increasing contrast between the hue and the grey. Moreover, the checkerboard that newborns show the smallest preference for is the checkerboard which presumably contains no contrast information. In other words, this pattern is one in which newborns perceive the hue and grey as "equally bright".

Figure 7. Three expected patterns of results for studies of newborns' hue detection (see text for more detailed explanation).

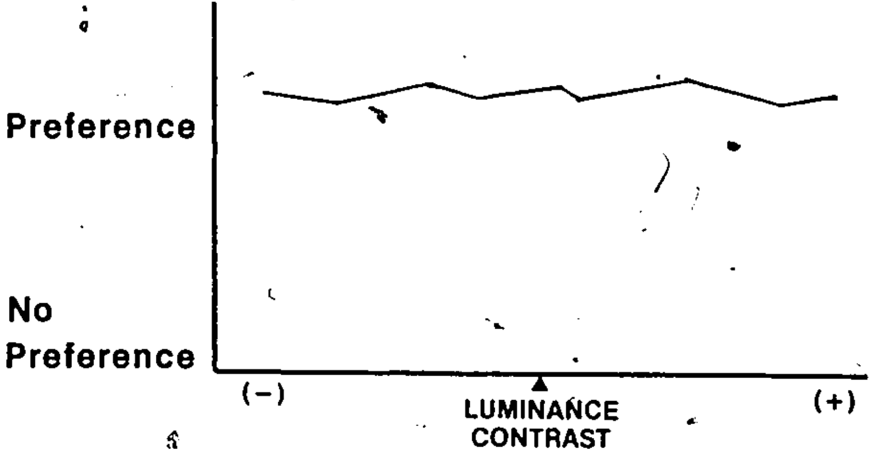
A) Contrast



B) Colour and Contrast



C) Colour



Part c of Figure 7 represents a pattern of results that would be expected if newborns show preferences for all the colored-and-grey checkerboards over the grey squares but their preferences are not influenced by contrast. Thus the magnitude of newborns' preferences remains fairly stable as contrast varies. In this case, newborns appear to "ignore" the varying amount of contrast in the checkerboards and infants' preferences are influenced simply by the fact that the colored checks differ from the grey checks. Although, like pattern b, such a result would allow one to conclude that newborns can differentiate the color from grey, one could not from c, predict where a brightness match for ~~the~~ color and the grey occurs.

The following series of experiments evaluated newborns' responses to the spectral colors green, yellow, red and blue. Newborns' pattern of preferences should reveal whether they respond to brightness contrast only, to hue only, or to both attributes.

Experiment 3

The first of these studies examined newborns' responses to a series of green-and-grey checkerboard patterns and their luminance-matched grey squares. Again, newborns' tendency to prefer patterned over unpatterned stimulation was used as an index of detection.

Method

Subjects

The subjects were 60 infants, one to five days of age ($\bar{x} = 3.2$ days), at least 38 weeks gestation and at least 2500 grams at birth. An additional 14 newborns were tested but not included in the sample: nine because of incomplete data, two because of a procedural error, and three because of poor interobserver reliability (Spearman rho < .80).

Stimuli

The stimuli were six green-and-grey 2 x 2 checkerboard patterns in which the green-and-grey checks would, to an adult, contrast by +22%, +13%, +3%, -7%, -16% and -25% (see Appendix 1). The dominant wavelength in the highly saturated green checks was 550 nm (range 505-590 nm) as measured by a Cary 14 Spectrophotometer. At the onset of the experiment, a slight color-cast existed on the achromatic checks. In order to eliminate this, small amounts of dichroic filtration were required. Two normal female trichromats adjusted the filter values until they reported that the color cast was effectively minimized. Since the two sets of filtration values corresponded very closely, the average value was chosen. These values were used for the duration of the experiment.

Each pattern was paired with its own plain-grey square which matched the mean luminance of the checkerboard. Both overall size and check size were identical to those described in Experiment 2.

Apparatus and Procedure

The 30 newborns in Group 1 viewed checkerboards in which the green-and-grey checks would, to an adult, contrast by +3%, -16% and -25% and their matched grey squares. The 30 newborns in Group 2 viewed patterns in which the checks would, to an adult, contrast by +22%, +13% and -7% and their matched grey squares.

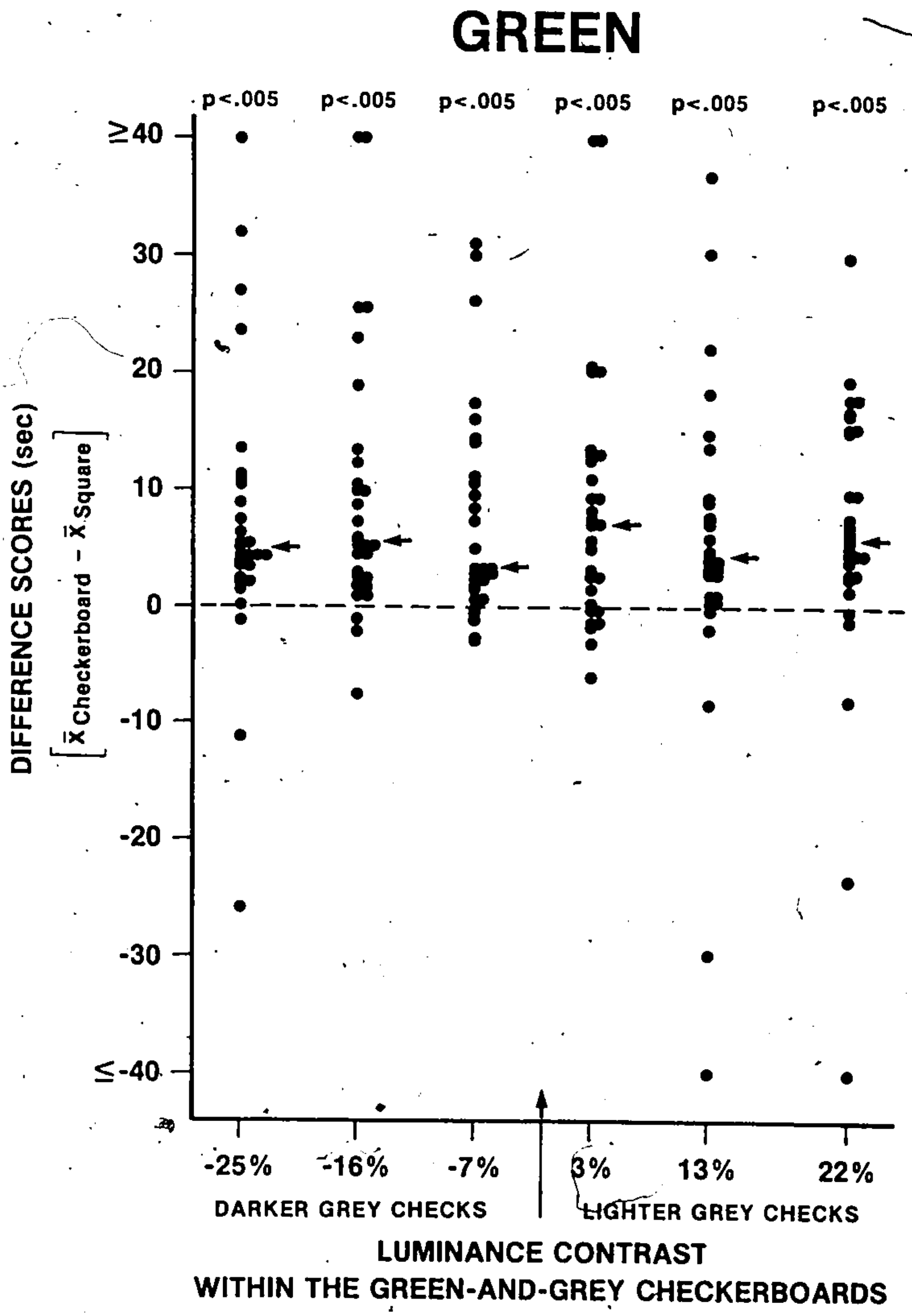
All other aspects of the apparatus and procedure remained identical to those described in Experiment 2. For the 60 subjects in the final sample, the mean interobserver Spearman coefficient was .93 (range = .83-1.00).

Results and Discussion

The data were reduced in the same manner as in previous experiments. Figure 8 shows that the majority of the differences in looking time between the checkerboard and the square were positive at all contrast values. Wilcoxon analyses confirmed that newborns looked significantly longer at the green-and-grey patterns with checks contrasting by +22% [T(30) = 42, $p < .005$], by +13% [T(30) = 19, $p < .005$], by +3% [T(30) = 43, $p < .005$], by -7% [T(30) = 31, $p < .005$], by -16% [T(30) = 38, $p < .005$] and by -25% [T(30) = 52, $p < .005$] than at each of their respective matched grey squares.

As pointed out in Chapter 1, a major problem in the interpretation of previous studies of newborns' color vision is that newborns may have differentiated chromatic from achromatic stimuli on the basis of brightness differences (see Bornstein, 1976; Teller & Bornstein, 1983; and Werner & Wooten, 1979, for reviews). In Experiment 2, I first examined newborns' sensitivity to contrast and then used this information to construct a series of green-and-grey stimuli. It was expected that with at least one of these stimuli, newborns could not detect any brightness differences between the colored and grey checks. Therefore a green-deficient newborn should not be able to differentiate this stimulus from the grey square and thus show no preference for the pattern. The results showed that, on the contrary, newborns showed

Figure 8. Distribution of the differences in looking time (mean looking time at the green-and-grey checkerboard minus the mean looking time at the grey square) at each contrast. Each dot represents the data from one newborn, and the horizontal arrows indicate the median difference score at each contrast. The fact that most of the points lie above zero illustrates that at all contrasts, newborns looked significantly longer at the green-and-grey checkerboards than at the luminance-matched grey squares. The vertical arrow at the bottom of the figure represents an estimated adult brightness match for green and grey (see Appendix B).


GREEN
p<.005
p<.005
p<.005
p<.005
p<.005
p<.005
≥40
30
20
10
0
-10
-20
-30
≤-40
DIFFERENCE SCORES (sec)
[X̄ Checkerboard − X̄ Square]
-25%
-16%
-7%
3%
13%
22%
DARKER GREY CHECKS
LIGHTER GREY CHECKS
LUMINANCE CONTRAST
WITHIN THE GREEN-AND-GREY CHECKERBOARDS

preferences for all the green-and-grey checkerboards. This suggests that newborns can differentiate green from grey. The results of Experiment 2 show that when viewing checkerboards composed of achromatic checks, newborns' preferences increase dramatically as a function of increasing contrast within the checkerboard. As can be observed in Figure 8, the median difference scores for green-and-grey checkerboards (indicated by the arrows) are approximately equal at all contrast values. Thus, it seems that the difference in hue between the green and grey checks was the factor primarily responsible for influencing newborns' visual behavior.

