

The Development of Contrast Constancy

BENJAMIN R. STEPHENS

Williams College

AND

MARTIN S. BANKS

University of California, Berkeley

The mature visual system possesses mechanisms that enable invariant perception of the contrast of an object and its features as the object undergoes changes in distance. This phenomenon, which has been called contrast constancy, obtains at suprathreshold contrasts only. Some models of contrast constancy assume the presence of narrowband spatial-frequency channels. An implication of M. S. Banks, B. R. Stephens, and E. E. Hartmann (1985, *Journal of Experimental Child Psychology*, 40, 501-527) is that contrast constancy should not be observed at 6 weeks but may be observed at 12 weeks. We examined this implication by investigating the development of contrast constancy in 6- and 12-week-old infants. Two sine wave gratings, differing in spatial frequency by .1 factors of 3, were presented side-by-side. The contrast of one grating was varied in order to estimate the contrast at which preference for the two gratings was equal. The equal preference points for 6-week-olds were predictable from their contrast thresholds. The 12-week-olds' equal preference points for low-contrast stimuli were predictable from their contrast thresholds, but those for intermediate and high-contrast stimuli were not. Thus, if one accepts the assumption that equal preference in infants is analogous to apparent contrast matches in adults, these data imply that contrast constancy is observed at 12 weeks but not 6 weeks. The perceptual consequences of this developmental transition are discussed. © 1985 Academic Press, Inc.

This research was supported by NIH Research Grant HD-12572 and by NIMH Research Scientist Development Award MH-00318 to M.S.B. It is based, in part, on a thesis presented to the University of Texas at Austin by Benjamin R. Stephens in partial fulfillment of the requirements for the doctoral degree. The authors thank Alice Andrews and Mark Viator for assisting in subject recruitment and data collection. Send reprint requests to Benjamin R. Stephens, Department of Psychology, Bronfman Science Center, Williams College, Williamstown, MA 01267.

One of the most sophisticated and important visual functions is the ability to recognize and identify objects on the basis of pattern information. Adults can do this reliably despite seriously complicating factors like changes in an object's position, orientation, and distance. Because these changes are irrelevant to an object's identity, the visual system must use recognition and identification algorithms that are not misled by position, orientation, and distance changes. One goal of this paper is to examine the development of such an algorithm. Specifically, we examine the development of mechanisms that allow the contrast of an object and its features to be perceived veridically despite changes in distance.

The second goal of this paper is to examine the validity of threshold based models of infant pattern vision under suprathreshold conditions. The current psychophysical literature on infant pattern vision is based almost entirely on measurements of detection thresholds, that is, on measurements of the minimum contrast or intensity required for reliable performance. These data have shown that pattern vision develops rapidly during the first 6 months of life (cf. Banks, 1983). For example, visual acuity and contrast sensitivity increase steadily during this period (Atkinson, Braddick, & Moar, 1977; Banks & Salapatek, 1978; Dobson & Teller, 1978; Harris, Atkinson, & Braddick 1976). Additionally, the companion paper to this one (Banks, Stephens, & Hartmann, 1985) demonstrated that adultlike, multiple spatial-frequency channels develop between 6 and 12 weeks. Thus, investigations of infants' visual behavior under threshold conditions have provided useful descriptions of what pattern information is detectable at different ages and important insights into the development of basic visual mechanisms. The visual environment, however, is populated by mostly high-contrast and, therefore, suprathreshold objects. For this reason, it is

important to understand the behavior of the visual system under suprathreshold conditions. Because there are no systematic data comparing the development of threshold and suprathreshold processes in infants, this paper considers whether observations and hypotheses derived from measurements of detection thresholds generalize to suprathreshold conditions. Specifically, young infants' processing of spatial frequency information is examined near threshold and above threshold.

The adult psychophysical literature indicates that there are important differences between visual processing near threshold and above threshold. The contrast sensitivity function (CSF) is a threshold function that has been an extremely useful index of the detectability of various sorts of pattern information (Banks & Salapatek, 1981; Comsweat, 1970). The CSF is defined as the reciprocal of the minimum contrast required to detect sine wave gratings of different spatial frequencies. Figure 1A shows a typical adult CSF. It shows that pattern information of intermediate grain (medium spatial frequencies) is detectable at much lower contrasts than fine (high-frequency) or coarse (low-frequency) information.