One final issue is the width of the contrast range used in the present experiment. The range (-25% to +22%) was chosen to represent a fairly conservative estimate of where a newborn's brightness match for green and grey may occur. Since adults' and 1-month-olds' spectral sensitivity curves are very similar in the green portion of the spectrum, one would expect that the luminance at which infants and adults would see the green and grey as equal would be very similar. However, one might argue that a newborn's brightness match for green and grey occurs outside this range (i.e. > +22% or < -25%). For example, if a newborn matched green with a +40% grey then the +22% grey would actually appear as a -18% stimulus. Since we know from Experiment 2 that newborns show a preference for contrasts of -11% or greater, a green-deficient newborn would show a preference for this pattern over its matching grey square based on the brightness differences between the checks. Since all of the green-and-grey checkerboards would appear to contain at least -18% contrast, even color-deficient newborns would show a preference for all the patterns in the series, as did the babies in the present study.

This problem of an appropriate range even seems less likely when one re-examines the results of Experiment 2. This experiment revealed a distinct pattern of newborns' visual behavior. As newborns detect greater contrast in the checkerboards, they show greater preferences for the patterns over the matched grey squares. Therefore, if a newborn's brightness match for green and grey were really at +40%, then the +22% stimulus would really appear as -18% and the +13% stimulus as a -27%. In light of the results of Experiment 2, a green-deficient newborn should show a greater preference for the -27% than the -18% stimulus. However, Figure 8 shows that all the preferences in the present experiment were approximately equal. Since we know the manner in which newborns respond to contrast as large as ±27% (from Experiment 2), the <u>effective range</u> within which we can interpret newborns' responses to green-and-grey checkerboards is now extended from +22% to +40%. This same analysis can be applied to the (-) portion of the range as well. Therefore, since previous studies (Teller et al., 1981) have found that about a ±20% range is adequate for locating where 1-month-olds fail to discriminate between certain hues, it is reasonable to assume that this ±40% range is adequate for "capturing" newborns' brightness matches.

Since newborns showed that they could differentiate green from grey, these data provide the first demonstration of any form of color vision in the human newborn. In addition, these data resembled pattern c of Figure 7. Pattern c showed that when hue was present, newborns showed no responses to the contrast existing in many of the checkerboards. Although this result is interesting, it unfortunately means that we cannot estimate at which luminances newborns perceive the green and the grey as equally bright. This may have been possible if the results had resembled pattern b.

Experiment 4

This study examined newborns' detection of a yellow hue by recording newborns' looking times to grey-and-yellow checkerboard patterns and luminance-matched grey squares.

Method

Subjects

The subjects were 60 infants, one to five days of age ($\bar{x} = 3.4$ days), at least 38 weeks gestational age and at least 2500 grams at birth. An additional six newborns were tested but not included in the sample: four because they did not contribute enough data and two because of low interobserver reliability (i.e. rho < .80).

Stimuli

The stimuli were six 2 x 2 checkerboard patterns in which the yellow-and-grey checks, to an adult, would contrast by +20%, +12%, +6%, -2%, -11% and -21% (see Appendix 1). The dominant wavelength in the highly saturated yellow checks was 585 nm (range = 530-625 nm) as measured by a Cary 14 Spectrophotometer. Each pattern was paired with its own plain grey square which matched the average luminance of the checkerboard. The size of these stimuli were identical to those described in previous experiments.

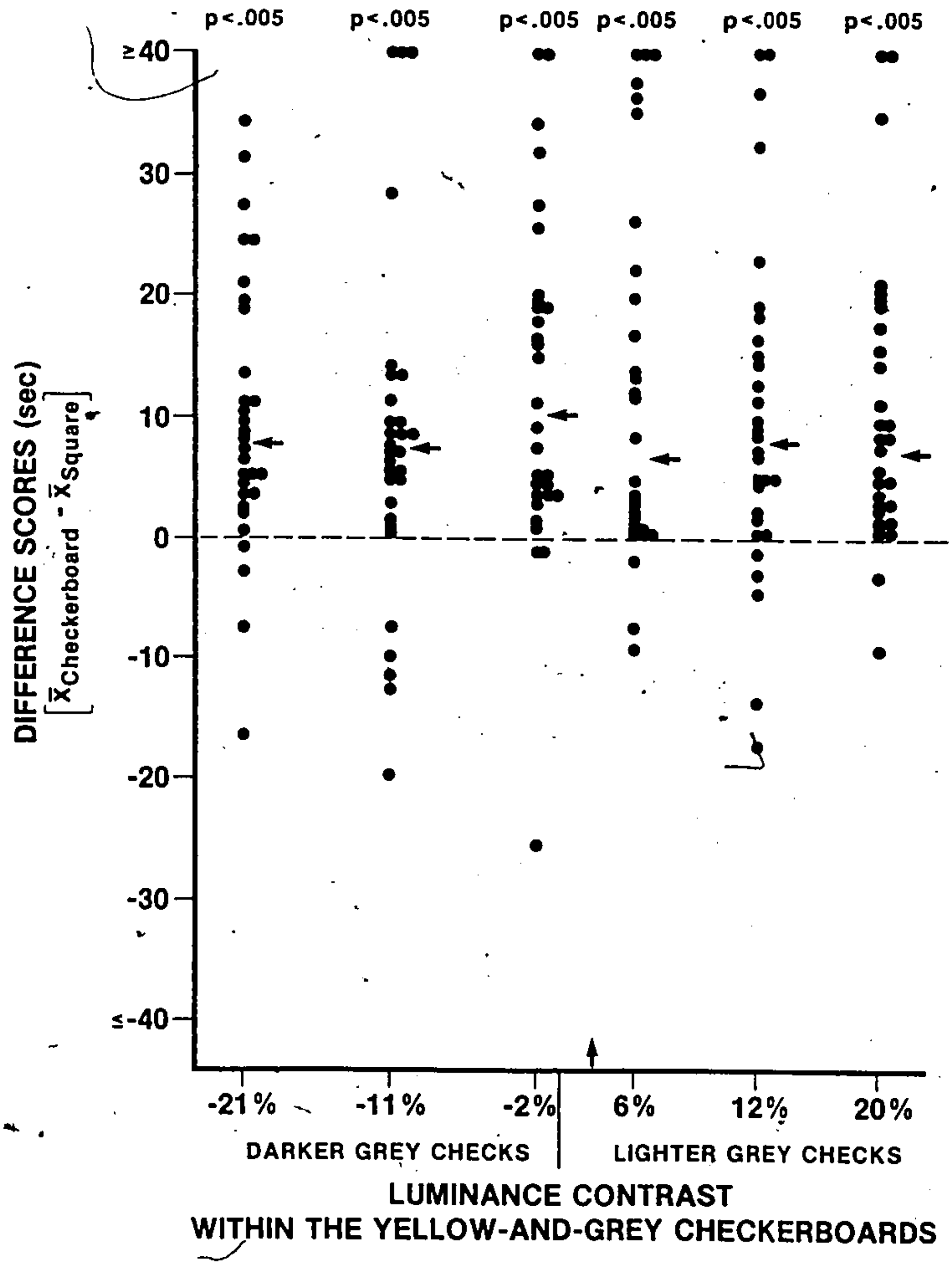
Apparatus and Procedure

The 30 newborns in Group 1 viewed checkerboard patterns in which the checks, to an adult, contrasted by +20%, +6%, and -20%. The 30 newborns in Group 2 viewed checkerboards in which the yellow-and-grey checks contrasted by +12%, -2% and -11%. All other aspects of the apparatus and procedure remained identical to those described earlier. For the 60 subjects in the final sample, the mean Spearman interobserver reliability coefficient was .95 (range = .80 - 1.00).

Results and Discussion

The data were reduced in the same manner as in Experiments 2 and 3. The group results are summarized in Figure 9 which indicates that at all contrasts, most of the difference scores for yellow-and-grey checkerboards were positive. Wilcoxon analyses revealed that newborns looked longer at the grey-and-yellow patterns with checks contrasting by +20% [$T(30) = 23$, $p < .005$], by +12% [$T(30) = 58$, $p < .005$], by +6% [$T(30) = 36$, $p < .005$], by -2% [$T(30) = 28$, $p < .005$], by -11% [$T(30) = 100$, $p < .005$] and by -21% [$T(30) = 44$, $p < .005$] than at their respective matching grey squares. It was expected that with at least one of these stimuli, newborns could not detect any brightness differences between the yellow and grey checks. Therefore, a color-deficient newborn should not be able to differentiate this stimulus from the grey square and he should show no preference for the pattern. The results indicated that newborns showed preferences for *all* the yellow-and-grey checkerboards. Also, as we had observed in the green study, the pattern of results in the present study (see Figure 9) indicates that the amount of contrast existing within some of the checkerboards

Figure 9. Distribution of the differences in looking time (mean looking time at the yellow-and-grey checkerboard minus the mean looking time at the grey square) at each contrast. Each dot represents the data from one newborn, and the horizontal arrows indicate the median difference score at each contrast. The fact that most of the points lie above zero illustrates that at all contrasts, newborns looked significantly longer at the yellow-and-grey checkerboards than at the luminance-matched grey squares. The vertical arrow at the bottom of the figure represents an estimated adult brightness match for yellow and grey (see Appendix B).



YELLOW

p<.005
p<.005
p<.005
p<.005
p<.005
p<.005
≥40
30
20
10
0
-10
-20
-30
≤-40
DIFFERENCE SCORES (sec)
$\left[\bar{x}_{Checkerboard} - \bar{x}_{Square}\right]$
-21%
-11%
-2%
6%
12%
20%
DARKER GREY CHECKS
LIGHTER GREY CHECKS
LUMINANCE CONTRAST
WITHIN THE YELLOW-AND-GREY CHECKERBOARDS

had no effect on the magnitude of newborns' preferences. This pattern was markedly different from the pattern shown when newborns viewed achromatic checkerboards (Exp. 2). In summary, these data suggest that newborns can discriminate a yellow hue from grey.

Experiment 5

This study used the same experimental techniques to examine newborns' detection of long-wavelength (red) stimulation.

Method

Subjects

The subjects were 60 infants, one to five days of age ($\bar{x} = 3.1$ days), at least 38 weeks gestational age and at least 2500 grams at birth. An additional 12 infants were tested but not included in the sample: eight because they did not contribute enough data and four because of low interobserver reliability (rho < .80).

Stimuli

The stimuli were six 2 x 2 checkerboard patterns in which the red-and-grey checks, to an adult, would contrast by +27%, +18%, +8%, -2%, -11% and -21% (see Appendix 1). The dominant wavelength in the highly saturated red checks was 650 nm (range = 590 - 685nm) as measured by a Cary 14 Spectrophotometer. Each pattern was paired with its own plain grey square which matched the mean luminance of the checkerboard. The size of the stimuli was the same as those previously described.

Apparatus and Procedure

The 30 newborns in Group 1 viewed checkerboard patterns in which the red-and-grey checks contrasted by +27%, +18%, and +8%. An additional 30 newborns were shown checkerboards containing contrasts of

-2%, -12% and -21%. All other aspects of the apparatus and procedure remained identical to those described in Expts. 2, 3, and 4. For the 60 subjects in the final sample, the mean Spearman interobserver reliability coefficient was .93 (range = .80 - .99).

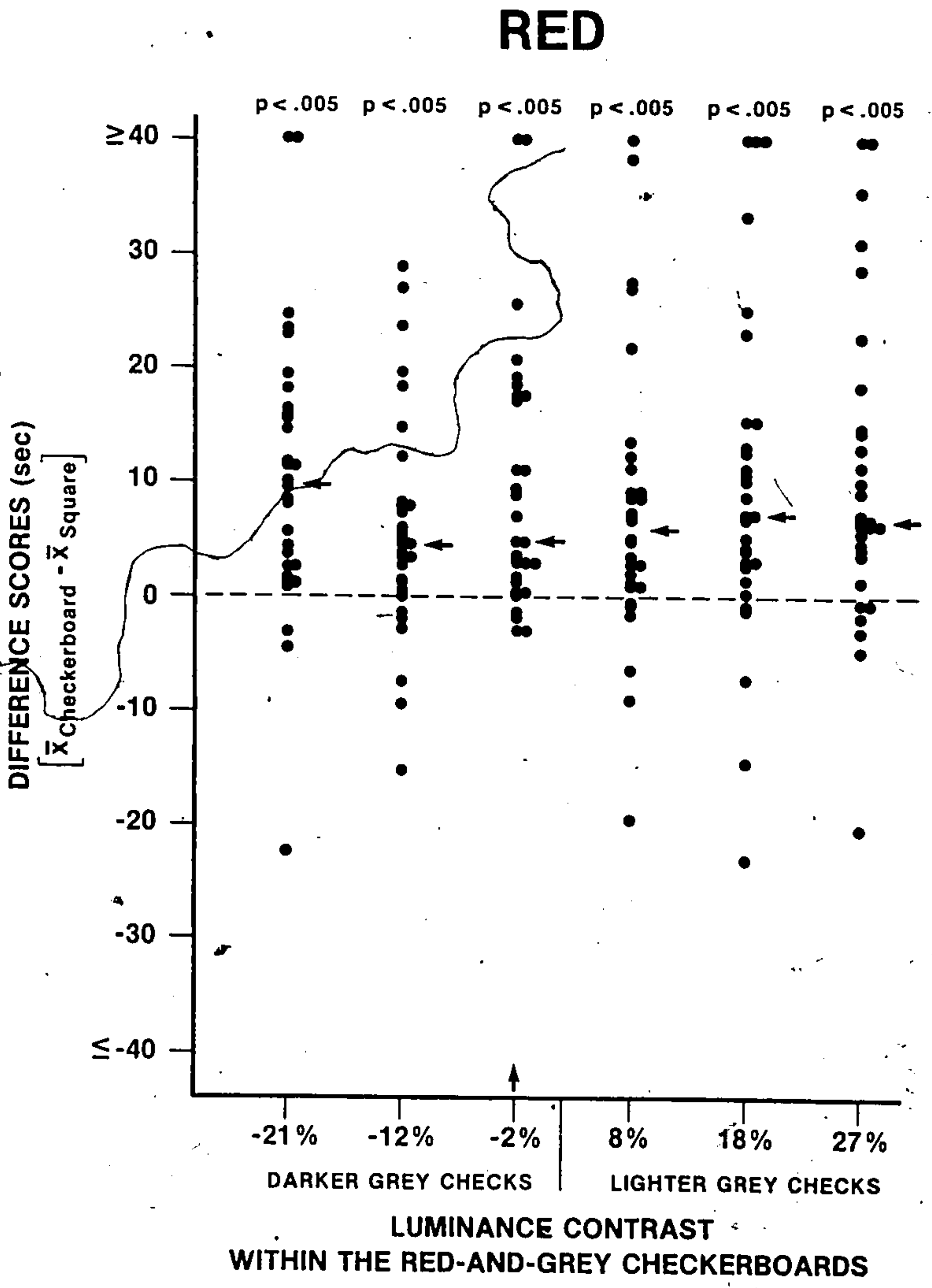
Results and Discussion

The data were reduced in the same manner as in previous experiments. In Figure 10, we can see that for all contrast values, the majority of the difference scores were positive. Wilcoxon analyses revealed that newborns looked longer at the red-and-grey patterns with checks contrasting by +27% [$T(30) = 46$, $p < .005$], by +18% [$T(30) = 71$, $p < .005$], by +8% [$T(30) = 73$, $p < .005$], by -2% [$T(30) = 32.5$, $p < .005$], by -12% [$T(30) = 86$, $p < .005$] and by -21% [$T(30) = 43$, $p < .005$] than at their respective matched grey squares. It was expected that with at least one of these stimuli, newborns could not detect any brightness differences between the red and grey checks. Therefore, a red-deficient newborn should not be able to differentiate this stimulus from the grey square and he should show no preference for the pattern. On the contrary, the results indicated that newborns showed preferences for all the red-and-grey checkerboards. Secondly, as was the case with green and yellow, the pattern of results shown in Figure 10 indicates that the amount of contrast had no effect on the magnitude of newborns' preferences. In summary, it appears that newborns can discriminate a red hue from grey.

Experiment 6

This study used the same experimental techniques to examine newborns' responses to short-wavelength (blue) stimulation. The range

Figure 10. Distribution of the differences in looking time (mean looking time at the red-and-grey checkerboard minus the mean looking time at the grey square) at each contrast. Each dot represents the data from one newborn, and the horizontal arrows indicate the median difference score at each contrast. The fact that most of the points lie above zero illustrates that at all contrasts, newborns looked significantly longer at the red and grey checkerboards than at the luminance-matched grey squares. The vertical arrow at the bottom of the figure represents an estimated adult brightness match for red and grey (see Appendix B).


RED
p < .005
p < .005
p < .005
p < .005
p < .005
p < .005
≥40
30
20
10
0
-10
-20
-30
≤-40
DIFFERENCE SCORES (sec)
[$\bar{X}_{\text{Checkerboard}} - \bar{X}_{\text{Square}}$]
-21%
-12%
-2%
8%
18%
27%
DARKER GREY CHECKS
LIGHTER GREY CHECKS
LUMINANCE CONTRAST
WITHIN THE RED-AND-GREY CHECKERBOARDS

of contrasts in this experiment is not centred around 0% as it was in the earlier experiments. In the first study (i.e. Group 1), newborns did not show a preference for the checkerboard in which the blue-and-grey checks contrasted by +16%. Therefore, in the second phase (Group 2), newborns were shown a checkerboard containing a contrast that was very similar (+14%). This was done in an effort to "replicate" the findings of Group 1 and secondly, to get a better estimate of the luminance at which newborns see blue and grey as equally bright. Since previous studies of infants' spectral sensitivity revealed that infants show relatively higher sensitivity in the short-wavelength region, it was expected that a newborn brightness match for blue and grey would be in the (+) region.

Method

Subjects

The subjects were 60 infants, one to five days of age ($\bar{x}$ age = 3.4 days), at least 38 weeks gestational age and at least 2500 grams at birth. An additional 10 newborns were tested but not included in the sample: six because they did not contribute enough data and four because of low interobserver reliability.

Stimuli

The stimuli were six checkerboard patterns in which the blue-and-grey checks would contrast by +33%, +25%, +16%, +14%, +5%, and -4%. The dominant wavelength within the highly saturated blue checks was 485 nm (range = 425 - 510 nm) as measured by a Cary 14 Spectrophotometer. All other aspects of the stimuli remained the same as those outlined in previous studies.

Apparatus and Procedure

The 30 newborns in Group 1 viewed checkerboards which, to an adult, had blue-and-grey checks which contrasted by +25%, +16% and +5%. An additional 30 newborns were shown checkerboards containing contrasts of +33%, +14% and -4%. All other aspects of the apparatus and procedure were identical to those described previously. For the 60 subjects in the final sample, the mean Spearman interobserver reliability coefficient was .95 (range = .80 - 1.00).