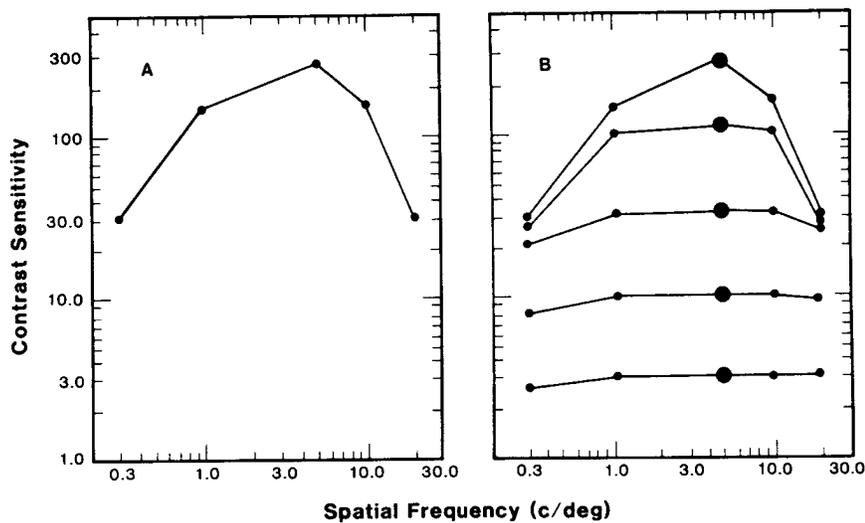


FIG. 1. Adult contrast sensitivity function and contrast-matching data from Georgeson and Sullivan (1975). (A) Contrast sensitivity function. Contrast sensitivity, the reciprocal of contrast at threshold, is plotted as a function of spatial frequency. (B) Contrast matching data. The procedure by which these data were obtained is described in the text. The reciprocal of the contrasts of the standard and comparison gratings is plotted as a function of spatial frequency. The large symbols represent the reciprocals of the contrasts of the 5 c/deg standard. The small symbols represent the reciprocals of the contrasts of the comparison gratings when they matched the standard in apparent contrast.

The height and shape of the CSF reflect the operation of several basic visual mechanisms. Consider, for example, the steady loss in contrast sensitivity that accompanies increases in spatial frequency. Measurements of the optical quality of the eye have revealed that less than 100% of the contrast of a stimulus is transmitted to the retina and that this percentage depends heavily on the spatial frequency of the stimulus. For example, the retinal image contrast of a 5 c/deg grating is about 70% of the stimulus contrast under normal viewing conditions whereas the retinal contrast of a 20 c/deg grating is only 15% of the stimulus contrast (Campbell & Green, 1965; Campbell & Gubisch, 1966). In other words, the contrast of very fine pattern information is reduced much more by the eye's optics than is the contrast of coarser pattern information. This optical effect accounts for most of the high-frequency loss in contrast sensitivity. Additional losses occur due to the spatial summing properties of early neural processing (Campbell & Green, 1965).

What are the effects of optical blur for the perception of suprathreshold stimuli? Several investigators have examined adults' processing of pattern information under suprathreshold conditions (e.g., Blakemore, Muncey, & Ridley, 1973; Georgeson & Sullivan, 1975; Kulikowski, 1976; Watanabe, Mori, Nagata, & Hiwatashi, 1968). Georgeson and Sullivan (1975) asked adults to adjust the contrast of a sine wave grating of one spatial frequency (the "comparison" grating) until

it appeared to match the contrast of a sine wave grating of a different frequency (the "standard" grating). In their main experiment, the standard was a grating of 5 c/deg, a value near the peak of the adult CSF. The results are illustrated in Fig. 113. When the contrast of the standard was near threshold, adults set the contrast of the comparison gratings to higher values. These values were predictable from the CSF. For example, a 20 c/deg comparison grating was set to a value eightfold higher than the contrast of the 5 c/deg standard, and this ratio was equal to the ratio of contrast thresholds for 5 and 20 c/deg. The most interesting result in this experiment occurred when the contrast of the standard was set to a value well above threshold. Adults in this situation adjusted the contrast of the comparison to the same physical value as the contrast of the standard. This is a surprising result because, as mentioned above, two gratings of equal contrast but different spatial frequencies will produce different retinal image contrasts. In other words, when the adults set 5 and 20 c/deg gratings to equal physical contrasts, they were accepting as equal in apparent contrast two gratings whose retinal image contrasts differed substantially. This implies that the visual system compensates at suprathreshold contrasts for the defocusing effects of the eye's optics.