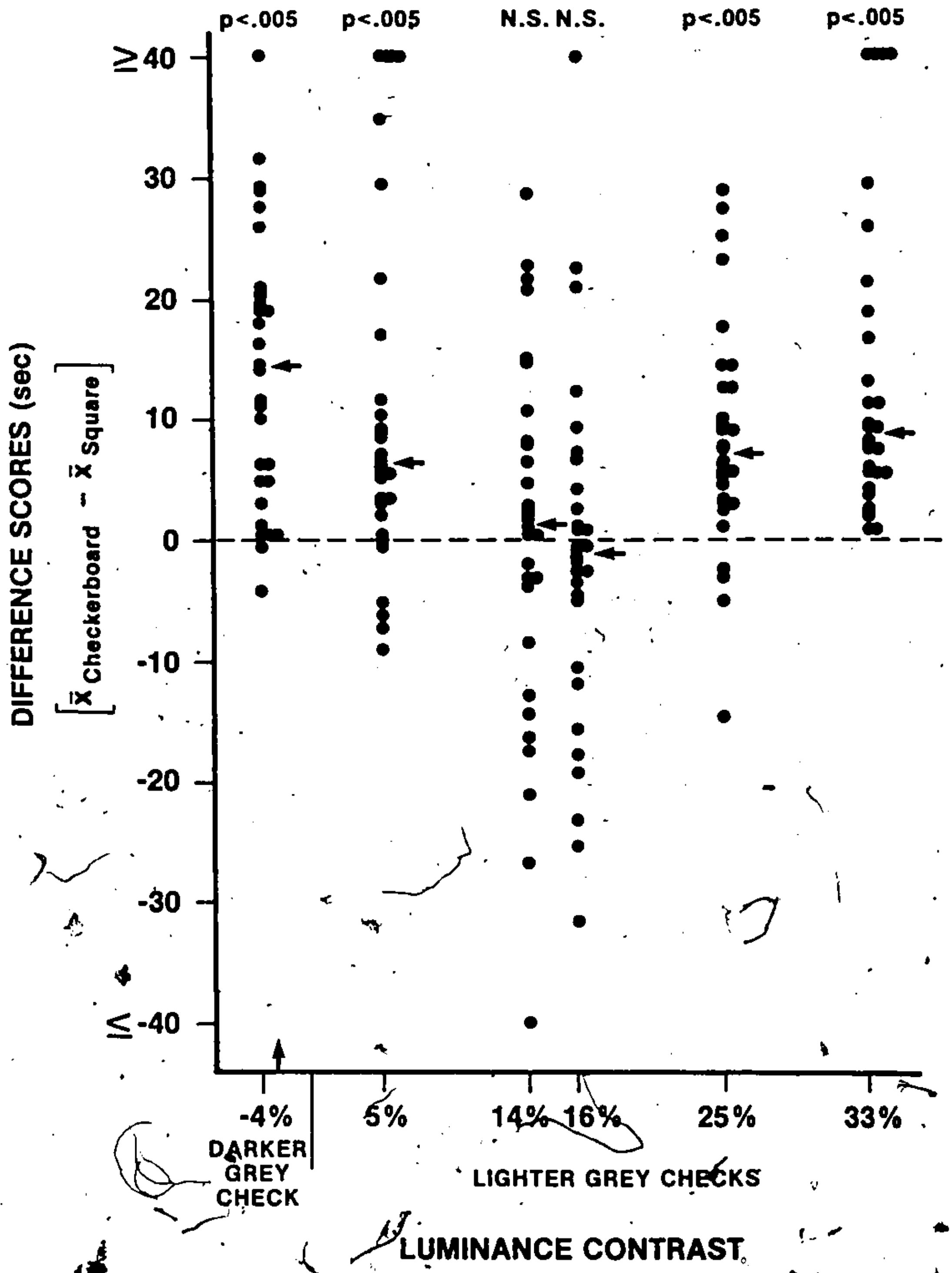
Results and Discussion

The data were reduced in the same manner as in previous experiments. In Figure 11, one can see that the pattern of results is quite different from those obtained in the studies of newborns' responses to green, yellow and red. With two of the blue-and-grey checkerboards, the distribution of differences is centred around zero. Wilcoxon analyses revealed that newborns did not look longer at the patterns in which the checks contrasted by +14% [T(30) = 140.5, n.s.] and +16% [T(30) = 196, n.s.] than at the matching grey squares. However newborns did show a preference for the checkerboards in which the blue-and-grey checks contrasted by +33% [T(30) = 0, $p < .005$], by +25% [T(30) = 43, $p < .005$], by 5% [T(30) = 56.5, $p < .005$] and by -4% [T(30) = 8, p < .005] than at the respective matching grey squares.

If newborns were able to discriminate the blue from the grey checks, then all the checkerboards would have appeared pattern-like and thus as in Experiments 3, 4, and 5, newborns should have shown a preference for all the blue-and-grey checkerboards over the grey squares. Since newborns showed no evidence of preferring +14% and +16%

Figure 11. Distribution of the differences in looking time (mean looking time at the blue-and-grey checkerboard minus the mean looking time at the square) at each contrast. Each dot represents the data from one newborn, and the horizontal arrows indicate the median difference score at each contrast. When newborns viewed contrasts of +14% and +16%, they looked about equally long at both the patterns and the squares. However, with the other checkerboards, most of the points lie above zero. This suggests that newborns looked significantly longer at these checkerboards than at the luminance-matched grey squares. The vertical arrow at the bottom of the figure represents an estimated adult brightness match for blue and grey (see Appendix B).

BLUE



p<.005
p<.005
N.S.
N.S.
p<.005
p<.005
≥40
30
20
10
0
-10
-20
-30
≤-40
DIFFERENCE SCORES (sec)
[x̄ Checkerboard − x̄ Square]
-4%
5%
14%
16%
25%
33%
DARKER GREY CHECK
LIGHTER GREY CHECKS
LUMINANCE CONTRAST WITHIN THE BLUE-AND-GREY CHECKERBOARDS

patterns over the plain squares, this implies that there was not enough visual information in these patterns to influence newborns' visual behavior. This pattern of results is what was expected if newborns could not differentiate blue from grey (see Fig. 7, Part a). However, newborns did show preferences for some of the "blue" and grey patterns over the grey squares. These preferences were most likely based on newborns' detection of achromatic contrast between the blue and grey checks. In addition, Figure 11 shows that the magnitude of newborns' preferences appear to increase with contrast values that are further and further from the +14% and +16% checkerboards. In Experiment 2, newborns showed dramatic increases in their preference for an achromatic checkerboard when its contrast was increased. Thus, most likely at some point near where adults would see the greys as +14% and +16% brighter than the blue, newborns perceive the brightness of the blue and grey as equal. Assuming for a moment that a typical newborn's brightness match (i.e. 0%) is actually at +15% for an adult, then the newborn would perceive the blue and grey checkerboards that contrast to an adult, by +25% and +33% as patterns of dark and light grey that contrast by about +10% and +18% respectively. Figure 11 shows that the magnitude of the preference is larger for the pattern containing the larger contrast. This same trend is evident on the left side of the figure. In this case, the newborn would perceive the checkerboards that contrast, to an adult by +5% and -4% as patterns of dark and light grey that contrast by -10% and -19%.

One final issue is the location of newborns' apparent brightness match for blue and grey. Studies of infant spectral sensitivity reveal that young infants show relatively elevated sensitivity in the short-wavelength region of the spectrum (Dobson, 1976; Moscowitz-Cook, 1979). Although data obtained from studies of spectral sensitivity cannot be used to directly estimate the luminances at which two stimuli will appear as equally bright, they can predict the general location where such matches may occur (c.f. Teller & Bornstein, 1983). The present data suggest that newborns see blue and grey as equally bright at a point where adults would see the blue as brighter than the grey. Thus, the finding that newborns show no evidence of detecting a blue hue in a region where adults would match the blue with a much lighter grey is consistent with the finding that young infants show relatively higher sensitivity in the short-wavelength region of the spectrum than do adults.

Experiment 6a

In Experiment 6, newborns did not show evidence of differentiating the blue from the grey checks within the checkerboard patterns. In Experiment 6a, I examined 1-month-olds' responses to blue-and-grey checkerboards by again using young infants' preference for a pattern over a plain stimulus. The spectral characteristics of the blue checks were the same as in Experiment 6. Based on the spectral sensitivity data obtained in young infants (Moscowitz-Cook, 1979), it was expected that 4- to 6-week-olds would see the blue-and-grey as equally bright at a point somewhere between where newborns do (about +15%) and where adults do (about 0%). As a result, only this part of the contrast range was explored. In addition, the maximum step size used in the present study was 6%. This was based on the finding that 2-

month-olds do not show a preference for a checkerboard in which the opposing grey checks contrast by 3% or less (Experiment 2a).

Method

Subjects

The subjects were 24 4- to 6-week-old infants ($\bar{x}$ = 5.2 weeks), at least 38 weeks gestational age and at least 2500 grams at birth. An additional seven infants were tested but not included in the sample: five because they did not contribute enough data, two because of low interobserver reliability and one because of a procedural error.

Stimuli

The stimuli were four 2 x 2 checkerboard patterns in which the blue-and-grey checks, to an adult, would contrast by +16%, +11%, +6%, and +2%. All other aspects of the stimuli remained identical to those described in previous experiments.

Apparatus and Procedure

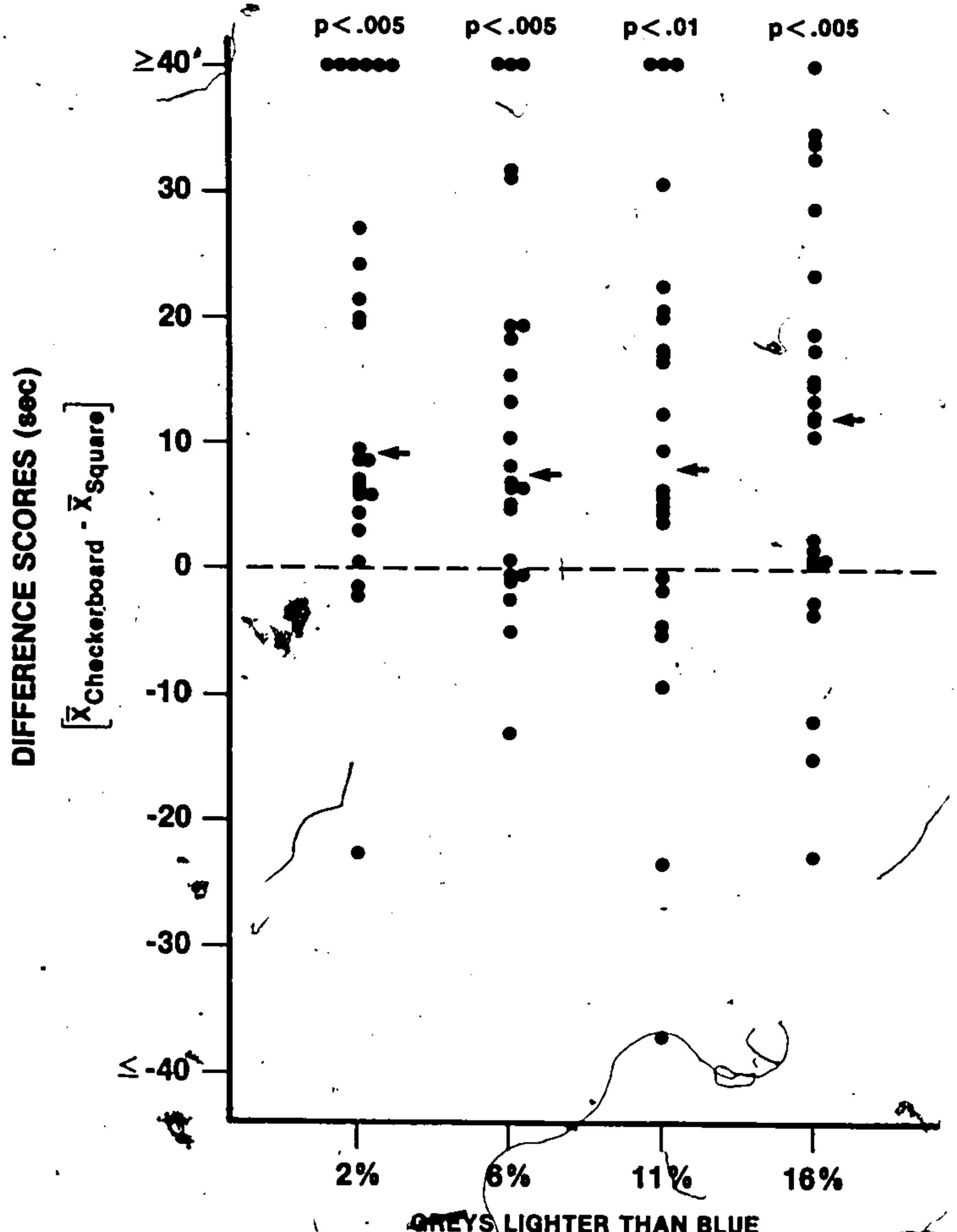
Each infant was shown all four patterns and the respective matching grey squares. The order of presentation was counterbalanced across subjects. All other aspects of the apparatus and procedure were identical to those outlined in Experiments 2, 3, 4, 5 and 6. For the 24 subjects in the final sample, the mean Spearman interobserver reliability coefficient was .96 (range = .80 - 1.00).

Results and Discussion

The data were reduced in the same manner as in previous experiments. In Figure 12, we can see that for all contrast values, the majority of the difference scores were positive. Wilcoxon analyses confirmed that 4- to 6-week-olds looked longer at the blue-and-grey

Figure 12. Distribution of the differences in looking time (mean looking time at the blue-and-grey checkerboard minus the mean looking time at the grey square) at each contrast. Each dot represents the data from a single 1-month-old, and the arrows indicate the median difference score at each contrast. The fact that most of the points lie above zero illustrates that at <u>all</u> contrasts, 1-month-olds looked significantly longer at the blue-and-grey checkerboards than at the luminance-matched grey squares.

1 MONTH OLDS
BLUE



CONTRAST BETWEEN THE BLUE & GREY CHECKS

checkerboards with checks contrasting by +16% [T(30) = 56, p < .005], by +11% [T(30) = 65, p < .01], by +6% [T(30) = 35, p < .005] and by +2% [T(30) = 21, p < .005] than at the matched grey squares. Since 4- to 6-week-olds demonstrated preferences for all of the contrasting checkerboard patterns, this implies that they were able to perceive the wavelength information within the patterns. Secondly, the pattern of results reveals that the magnitude of these preferences are fairly stable across all contrasts. Thus, as observed in the studies examining newborns' responses to green, yellow, and red, once the visual system is capable of detecting wavelength information, color appears to play a larger role than contrast in influencing visual preferences. However this final suggestion will remain tentative until we have examined how 1-month-olds respond to differences in contrasts. It is possible that like 2-month-olds, 1-month-olds may not show greater preferences for greater contrast. In any case, Experiment 6A shows that by one month of age, infants show some sensitivity to low-wavelength hues.

CHAPTER 5: General Discussion

The findings of this research reveal that newborn human infants are sensitive to certain forms of visual stimulation previously believed to be beyond their sensory capabilities.

Experiment 2 showed that newborns are sensitive to contrasts as small as 11%. Earlier studies using evoked potentials and optokinetic nystagmus (Atkinson et al., 1979; Doris et al., 1967) estimated that newborns' detection threshold for contrast is about 35-50%. Under similar luminance conditions, adults detect contrasts that are less than 1% (Steinhardt, 1936). The difference in sensitivity between newborns and adults is likely due to the immaturity of the newborn visual system. A number of visual system structures have been found to be anatomically immature. These include the foveal cones (Abramov et al., 1981), axonal myelinization and the visual cortex (DeCoursey, 1977).

Experiment 2a demonstrated the applicability of the methodology to older infants. Two-month-olds showed evidence of preferring checkerboard patterns in which the contrast was as small as 5%. Under similar experimental conditions, previous studies had reported that 2-month-olds' maximal sensitivity was extremely variable (i.e. 3% - 47%, c.f. Banks & Salapatek, 1981). In addition, 2-month-olds revealed a different pattern of results than did newborns. Newborns showed a very dramatic increase in the magnitude of their preferences (see Figure 4) when they were shown checkerboards of higher contrast. However, 2-month

-olds (see Figure 5) did not show a greater preference for patterns of higher contrast over those of lower contrast.

The differences between the way in which newborns and 2-month-olds respond to higher contrast may be accounted for by the size and number of checks within the checkerboards used in these studies. In the present studies, a 2 x 2 checkerboard with 8° checks was chosen because very young infants prefer it to other patterns that are more complex (Brennan et al., 1966). However, Brennan et al. found that 2-month-olds prefer an 8 x 8 checkerboard over others that are both more simple (2 x 2) and more complex (16 x 16). Thus the 2 x 2 checkerboard used in the present study is not a stimulus which 2-month-olds prefer. This may account for the fact that 2-month-olds did not show increasing preferences with increasing contrast. The 2-month-old may see a 2 x 2 checkerboard as a very simple stimulus and therefore, find it uninteresting regardless of its contrast. For future tests of 2-month-olds' contrast detection, one suggestion would be to decrease the size of the checks (i.e. use an 8 x 8 checkerboard). This more optimal check size would better reveal whether the magnitude of 2-month-olds' preferences for a patterned over a plain stimulus varies as a function of contrast.

A second reason for proposing this type of experiment stems from estimates of infants' contrast sensitivity thresholds. A number of studies (e.g. Banks & Salapatek, 1978) have shown that [illegible]onth-olds show greater sensitivity to contrast with stimulus elements smaller than those used in the present 2-month-old study. Therefore, if 2-month-olds viewed patterns containing smaller components, they might show evidence of detecting smaller contrasts (i.e. < 5%).

In summary, these data have revealed that the young infant is quite sensitive to contrast. Newborns' and 2-month-olds' fine detection of brightness contrast should be of great benefit in allowing them to discriminate among many objects in the visual world. The development of the ability to detect contrast also appears quite rapid. The data of the present studies, in addition to those investigations of infants' contrast sensitivity, suggest that infants' ability to perceive contrast improves within the first few months (c.f. Banks & Salapatek, 1981). This is most likely due to very rapid development of the nervous system in early infancy, particularly improvements in the retina, in myelinization and in the visual cortex (reviewed in Maurer, 1975). The present data also have shown that in addition to the fact that 2-month-olds are more sensitive to contrast than newborns, the manner in which these two age groups respond to various contrasts may also differ. However, as pointed out earlier, this suggestion requires further evaluation.

The results from the studies of color vision (Exps. 3, 4, 5, and 6) have revealed that newborns show evidence of detecting three of the four primary hues. Newborns demonstrated that they can discriminate grey from green, from yellow and from red. In these experiments, newborns viewed a series of colored-and-grey checkerboards each of which contained a different contrast. The range of contrasts in the series was large. It was also centred upon the luminance at which studies of adult spectral sensitivity predict a color and a grey should appear equally bright (see also Appendix B). Since the difference in contrast between the checkerboards changed in small steps, it was assumed that newborns would perceive the brightness of the color and the grey as equal in at least one of the checkerboard patterns. Yet newborns looked longer at each of the contrasting green, yellow and red checkerboards than at the grey squares. In addition, the pattern of newborns' preferences differed markedly from the pattern shown when newborns viewed achromatic checkerboards in Experiment 2. These data provide the first demonstration of color vision in the human newborn (c.f. Adams & Maurer, 1983). In the literature, previous studies in which the brightness problem was minimized revealed that both 2-month-olds (Oster, 1975; Peeples & Teller, [illegible] and 3-month-olds (Bornstein, 1975; Schaller, 1975) are capable of detecting hue. The present data reveal that this ability is present immediately after birth. Some earlier electrophysiological studies (Barnet et al., 1965; Fischel, 1969; Lodge et al., 1969) found the amplitude of newborns' VEPs varied with different colors. However these data are difficult to interpret since they used colored stimuli that were based on colors that adults perceived as equally bright. As pointed out many times in Chapter 1, this is an inappropriate control for studies of infants' color vision.

However, when newborns were shown the blue-and-grey checkerboards, the pattern of results was very different and strongly resembled newborns' responses to achromatic checkerboards of various contrasts (Experiment 2). In Experiment 2, newborns did not show a preference for a checkerboard over the matched grey squares when the contrast in the checkerboard was < 5%. However, when viewing checkerboards of greater contrast (i.e. > 11%), newborns' preferences varied as a function of the contrast between the checks. In Experiment 6, newborns displayed a similar pattern of results. When shown the blue-and-grey checkerboards in which the contrast was +14% or +16%, newborns showed no preference for these stimuli over the matched grey squares. Presumably, newborns perceived these checkerboards as containing no contrast information. Therefore, the grey-and-blue checks must have appeared very similar in brightness. However, newborns did show increasing preferences for the checkerboards in which the brightness difference presumably differed most from the checkerboards that contained no contrast information. The striking similarity between the results of Experiment 2 and 6 suggests that when newborns viewed blue-and-grey checkerboards, they detected only the contrast and not the hue information existing within the stimuli.

The finding that newborns show no evidence of discriminating blue from grey is not surprising given the recent studies of chromatic adaptation in infancy. Chromatic adaptation (c.f. Hurvich, 1982) refers to the "fatigue" of one or more of the receptor systems (the short-wavelength - sensitive, mid-wavelength - sensitive and the long-wavelength - sensitive, abbreviated as SWS, MWS, and LWS) by flooding the retina with light of a given wavelength. The purpose of adapting a chromatic system(s) is so that other systems can be studied in isolation (Stiles, 1959). In adults, this is accomplished by observing shifts in relative photopic sensitivity under conditions of adaptation. When two of the three chromatic systems are sufficiently adapted, spectral sensitivity is determined only by the third system. If all systems are functioning normally, spectral sensitivity should differ from the pre-adapted state (i.e. when all three systems operate). Pulos, Teller & Buck (1980), examined the effects of chromatic adaptation in 2-month-olds. They were particularly interested in effects on the SWS system since some previous data (Teller et al., 1978) had shown that 2-month-olds may possess a tritan-like color defect. Tritanopes are dichromats who are believed to be missing SWS cones (Hurvich, 1982). Pulos et al. adapted 2-month-olds and adults to broad-band yellow light. This presumably fatigued both the MWS and LWS systems leaving only the SWS free to function normally. When test spots between 420 and 560 nm were imposed on the yellow adapting background, adults' curves showed maximal sensitivity with test spots of about 440 to 450 nm. This curve strongly resembled a microspectrophotometrically derived SWS function (Brown & Wald, 1963; Marks, Dobelle & MacNichol, 1963). However, when 2-month-olds viewed the same test spots, their sensitivity did not change from what it was in the pre-adapted state. In fact, the curve increased monotonically from 420 to 560 nm and thus resembled a rod function (c.f. Hurvich, 1982). However, Pulos et al. did notice that under yellow adaptation, 2-month-olds showed many individual differences. A few subjects' curves did peak in the short-wavelength region and thus were different from their curves in the pre-adapted state.

Pulos et al. also tested infants after adaptation to blue light. In this case, 2-month-olds, like adults, showed shifts in spectral sensitivity after adaptation. These changes were consistent with what would be expected by the presence of at least two chromatic systems (most likely the MWS and LWS systems).

Thus, the results from Pulos et al.'s study of chromatic adaptation in 2-month-olds generally support the findings of this thesis: The system mediating the detection of short-wavelength light appears to develop more slowly than the systems primarily responsible for mediating detection of medium and long-wavelength light.

Pulos et al. also tested a group of 3-month-olds under the same conditions in which 2-month-olds were tested. The results indicated that the majority of 3-month-olds did not show shifts in spectral sensitivity after yellow adaptation. Thus, Pulos et al. concluded that the SWS system probably becomes fully functional at some point beyond three months.