Georgeson and Sullivan called this phenomenon "contrast constancy" and noted an important perceptual consequence. As an object moves away from an observer, its spatial-frequency content shifts to progressively higher values. For low-contrast objects, apparent contrast would change according to the CSF; so for medium-sized (midfrequency) objects, apparent contrast would decrease as viewing distance increased because contrast sensitivity decreases monotonically for higher frequencies. Georgeson and Sullivan's observations imply, however, that the apparent contrast of high-contrast objects would not change with viewing distance. Thus, contrast constancy confers a useful property on the perception of real objects: so long as the contrast that defines an object and its features is above threshold, apparent contrast remains invariant across a wide range of distances.

How is contrast constancy achieved? Georgeson and Sullivan pointed out that the central visual system must in some way undo the optical attenuation that occurs in the formation of the retinal image. They have proposed a simple model based on multiple spatial-frequency channels with narrow tuning. The model states that high-frequency channels have steeper contrast-response functions (that is, their activity increases more rapidly with an increase in stimulus contrast) than medium-frequency channels. Near threshold, apparent contrast matches between a medium-frequency and a high-frequency grating would reflect differences in contrast threshold. Above threshold, however, the activity of high-frequency channels would increase more rapidly so apparent contrast matches would become veridical. Experimental evidence suggests that the visual cortex is the site at which this differential response to contrast occurs (Georgeson & Sullivan, 1975; Hess, Bradley, & Piotrowski, 1983).

The companion paper by Banks et al. (1985) demonstrated that 12-week-olds, but not 6-week-olds, possess multiple spatial-frequency channels with narrow tuning. Thus, if Georgeson and Sullivan's model is correct, contrast constancy should not be observed at 6 weeks. One is tempted to predict that contrast constancy should be observed at 12 weeks, but this is not a logical implication. Georgeson and Sullivan's model claims that multiple channels are necessary, but not sufficient, for the realization of contrast constancy. Sufficiency requires the additional assumption that the various channels have different contrast-response functions.

The infant literature provides few clues about the development of contrast constancy. Two groups of investigators (Banks & Ginsburg, 1985; Banks & Salapatek, 1981; Gayl, Roberts, & Werner, 1983) have shown that infants' preferences among complex patterns can be predicted quite accurately by linear systems models. These models assume that infants will prefer patterns that contain the greatest contrast once filtered by the infant CSF. Thus, these models assume that the CSF describes the relative salience of different bands of pattern information whether the information is near or well above threshold. In other words, they assume that contrast constancy is not present early in life. If contrast constancy were present, it would imply that the infant CSF is not an accurate representation of pattern processing under suprathreshold conditions.

The experiment reported here concerns 6- and 12-week infants' responses to near-threshold and suprathreshold pattern information. We employed a standard pattern preference procedure to examine the effects of spatial frequency and contrast on infants' pattern preferences and, by inference, on their apparent contrast matches. The results suggest that contrast constancy is not present at 6 weeks and that it is present at 12 weeks. Thus, the emergence of contrast constancy corresponds roughly with the functional development of multiple spatial-frequency channels.

METHODS

Subjects

Infants were recruited by letter and phone. Those infants with known ocular or general pathology were excluded. Twenty 6-week-olds and twenty-three 12-week-olds were tested. Of those infants, eleven 6-week-olds (6 male, 5 female) and twelve 12-week-olds (5 male, 7 female) completed testing. The other infants were unable to complete testing due to fussiness, sleepiness, equipment malfunction, or experimenter error.

Apparatus and Stimuli

Sine wave gratings were generated on a Hewlett-Packard 1317A CRT (P31 phosphor) using the method of Campbell and Green (1965). At the 35-cm viewing distance, the display subtended 54 x 46'. Space-average luminance was 8 cd/m'. The surround was dark. Contrast was varied using a programmable dB-step attenuator. The contrast of each stimulus used was measured using a photometer calibrated with a standard source.