The results of this thesis show that a 1-month-old is capable of detecting a stimulus composed mainly of short-wavelength light. Yet a study of chromatic adaptation reveals that the chromatic system chiefly responsible for responding to short-wavelengths is slow in developing. However, as mentioned in Chapter 1, studies of spectral sensitivity and hue detection cannot be directly compared. Although Pulos et al.'s data show no evidence of a SWS system in 1- to 3-month-old infants, it is possible that other systems (e.g. the MWS system) can respond, at least to some degree, within the blue region. Studies of color matching (Thomson & Wright, 1953) and microspectrophotometry (Marks et al., 1963) reveal that the adult MWS system responds to wavelengths between 450 and 600 nm, although it responds most strongly to wavelengths between 510 and 560 nm. The blue stimulus used in Experiments 6 and 6a was composed of wavelengths from 420 to 510 nm (see Appendix C for spectral characteristics of all stimuli). Since the response curve for the MWS system and the spectral characteristics of the blue stimulus used in the present study do overlap, it is possible that the MWS system may be responsible for mediating 1-month-olds' detection of the blue hue in the checkerboard pattern. In addition, it is possible that the LWS system may be mediating the detection of this blue stimulus since in adults the LWS system responds to wavelengths as low as about 500 nm (Marks et al., 1963; Thomson & Wright, 1953). At birth, the MWS and LWS systems may be too immature to mediate detection of short-wavelength light.

In summary, the present data reveal that newborns show no evidence of detecting a blue light whereas 1-month-olds do appear to detect this hue. Although Pulos et al.'s study of chromatic adaptation suggests that the SWS system becomes fully functional at some point beyond three months of age, the positive evidence of blue detection shown by 1-month-olds in the present study may be mediated by one or more of the other chromatic systems, or by a weakly functioning SWS system itself.

Another issue that remains to be discussed is the size of the chromatic fields used in the present studies. As mentioned in the method of Experiment 3, the size of each check was 8° x 8°. Some recent data suggests that relative to adults, infants show detection of hue only with large test fields like those used in the present experiments. Teller and Hartmann (1981) have found that 1-, 2-, and 3-month-olds seem to discriminate hue only when test fields are larger. Teller and Hartmann found that 3-month-olds could discriminate both 2° and 4° diameter red spots from a yellow background but showed no evidence of discriminating the red from yellow when the spot size was smaller; 2-

month-olds could discriminate a yellow background from a 4° but not from a 2° red spot; 1-month-olds could only discriminate these two hues when the red was at least 8°. Thus, these data show a clear developmental trend: The younger the baby, the larger the size of the hue needs to be in order for the infant to demonstrate that he can differentiate it from the background.

Field size may also have affected the results in the study of Teller et al. (1978). In that experiment, 2-month-olds did not appear to discriminate a narrow (1° x 13.0°) bar of yellow-green or mid-purple from a white background. It is possible that with a wider bar, 2-month-olds would have detected these hues. The results of this thesis show that newborns discriminate large 8° x 8° red, green and yellow checks from grey. However, newborns did not show evidence of detecting an 8° x 8° blue field. Perhaps if the size of the blue checks were increased, newborns would show that they detect this hue.

The questions that arise from studies of field size are: 1) What factors underlie the developmental trends in the effects of field size on hue discrimination? and, 2) Does the effect of field size vary for different hues? Some recent evidence from studies of adult dichromats may aid in providing answers to these questions. Smith and Pokorny (1977) have shown that adult dichromats can make wavelength discriminations in certain spectral regions only when the stimuli are large. Similarly, Nagy and Boynton (1979) found that with large test fields, dichromats can actually name, in a consistent fashion, colors that under most conditions, appear achromatic or are confused with other colors. This phenomenon has also been observed in cats, a species which under most conditions, appears to be color deficient (Jacobs, 1976). Loop, Bruce and Petchowski (1979) have shown that cats, like adult dichromats, show evidence of hue detection only when the size of the test field is very large.

Teller and Hartmann (1981) argue that larger test fields evidently allow red-green dichromats, cats, and apparently infants, the use of a receptor type (e.g. rods or "hidden" cones) which are non-functional with smaller stimuli. Teller and Hartmann state, "perhaps in all of these cases, a relative scarcity of one or more of the receptor types makes it necessary to use large stimulus fields if wavelength information is to be preserved" (pg. 17). Thus, dichromats, cats and young infants may possess the necessary receptor type(s), but the density or number of functional units in any given retinal area may be lower than in normal adult trichromats. Therefore, a small patch of chromatic light would stimulate relatively fewer retinal receptors. As a result, the combined output from these receptors would be insufficient to signal the presence of wavelength information. This suggestion is supported by data from a study of peripheral color vision. The peripheral retina contains relatively fewer retinal cones per unit area than does the central retina (Guyton, 1976). Therefore, the size of a chromatic stimulus should be an important variable in predicting the color appearance of a stimulus impinging upon the central or peripheral retina. In a color naming experiment, Gordon and Abramov (1977) found that subjects reported that a 1.5° x 1.5° color field appeared highly chromatic when presented to the central retina but appeared desaturated when presented at 45° in the periphery. However, when presented with a

6.5° x 6.5° color field in the periphery, subjects reported that the stimulus appeared highly chromatic. These data suggest that the perceived chromaticity of a stimulus is determined by the number of retinal receptors that are affected by that stimulus.

This may provide a clue as to why young infants do not show evidence of possessing a functional SWS system (Pulos et al., 1980). Recent anatomical evidence (Abramov, Gordon, Hendrickson, Hainline, Dobson & LaBossiere, 1982) shows that the newborn retina is quite immature. It contains a sparse distribution of cone receptors, particularly in the foveal region. Additionally, the human adult retina possesses many fewer SWS than MWS or LWS cones (Bowmaker, Dartnell & Mollon, 1979). Therefore, the probability of finding a dense distribution of SWS cones in the newborn's retina is small. Thus, if a SWS actually existed in young infants, one would expect that only a very large stimulus could activate it. To date, the largest stimulus used to test the presence of a SWS system is an 18° x 1.6° field (Pulos et al., 1980). A possibility for future research would be to employ larger fields in order to observe if the SWS system is functional at all in young infants.

The present data also have implications for assessing the physiological maturation of the visual system at birth. Since newborns show evidence of detecting green, yellow and red hues, this implies that at least one wavelength-sensitive system is active, at least to some degree. Since the red, green and yellow stimuli used in this research were all broad-band, they contain wavelengths that both the adult MWS and LWS systems are particularly sensitive to. Future studies using more narrow-band stimuli may determine more precisely the degree to which either or both of these systems function in young infants.

Beyond the receptor level, single-cell electrophysiological studies of old-world primates (organisms who are neuroanatomically and neurophysiologically similar to humans (c.f. Jacobs, 1976; DeValois, 1973), have provided many insights into the processing of chromatic information by the nervous system. From the cones, chromatic information is relayed to X-cells in the ganglion layer (6),(7) where the raw cone receptor signals are channeled into opponent processes (DeMonasterio, 1978a,b). From the retina, chromatic information is relayed along the optic tract (Marrocco, 1973) to the parvocellular layers of the LGN (Dreher, Fukada & Rodieck, 1976; Schiller & Malpeli, 1978). From the LGN, color information is relayed primarily to layer 4b within the primary visual cortex (Hubel & Weisel, 1966). However responses to chromatic stimuli, although more rare, have also been reported in all other layers of the primary visual cortex (Dow & Gouras, 1973; Gouras, 1974), as well as other cortical structures including the visual association areas (DeValois, 1973) and the prestriate cortex (Zeki, 1973).

Since the data of this thesis show that the human newborn is capable of differentiating three of the four primary hues from grey, this implies that at least part of this "chromatic" pathway is functional to some degree immediately after birth. The prevailing view for many years was that the infant's visual cortex was not active until one month after birth (c.f. Bronson, 1966). However, some recent work has shown that newborns discriminate form (Fantz & Miranda, 1975), maintain fixation on a stimulus (Lewis & Maurer, 1980), and discriminate orientation (Slater & Sykes, 1979). These data have supported theorists such as Haith (1975) who propose that the geniculostriate pathway is operational at birth. However, newborns also fail to demonstrate some visual behaviors that are thought to be mediated cortically. As a result, Maurer and Lewis (1979) have proposed that only some pathways to the cortex are functional in the newborn. Maurer and Lewis argue that the X-system projecting to the cortex is functional to some degree at birth. Since the X-system is believed to be the one sensitive to color (DeMonasterio, 1978a), Maurer and Lewis have predicted that human newborns should possess some form of color vision. The results of the present series of investigations, for the most part, support this prediction of Maurer and Lewis.

The findings of this thesis may provide some insights into how the newborn perceives the external world. First, newborns appear to be sensitive to some hues. When they are capable of detecting hue in a stimulus, hue appears to play a major role in directing their visual behavior. This was demonstrated in Experiments 3, 4, and 5, when the magnitude of newborns' preferences was relatively stable across contrast. However, when no color information is available, contrast plays a strong role in determining newborns' preferences. As was demonstrated in Experiment 2 with achromatic patterns and Experiment 6 with blue-and-grey patterns, the magnitude of newborns' preferences was greater as a function of greater contrast between the checks.

In conclusion, the present data have provided the first demonstration of color vision in the newborn infant. In adequately minimizing the potential confounding of brightness and hue this thesis has shown that newborns can differentiate grey from red, from green and from yellow. However, newborns' color vision is not complete: Newborns did not show that they could differentiate grey from blue. This result may be due to the immaturity of the short-wavelength-sensitive system. The present data do suggest that either or both the mid- and long-wavelength-sensitive system(s) are operational at birth. Future studies examining chromatic adaptation and stimulus field size will provide us with more insights into the development of the chromatic systems in early infancy.

References

Abramov, I., Gordon, J., Hendrickson, A., Hainline, L., Dobson, V., & LaBossiere, E. The retina of the newborn human infant. Science, 1982, 217, 265-267.

Adams, R.J. Newborns' detection of visual contrast. Paper presented at 3rd I.C.I.S., Austin, Texas, 1982.

Adams, R.J., & Maurer, D. A demonstration of color perception in the newborn. Paper presented at S.R.C.D., Detroit, Michigan, 1983.

Adrian, E.D. The electric response of the human eye. J. Physiol. (London), 1945, 104, 84-104.

Atkinson, J., Braddick, O., & French, J. Contrast sensitivity of the human neonate measured by the visual evoked-potential. Inves. Opthal. Vis. Science, 1979, 18, 210-213.

Atkinson, J., Braddick, O., & Moar, K. Development of contrast sensitivity in the first three months of life in the human infant. Vis. Res., 1977, 17, 1037-1044.

Banks, M.S., & Salapatek, P. Acuity and contrast sensitivity in 1-, 2-, and 3-month-old human infants. Inves. Opthal. Vis. Science, 1978, 17, 361-365.

Banks, M.S., & Salapatek, P. Infant pattern vision: A new approach based on the contrast sensitivity function. J. Exp. Child Psychol., 1981, 31, 1-45.

Barnet, A.B., Lodge, A., & Armington, J.C. Electroretinogram in newborn human infants. Science, 1965, 148, 651-654.