Two sine wave gratings differing by a factor of 3 in spatial frequency were presented to each infant. The spatial frequencies were chosen so that the lower frequency (F) was at the peak of the CSF for that age group (Atkinson et al., 1977; Banks & Salapatek, 1978). For 6-week-olds, the frequencies of F and $3F$ were 0.3 and 0.9 c/deg, respectively. For 12-week-olds, F and $3F$ were 0.5 and 1.5 c/deg. The display was split electronically at midline so that F and $3F$ could be presented side by side on the CRT. The two sides of the display were equal in space-average luminance, hue, and size. A PDP 11 /04 computer selected stimuli to be presented, controlled trial duration, and recorded observer responses.

Procedure

Infants were tested in one session lasting between 30 and 50 min. Parents positioned their infant in front of the display usually by holding him or her on the lap, although some infants were held over the shoulder or were placed in an infant seat. A curtain blocked the parent's view of the display. An observer, positioned behind the display, viewed the infant through a 5-cm slot and was unable to see the display.

Between trials, the display was uniformly illuminated. The observer attracted the infant's attention to the center of the display with a noisemaking toy. When the infant appeared to be fixating midline, the observer lifted the toy from view and initiated a trial. The F and $3F$ gratings appeared immediately on either side of the screen and remained visible for 20 s. The observer then judged the infant's eye position and pressed buttons corresponding to left stimulus, right stimulus, and off-screen fixations. A trial was rejected if the infant became excessively fussy or sleepy.

All infants were presented three contrasts of $3F$ (0.14, 0.34, and 0.79) paired in all possible combinations with six contrasts of F (0.09, 0.14, 0.21, 0.34, 0.55, and 0.79). We will refer to $3F$ as the standard and to F as the comparison. These 18 pairs of F and $3F$ were presented in a random sequence with left-right position chosen randomly. Then the procedure was repeated, with left-right position counterbalanced. Thus, completion of the experiment entailed 36 trials. Data from infants who did not complete all 36 trials in a session were discarded. An attempt was made to retest those infants on all 36 trials in another session.

The data for each stimulus pairing were represented as preferences for F over $3F$. This was defined as the sum, across two counterbalanced trials, of the total duration of fixation on F , divided by the duration on F and $3F$. Thus, preference scores could range between 0.0 and 1.0.

Two adults, one with 20/20 vision uncorrected and one with 20/20 vision corrected, were tested in the same apparatus using Georgeson and Sullivan's contrast-matching task. The comparison grating, F , was a 4 c/deg sine wave grating and the standard, $3F$, was a 12 c/deg grating. The contrast threshold for F was about three times lower than the contrast threshold for $3F$. The adults adjusted the contrast of F to match the apparent contrast of $3F$ for several different contrasts of $3F$.

RESULTS

The adults' average contrast matches were nearly identical. For simplicity, we display one adult's data in Fig. 2. The abscissa plots the various contrasts of $3F$ that were presented. The ordinate plots the contrasts to which the adult set F in order to match the apparent contrast of $3F$. The diagonal line shows where the data points would fall if matching were veridical. The data are below this line at low contrasts, which indicates that the subject required less contrast in F to match the apparent contrast of $3F$. At the lowest contrast, $3F$ was three times higher than F at the match point. This difference is the same as the three-fold difference in contrast thresholds. At higher contrasts, the data points fell on the diagonal line. Thus, the adult matched contrast veridically at suprathreshold levels. These data replicate previous observations (Georgeson & Sullivan, 1975; Hess & Bradley, 1980).

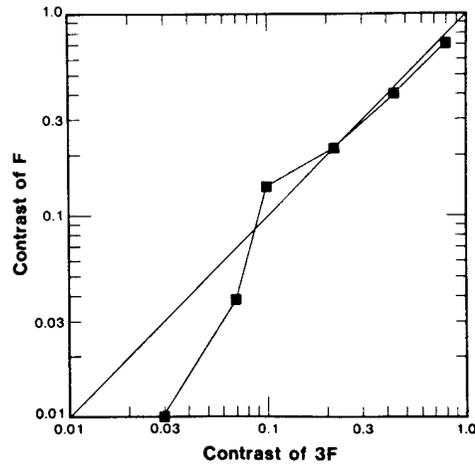


FIG. 2. Summary of the adult contrast matching data. The contrast of the 4 c/deg standard grating is plotted against the contrast of the 12 c/deg comparison grating at the apparent contrast match point. The diagonal line indicates where the data would lie if apparent contrast matches were veridical.

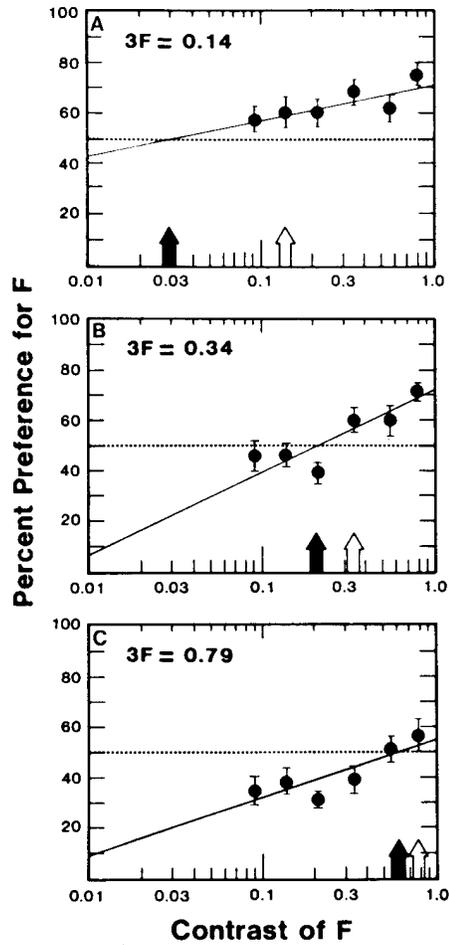


FIG. 3. Average preference data for the 12-week-olds. (A) Data obtained when the contrast of $3F$ was 0.14 (indicated by the open arrow). (B) Data obtained when the contrast of $3F$ was 0.34 (again indicated by the open arrow). (C) Data obtained when the contrast of $3F$ was 0.79 (open arrow). The ordinate of each panel represents the percent preference for F. The abscissa of each panel represents the contrast of F. The dashed lines indicate the preference value that corresponds to equal preference for F_2 and $3F$. The solid arrows indicate the estimates of the contrast of F that was associated with 50% preference for F. These then are the equal preference points.

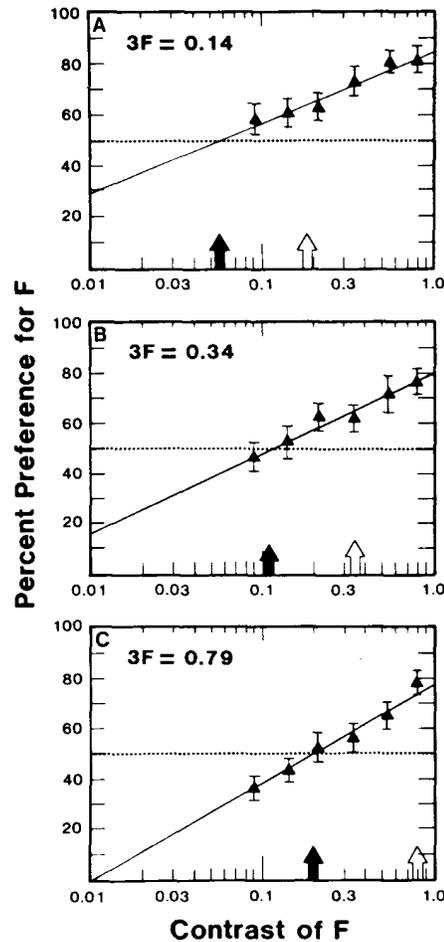


FIG. 4. Average preference data for the 6-week-olds. All conventions and symbols are the same as in Fig. 3.

The 12- and 6-week-old infants' data are represented in Fig. 3 and 4, respectively. Each panel displays the mean preference scores for different contrasts of F . The upper, middle, and bottom panels display data for different contrasts of $3F$; those contrasts are indicated by the unfilled arrows. These data indicate that as the contrast of F increased, the preference for F increased monotonically. Conversely, as the contrast of $3F$ increased, the preference for F generally decreased. The data were analyzed in a 3 (Contrast of $3F$) \times 6 (Contrast of F) \times 2 (Age) analysis of variance in which Contrast of $3F$ and Contrast of F were within-subjects factors and Age was a between-subjects factor. The analysis revealed significant main effects for both. Contrast factors (for $3F$, $F(2, 42) = 36.13$, $p < .0001$; for F , $F(5, 105) = 20.68$, $p < .0001$; and for the Age factor ($F(1, 21) = 8.06$, $p < .01$). The Age factor was significant because 6-week-olds tended to show a higher preference for F than 12week-olds did. No significant interactions were obtained.