Bornstein, M.H. Infants are trichromats. J. Exp. Child Psychol., 1976, 21, 425-445.

Bornstein, M.H. Chromatic vision in infancy. In H.W. Reese & L.P. Lipsitt (Eds.), Advances in child development and behavior (Vol. 12). New York: Academic Press, 1978.

Bowmaker, J.K., Dartwell, H.J.A., & Mollon, J.D. The violet-sensitive receptors of primate retinae. J. Physiol., 1979, 292, 31.

Brennan, W.M., Ames, E.W., & Moore, R.W. Age differences in infants' attention to patterns of different complexities. Science, 1966, 151, 354-356.

Bronson, G. The postnatal growth of visual capacity. Child Devel., 1974, 45, 873-890.

Brown, P.K., & Wald, G. Visual pigments in single rods and cones of the human retina. Science, 1964, 144, 45-52.

Bunt, A.H., Hendrickson, A.E., Lund, J.S., Lund, R.D., & Fuchs, A.F. Monkey retinal ganglion cells: Morphometric analysis and tracing of axonal projections, with a consideration of the peroxidase technique. J. Comp. Neurol., 1975, 164, 265-286.

Chase, W.P. Color vision in infants. J. Exp. Psychol., 1937, 20, 203-222.

Cleland, B.G., Dubin, M.W., & Levick, W.R. Sustained and transient neurons in the cat's retina and lateral geniculate nucleus. J. Physiol. (London), 1971, 217, 473-496.

Darwin, C.H. A biographical sketch of a young child. Kosmos, 1877, 1, 367-376.

De Monasterio, F.M. Centre and surround mechanisms of opponent-color X and Y ganglion cells of retina of macaques. J. Neurophysiol., 1978, 41, 1418-1434.

De Monasterio, F.M., Gouras, P., & Tolhurst, D.J. Spatial summation, response pattern and conduction velocity of ganglion cells of the rhesus monkey retina. Vis. Res., 1976, 16, 674-678.

DeValois, R.L. Central mechanisms of color vision. In R. Jung (Ed.), Handbook of sensory physiology (Vol. VII). Central processing of visual information Berlin: Springer-Verlag, 1973.

Dobson, V. Spectral sensitivity of the 2-month-old infant as measured by the visually evoked cortical potential. Vis. Res., 1976, 16, 367-374.

Doris, J., Casper, M., & Poresky, R. Differential brightness thresholds in infancy. J. Exp. Child Psychol., 1967, 5, 522-535.

Doris, J., & Cooper, L. Brightness discrimination in infancy. J. Exp. Child Psychol., 1966, 3, 31-39.

Dow, B.M., & Gouras, P. Color and spatial specificity of single units in rhesus monkey foveal striate cortex. J. Neurophysiol., 1973, 36, 79-100.

Dreher, B., Fukada, Y., & Rodieck, R.W. Identification, classification and anatomical segregation of cells with X-like and Y-like properties in the lateral geniculate nucleus of old-world primates. J. Physiol., 1976, 258, 433-452.

Enroth-Cugell, C., & Robson, J.G. The contrast sensitivity of retinal ganglion cells of the cat. J. Physiol., 1966, 187, 517-552.

Fagan, J.F. Infant color perception. Science, 1974, 183, 973-975.

Fantz, R.L. Pattern vision in newborn infants. Science, 1963, 140, 296-297.

Fantz, R.L., & Miranda, S.B. Newborn infant attention to form of contour. Child Devel., 1975, 46, 224-228.

Fantz, R.L., Ordy, J.M., & Udelf, M.S. Maturation of pattern vision in infants during the first six months. J. Comp. & Physiol. Psychol., 1962, 55, 907-911.

Field, T., Woodson, R., Greenberg, R., & Cohen, D. Newborns' responses to facial expressions. Science, 1982, 218, 179-180.

Fischel, H. Visual evoked potential in prematures, newborns, and children by stimulation with colored light. Electroenceph. Clin. Neurophysiol., 1969, 27, 660.

Fukada, Y. Receptive field organization of cat optic nerve fibres with special reference to conduction velocity. Vis. Res., 1971, 11, 209-226.

Gordon, J., & Abramov, I. Color vision in the peripheral retina. II. Hue and saturation. J. Optical Soc. of Amer., 1977, 67, 202-207.

Gouras, P. Opponent-color cells in different layers of foveal striate cortex. J. Physiol., 1974, 238, 583-602.

Graham, C.H. Color: Data and theories. In C.H. Graham (Ed.), Vision and visual perception. New York: John Wiley & Sons, 1965.

Guyton, A.C. Structure and function of the nervous system, 2nd ed. Philadelphia: W.B. Saunders Co., 1976.

Haith, M.M. Visual competence in early infancy. In R. Held, H. Leibowitz, & H.L. Teuber (Eds.), Handbook of Sensory Physiology (Vol. VIII). Berlin: Springer-Verlag, 1975.

Hamer, R.D., Teller, D.Y., & Morris, L.A. Rayleigh discriminations in 1-, 2-, and 3-month-old infants. A paper presented at meetings of O.S.A., Sarasota, Florida, 1980.

Harris, P. Eye movements between adjacent stimuli: An age change in infancy. Brit. J. Psychol., 1973, 64, 215-218.

Hering, E. Principles of a new theory of the color sense. Vienna, 1878. (Translated by Kay Butler.)

Hershenson, M. Visual discrimination in the human newborn. J. Comp. Physiol. Psychol., 1964, 58, 270-276.

Holden, W.A., & Bosse, K.K. The order of development of color perception and of color preference in the child. Archives of Ophthal., 1900, 29, 261-277.

Horowitz, F.D., Paden, L., Bhana, K., & Self, P. An infant-control procedure for studying infant visual fixations. Devel. Psychol., 1972, 8, 90.

Hsia, Y., & Graham, C.H. Color blindness. In C.H. Graham (Ed.), Vision and visual perception. New York: Wiley, 1965.

Hubel, D.H., & Weisel, T.N. Receptive fields and functional architecture of monkey striate cortex. J. Physiol., 1968, 195, 215-243.

Hurvich, L. Color vision. New York: Wiley, 1982.

Hurvich, L.M., & Jameson, D. An opponent process theory of color vision. Psychol. Rev., 1957, 64, 384-404.

Ikeda, H., & Wright, M.J. Differential effects of refractive errors and receptive field organization of central and peripheral ganglion cells. Vis. Res., 1972, 12, 1465-1476.

Jacobs, G.H. Color vision. Annual Rev. Psychol., 1976, 27, 63-89.

Kessen, W., & Bornstein, M.H. Discriminability of brightness change for infants. J. Exp. Child Psychol., 1978, 25, 526-530.

Keesey, U. Flicker and pattern detection: A comparison of thresholds. J. Ophth. Soc. Amer., 1972, 62, 446-448.

King-Smith, P.E., & Kulikowski, J.J. Pattern and flicker detection analysed by subthreshold summation. J. Physiol., 1975, 249, 519-549.

Kulikowski, J.J., & Tolhurst, D.J. Psycho-physical evidence for sustained and transient detectors in human vision. J. Physiol., 1973, 232, 149-162.

LeGrand, Y. Spectral luminosity. In D. Jameson & L.M. Hurvich (Eds.), Handbook of sensory physiology (Vol. VIII/4). New York: Springer-Verlag, 1972.

Lennie, P. Parallel visual pathways: A review. Vis. Res., 1980, 20, 561-594.

Lewis, T.L., & Maurer, D. Central vision in the newborn. J. Exp. Child Psychol., 1980

Lodge, A., Armington, J.C., Barnet, A.B., Shanks, B.L., & Newcomb, C.N. Newborn infants' electroretinograms and evoked electroencephalographic responses to orange and white light. Child Dev., 1969, 40, 267-293.

Loop, M.S., Bruce, L.L., & Petuchowski, S. Cat color vision: The effect of stimulus size, shape and viewing distance. Vis. Res., 1979, 19, 507-543.

Mann, I. The development of the human eye. Cambridge: Cambridge University Press, 1928.

Marks, W.B., Dobelle, W.H., & MacNichol, E.F. Visual pigments of single primate cones. Science, 1963, 143, 1181-1183.

Marrocco, R.T. Responses of monkey optic tract fibres to monochromatic lights. Vis. Res., 1972, 12, 1167-1174.

Marrocco, R.T. Sustained and transient cells in monkey lateral geniculate nucleus: Conduction velocities and response properties. J. Neurophysiol., 1976, 39, 340-353.

Marsden, R.E. Discussion and apparatus. A study of the early color sense. Psych. Rev., 1903, 10, 37-47.

Maurer, D. Infant visual perception: Methods of study. In L. Cohen & P. Salapatek (Eds.), Infant perception: From sensation to cognition (Vol. I). New York: Academic Press, 1975.

Maurer, D., & Lewis, T.L. A physiological explanation of infants' early visual development. Can. J. Psychol., 1979, 33, 232-252.

McDougall, W. An investigation of the colour sense of two infants. Brit. J. Psychol., 1908, 2, 338-352.

Michael, C.R. Color vision mechanisms in monkey striate cortex: Dual-opponent cells with concentric receptive fields. J. Neurophysiol., 1978, 41, 572-588.

Moskowitz-Cook, A. The development of photopic spectral sensitivity in human infants. Vis. Res., 1979, 19, 1133-1142.

Myers, C.S. Some observations on the development of the colour sense. Brit. J Psychol., 1908, 2, 353-362.

Nagy, A.L., & Boynton, R.M. Large-field color naming of dichromats with rods bleached. J. Opt. Soc. Amer., 1979, 69, 1259-1265.

Oster, H.S. Color perception in ten-week old infants. Paper presented at the meeting of S.R.C.D., Denver, Colorado, 1975.

Peeples, D.R., & Teller, D.Y. Color vision and brightness discrimination in two-month-old human infants. Science, 1975, 189, 1102-1103.

Peeples, D.R., & Teller, D.Y. White-adapted photopic spectral sensitivity in human infants. Vis. Res., 1978, 18, 49-53.

Pirchio, M., Spinelli, D., Fiorentini, A., & Maffai, L. Infant contrast sensitivity evaluated by evoked potentials. Brain Res., 1978, 141, 174-184.

Pratt, K.C., Nelson, A.K., & Sun, K.H. The behavior of the newborn infant. Columbus: Ohio State University Press, 1930.

Pulos, E., Teller, D.Y., & Buck, S.L. Infant color vision: A search for short-wavelength-sensitive mechanisms by means of chromatic adaptation. Vis. Res., 1980, 20, 485-493.

Salapatek, P. Behavioral and electrophysiological evaluation of the infant contrast sensitivity function. In J. Jampelsky & L. Proenza (Eds.), Proceedings of the symposium on application of psychophysics to clinical problems. Washington, D.C.: National Academy of Science, 1979.