These results clearly show that preference varied predictably with the contrast of the targets. Our primary interest, however, was to estimate the contrast of F that matched the apparent contrast of $3F$. For want of an alternative, we assumed that the equal preference point corresponded to the apparent contrast match. The validity of this assumption is discussed below. For each contrast of $3F$, we estimated the contrast of F associated with 50% preference by fitting least-squares regression lines to the preference functions in Fig. 3 and 4. These regression lines are represented by the solid lines. The value of F where the regression line crossed 50% was taken as the estimate of the equal preference point. We will refer to this contrast as P . The values of P are indicated by the filled arrows in each panel.

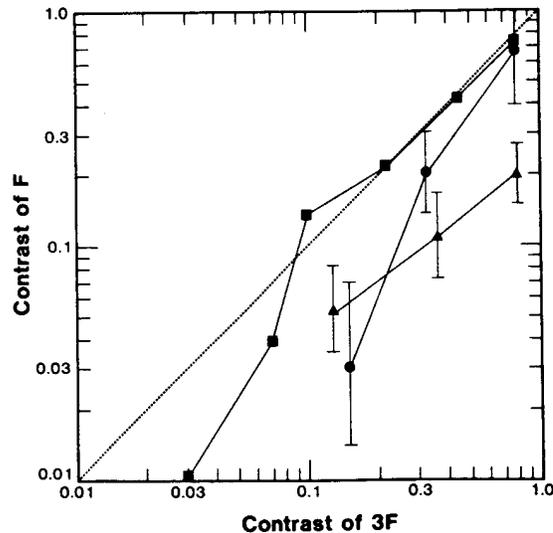


FIG. 5. Summary of the equal preference data for infants and contrast matches for adults. As in Fig. 2, the contrast of the comparison grating F is plotted on the ordinate and the contrast of the standard grating ($3F$) is plotted on the abscissa. The diagonal line indicates where the data would fall if matches occurred at equal physical contrasts. The circles represent the 12-week-olds' equal preference data, and the triangles the 6-week-olds' equal preference data. The error bars are explained in the text.

We used the format of Fig. 2 to replot the estimates of P in Fig. 5. This figure displays P , the estimated contrast of F associated with 50% preference, for the different contrasts of $3F$. The error bars represent ± 1 standard error of the mean (see below). The adult data (squares) are replotted in Fig. 5 for comparison. The diagonal dashed line represents the functions that would be obtained if equal preference occurred when the physical contrasts of F and $3F$ were equal. Consider the 12-week estimates first (circles). When the contrast of $3F$ was 0.14, the estimate of P was 0.031. Thus, at the equal preference point, the contrasts of F and $3F$ differed by a factor of 4.5, a value quite close to the ratio of contrast thresholds obtained for these stimuli in our earlier experiment (Banks et al., 1985). When the contrast of $3F$ was 0.34, P was 0.21; these values differed by only a factor 1.7. Finally, when the contrast of $3F$ was 0.79, P was 0.66; these values differed by a factor of 1.2 only. These data show quite clearly that the contrasts of F and $3F$ at the equal preference point became more similar as contrast was increased. If our assumption is correct that equal preference corresponds to equal apparent contrast, the 12-week data are very similar to adult contrast-matching data. (The difference in the horizontal location of the infant data relative to the adult's is due to the difference in adult and infant contrast thresholds.)

The 6-week data (triangles) were quite different. When $3F$ was 0.14,

was 0.053. These values differed by a factor of 3.2, a value quite close to the ratio of contrast thresholds obtained for these stimuli in our earlier experiment (Banks et al., 1985). When $3F$ was 0.34, P was 0.11 (a factor of 3.0), and when $3F$ was 0.79, P was 0.20 (a factor of 3.9). Thus, the ratios of contrasts of F and $3F$ at the equal preference point were similar for contrasts spanning the range of useful vision at this age. These data then were quite different from those of the older infants.

To assess the robustness of these effects, we used another procedure to estimate the contrast of P . We scored each trial dichotomously as a preference for F or for $3F$ depending on which grating was fixated longer. We then collapsed these dichotomous data across subjects and calculated the percentage of trials in which F was preferred for each combination of F and $3F$ contrasts. This procedure yields values that could range between 0 and 100%. The values reflect the probability that infants fixated one pattern over the other and are not affected by the magnitude of a preference. Since these are dichotomous data, probit analysis (Finney, 1971) could be employed to estimate the contrast of F associated with 50% probability of preference for F . The results of this procedure are presented in Table I along with the linear regression estimates. Note that the probit analysis estimates were very similar to the linear regression estimates. This shows that our estimates of the equal preference point were not an artifact of a particular estimation procedure.

To assess the statistical reliability of the linear regression and probit estimates, two procedures were employed. The first procedure involved the linear regression estimates. We estimated the standard deviation of P for each contrast of $3F$ by computing the standard deviation of the preference scores used to estimate P . The standard deviation of the preference scores was then used to calculate the contrast associated with the standard deviation of P . We calculated the standard error of the P estimates using these estimates of variability. These standard errors are represented in Fig. 5 by the error bars. We then examined whether the contrasts of k were statistically similar or dissimilar to the contrast of $3F$ for the various conditions of this experiment. T tests based on the above-mentioned estimates of variability were conducted. For 6-weekolds, these tests revealed that the contrast of P was significantly lower than the contrast of $3F$ for all contrasts of $3F$ (at $3F = 0.14$, $t(10) = 2.23$, $p < .025$, one tailed; at $3F = 0.34$, $t(10) = 2.54$, $p < .025$, one tailed; at $3F = 0.79$, $t(10) = 4.19$, $p < .001$, one tailed). For 12-weekolds, the contrast of k was significantly lower than the contrast of $3F$ at low contrast (at $3F = 0.14$, $t(11) = 1.82$, $p < .05$, one tailed) but was not significantly lower than the contrast of $3F$ at medium and high contrasts (at $3F = 0.34$, $t(11) = 1.25$, at $3F = 0.79$, $t(11) = 0.33$, p 's $> .05$, one tailed).

We also conducted t tests based on the linear regression data to determine whether the equal preference points for the two age groups differed significantly. The 12-week estimates of k were similar to the 6-week estimates at low (0.14) and medium (0.34) contrasts of $3F$ ($t(21) = 0.58$ and 1.08 , p 's $> .05$, one tailed). However, the 12-week estimates of P were significantly greater than the 6-week estimates at high contrast (0.79) ($Q(20) = 1.98$, $P < .05$, one tailed).

TABLE 1
COMPARISON OF \hat{F} AND 95% FIDUCIAL LIMITS FOR LINEAR REGRESSION AND PROBIT ANALYSES

	$3F$	\hat{F}	Linear regression		\hat{F}	Probit analysis	
			Upper limit	Lower limit		Upper limit	Lower limit
6 weeks	0.14	0.05	0.11	0.02	0.06	0.11	0.00
	0.34	0.11	0.25	0.05	0.12	0.18	0.03
	0.79	0.20	0.35	0.11	0.28	0.38	0.21
12 weeks	0.14	0.03	0.14	0.01	0.02	0.10	0.00
	0.34	0.20	0.42	0.10	0.18	0.77	0.00
	0.79	0.66	1.13	0.38	0.73	10.70	0.40

The second procedure employed different estimates of variability. Specifically, this procedure used the fiducial limits obtained from the probit analysis routine as the estimates of the variability of P . These limits are presented in Table 1. Note that the fiducial limits are entirely consistent with the statistical conclusions obtained from the tests. Therefore, these two procedures lead to the same conclusions. Six-week-olds required more contrast in $3F$ than in F to reach the equal preference point for all of the experimental conditions. On the other hand, 12-week-olds required more contrast in $3F$ than in F at low contrasts only.