Salapatek, P., & Banks, M.S. Infant sensory assessment: Vision. In F.D. Minifie & L.L. LLoyd (Eds.), Communicative and cognitive abilities--Early behavioral assessment. Baltimore: Univ. Paris Press, 1977.

Schaller, M.J. Chromatic vision in human infants. Bull. Psychonom. Soc., 1975, 6, 39-42.

Schiller, P.H., & Malpeli, J.G. Functional specificity of lateral geniculate nucleus laminae of the rhesus monkey. J. Neurophysiol., 1978, 41, 788-797.

Slater, A., & Sykes, M. Newborn infants' visual responses to square wave gratings. Child Devel., 1977, 48, 545-554.

Smith, J.M. The relative brightness values of three hues for newborn infants. Univ. of Iowa Studies in Child Welfare, 1936, 12, 93-140.

Smith, V.C., & Pokorny, J. Large-field trichromacy in protanopes and deuteranopes. J. Opt. Soc. Amer., 1977, 67, 213-220.

Spears, W.C. Assessment of visual preference and discrimination in the four-month-old infant. J. Comp. Physiol. Psychol., 1964, 57, 381-386.

Steinhardt, J. Intensity discrimination in the human eye. J. Gen. Physiol., 1936, 20, 185-209.

Teller, D.Y., & Bornstein, M.H. Infant color vision and color perception. In P. Salapatek & L.B. Cohen (Eds.), Handbook of infant perception. New York: Academic Press, 1983.

Teller, D.Y., & Hartmann, E.E. Test field size and infant color vision. Paper presented at A.R.V.O., Sarasota, Florida, 1981.

Teller, D.Y., Morris, L., & Alexander, K. Rayleigh discriminations in young human infants: A progress report. Paper presented at A.R.V.O.,Sarasota, Florida, 1979.

Teller, D.Y., Peeples, D.R., & Sekel, M. Discrimination of chromatic from white light by two-month-old human infants. Vis. Res., 1978, 18, 41-48.

Tolhurst, D.J. Sustained and transient channels in human vision. Vis. Res., 1975, 15, 1151-1155.

Valentine, C.W. The colour perception and colour preferences of an infant during its fourth and eighth months. Brit. J. Psychol., 1913-1914, 6, 363-386.

Werner, J.S. Development of scotopic sensitivity and the absorption spectrum of the human ocular media. Opt. Soc. Amer., 1982, 72, 247-253.

Werner, J.S., & Wooten, B.R. Human infant color vision and color perception. Infant Beh. & Devel., 1979, 2, 241-274.

Wiesel, T.N., & Hubel, D.H. Spatial and chromatic interactions in the lateral geniculate body of the rhesus monkey. J. Neurophysiol., 1966, 29, 1115-1156.

Wooley, H.T. Some experiments on the color perceptions of an infant and their interpretation. Psych. Rev., 1909, 16, 363-376.

Zeki, S.M. Color coding in rhesus monkey prestriate cortex. Brain Res., 1973, 53, 422-427.

Footnotes

1) The Munsell System, developed in 1910 and widely used in art, industry and research, is a set of chromatic and achromatic chips. These chips have been rated for their hue, brightness and saturation by sampling large groups of adults. Therefore, it is possible to choose chips which adults rate as equally bright.

2) It is not clear why the results from studies of infants' spectral sensitivity by Peeples and Teller (1978), Dobson (1976) and Moscowitz-Cook (1979) differ. One possibility may be because they used different measures. It has been documented in many places that VEP data differ quite substantially from data obtained from studies of preferential looking (c.f. Adams & Maurer, 1983; Bornstein, 1976; and Maurer, 1975). A reason for this discrepancy is because evoked potential measures are an index of the underlying neural activity and preferential looking is more an index of overt visual behavior.

3) This is a psychophysical procedure in which the subject adjusts the brightness of one hue until he judges it to match the brightness of a second hue. After repeating this a number of times, the average value that the subject used to make the match is taken as an estimate of his brightness match for the two hues.

4) Dichromacy, composed of three subclasses (protanopia, deuteranopia and tritanopia), is defined as the ability to distinguish certain

portions of the visible spectrum from achromatic light. These neutral zones are centred at 493nm for the typical adult protanope, 498nm for the deuteranope and 575nm for the tritanope (Hsai & Graham, 1966).

5) Two recent studies have reported a successful application of an infant control procedure: These include Field et al. (1982) who studied newborns' responses to facial expressions and Antell and Keating (1982) who studied newborns' responses to number.

6) A substantial amount of recent physiological research has shown that certain visual information is processed by special neural pathways. The two independent systems believed to underly this form of processing have been designated the X and Y systems (see Lennie, 1980 for a review). The components of these systems, the X and Y cells, form specific pathways within the cat and monkey visual system(s) and have identifiable electrophysiological properties (Cleland, Dubin & Levick, 1971; Enroth-Cugell & Robson, 1966; Fukada, 1971; and Ikeda & Wright, 1972). X and Y cells have also been identified by single-cell electrophysiological studies in many portions of the primate nervous system (Demonasterio, 1978a,b; DeMonasterio, Gouras & Tolhurst, 1976; Gouras, 1974; Marrocco, 1976; Marrocco & Brown, 1976; and Michael, 1978). Moreover, some elegant human psychophysical studies examining thresholds for pattern and flicker detection have suggested that two similar discrete processing systems may be present in humans (Keesey, 1972; King-

Smith & Kulikowski, 1975; Kulikowski & Tolhurst, 1973; and Tolhurst, 1975). In terms of relating this electrophysiological work to the present thesis, a large number of single-cell electrophysiological studies of the primate visual system (DeMonasterio, 1978a; DeMonasterio et al., 1976; Dreher et al., 1976; Gouras, 1968; Marrocco & Brown, 1975) have found that only X-cells respond to chromatic stimulation.

7) A third class of cells, denoted as W-cells have also been identified (see Lennie, 1979). However, it is not clear what role these cells play (particularly in terms of color vision) so their discussion will not be pursued.

APPENDIX A

Luminance values (expressed in candelas per metre squared and log candelas per metre squared) of the stimuli used in Experiments 2, 3, 4, 5, and 6.

Experiment 2 - Achromatic Checkerboards

Stimulus Contrast	27%	23%	17%	11%	5%	3%
Luminance of the Standard Grey Check						
cd/m^2	5.21	5.21	5.21	5.21	5.21	5.21
log cd/m^2	.72	.72	.72	.72	.72	.72
Luminance of the Opposing Grey Check						
cd/m^2	3.00	3.27	3.68	4.21	4.69	4.88
log cd/m^2	.47	.51	.57	.62	.67	.69

Experiment 3 - Green-and-grey Checkerboards

Stimulus Contrast	+22%	+13%	+3%	-7%	-16%	-25%
Luminance of the Green Check						
cd/m^2	4.0	4.0	4.0	4.0	4.0	4.0
log cd/m^2	.60	.60	.60	.60	.60	.60
Luminance of the Opposing Grey Check						
cd/m^2	6.20	5.21	4.21	3.48	2.87	2.42
log cd/m^2	.79	.72	.62	.54	.46	.38

Experiment 4 - Yellow-and-grey Checkerboards

Stimulus Contrast	+20%	+12%	+6%	-2%	-11%	-21%
Luminance of the Yellow Check						
cd/m^2	4.15	4.15	4.15	4.15	4.15	4.15
log cd/m^2	.62	.62	.62	.62	.62	.62
Luminance of the Opposing Grey Check						
cd/m^2	6.20	5.31	4.71	4.02	3.30	2.69
log cd/m^2	.80	.73	.67	.60	.52	.43

Experiment 5 - Red-and-grey Checkerboards

Stimulus Contrast	+27%	+18%	+8%	-2%	-11%	-21%
Luminance of the Red Check						
cd/m^2	3.69	3.69	3.69	3.69	3.69	3.69
log cd/m^2	.57	.57	.57	.57	.57	.57
Luminance of the Opposing Grey Check						
cd/m^2	6.45	5.33	4.35	3.57	2.96	2.42
log cd/m^2	.81	.73	.64	.55	.47	.38

Experiment 6 - Blue-and-grey Checkerboards

Stimulus Contrast	+33%	+25%	+16%	+14%	+5%	-4
Luminance of the Blue Check						
cd/m^2	3.70	3.70	3.70	3.70	3.70	3.7
log cd/m^2	.57	.57	.57	.57	.57	.5
Luminance of the Opposing Grey Check						
cd/m^2	7.32	6.21	5.14	4.93	4.10	3.4
log cd/m^2	.86	.79	.71	.69	.61	.5

APPENDIX B

Adults' ratings of the contrast of the chromatic checkerboards.

As was discussed in Chapter 1 (pg. 8-9), perceived brightness and luminance (what is read from a photometer) are not identical. The luminance readings are calibrated against a normal adult photopic spectral sensitivity function. However, for a number of reasons (e.g. stimulus size or the characteristics of the background), luminance values and human ratings often differ.

In order to find out how adults would rate the stimuli in the present studies, three normal female trichromats (as evaluated by the Ishihara Color Plates) were recruited. To orient them, the subjects were first shown the series of achromatic checkerboards from Experiment 2 and were told the values of each of the contrasts (from 3% – 27%). The subjects were then allowed to inspect these stimuli for as long as they required. The subjects were then shown the colored patterns and were asked to rate the contrast of each. If subjects perceived the grey as darker, they were to rate the checkerboard as a (-) contrast of some value. If subjects perceived the grey as lighter, they were told to rate it as a (+) contrast of some value.

I was mainly interested in the 0% (no perceived contrast) point to see how it corresponded with the equal-luminance point (the arrows in Figs. 8 to 12) estimated by the photometer. To do this, I averaged all of the subjects' ratings for each of the checkerboards and interpolated where the 0% point would be. As we can see in the table, the perceived values for all hues closely match the luminance values obtained from the photometer.

	Luminance Contrast	Perceived Contrast
Green	0%	0%
Yellow	0%	+4%
Red	0%	-2%
Blue	0%	-3%

APPENDIX C

Transmission spectra of chromatic and achromatic stimuli used in Experiments 2,2a,3,4,5,6 and 6a. The achromatic stimulus chosen was a grey square of approximately average luminance (4.1 cd/m^2) from the range used in these experiments. These measurements were made by using a Cary 14 spectrophotometer.

ACHROMATIC

Wavelength	400	450	500	550	600	650	700
% Transmission	20	23	25	24	25	26	27

GREEN

Wavelength	500	520	540	560	580	600
% Transmission	0	28	55	47	15	0

YELLOW

Wavelength	520	540	560	580	600	620	640	660
% Transmission	0	12	42	60	54	30	5	0

RED

Wavelength	580	600	620	640	660	680	700
% Transmission	0	40	71	82	80	78	78

BLUE

Wavelength	400	420	440	460	480	500	520
% Transmission	0	12	31	45	52	20	0