DISCUSSION

Some aspects of our results were similar for 6 and 12-week-olds. In particular, pattern preferences changed at both ages in an orderly fashion with changes in stimulus contrast. When the contrast of $3F$ was held constant, increases in the contrast of F led to systematic increases in the preference for F . The most important aspect of the results, however, revealed dissimilarity between 6 and 12-week preferences. For 12week-olds, the estimate of P (the contrast of F associated with 50% preference) was much lower than $3F$ at near-threshold contrasts but became similar to $3F$ at suprathreshold contrasts. Thus, 12-week-olds' equal preference points behaved much like adults' apparent contrast matches. Near threshold, the contrast of $3F$ had to be significantly higher than that of F to achieve equal preference just as adults require more contrast in a high-frequency than in an intermediate-frequency grating to achieve equal apparent contrast. Above threshold, on the other hand, 12-week-olds' equal preference occurred when the contrasts of F and $3F$ were similar physically just as adults' apparent contrast matches behave. The

6-week-olds exhibited a different pattern of results. The estimates of JP were much lower than the contrast of $3F$ at both threshold and suprathreshold contrasts. Thus, 6-week-olds' equal preference points did not behave like adults' apparent contrast matches.

Our data can be interpreted as demonstrating that contrast constancy emerges between 6 and 12 weeks of age. Some alternative explanations should, however, be considered before accepting this interpretation. One might argue that the two age groups differed only because they were presented different spatial frequencies. Perhaps the younger infants would have exhibited the 12-week pattern if they had been presented 0.5 and 1.5 c/deg gratings. This explanation is impractical. A grating of 1.5 c/deg is close to or above the highest detectable spatial frequency at 6 weeks (Dobson & Teller, 1978). Consequently, some if not all of our younger infants probably could not have detected the 1.5 c/deg gratings presented to the older infants. Our experiment was designed to test a major portion of the range of useful vision at this age, so the grating frequencies were placed at the peak of the age group's CSF and a factor of three higher. Our conclusions then concern stimuli that were similar in detectability at the two ages, although they were different spatial frequencies.

Another explanation should be considered before accepting the conclusion that contrast constancy emerges between 6 and 12 weeks of age. To draw this conclusion, one must assume that equal preference for F and $3F$ corresponds to an apparent contrast match. Unfortunately, there is no direct way to test the validity of this assumption. One can address this issue indirectly, however, by comparing the implications of various assumptions about the relationship between preference and apparent contrast.

Let us first consider the implications of assuming that equal preference among sine wave gratings corresponds to equal apparent contrast. If we accept this assumption, the following picture of development emerges. At 12 weeks, the visual system compensates above threshold for differences in detectability that result from optical defocus and from spatial summation by early stages in the visual pathway. Thus, contrast constancy is present much like it is in adults. At 6 weeks, however, no such compensation occurs, at least for the spatial frequencies we tested. Contrast constancy then does not seem to be present at that age. Current models of contrast constancy are based on the operation of multiple spatial-frequency channels. The companion paper (Banks et al., 1985) showed that multiple channels develop between 6 and 12 weeks after birth. Those data then are consistent with current models of contrast constancy because the age at which multiple channels emerge is similar to the age at which contrast constancy is observed. In summary, acceptance of the assumption that equal preference corresponds to an apparent contrast match leads to a simple developmental picture that is quite consistent with prevailing models of contrast processing.

The alternative assumption is that infants' preferences among sine wave gratings are determined by a combination of perceived contrast and some other property or by those other properties alone. For example, Karmel and Maisel (1975) have proposed that infant preferences are determined by contour density. (They did not state whether contrast is an important determinant as well because the patterns they used were all of equal contrast.) Within the framework of the contour density model, our 6-week data would be easy to explain: F was always preferred to $3F$, when they were equal in physical contrast, because F had a more optimal contour density at that age. Our 12-week data would not be so easy to explain. The preference for F over $3F$ varied significantly with contrast. The contour density metric could not predict this because the contour densities of F and $3F$ do not vary with contrast. Consequently, an additional assumption would be required that the most preferred contour density varies with stimulus contrast. It is not clear why the optimal contour density should change with contrast for older infants but not younger infants.

Other properties that might influence preferences among sine wave gratings are the size and number of stripes (Fantz & Faga, 1975) and the sharpness of contours ($3F$ has sharper contours than F). Accounts based on these properties would also require the assumption that the preference rule changes with contrast for 12-week-olds but not 6-week-olds. We cannot rule out these alternative accounts, but the assumption that equal preference corresponds to equal apparent contrast leads to an account that is both simpler and meshes better with visual theory.

In the next section we discuss in more detail Georgeson and Sullivan's multiple-channel model of contrast constancy in adults and consider some interesting developmental implications. As described in the introduction, the model holds that the compensation implied by contrast constancy is accomplished by setting the gains of different spatial-frequency channels to different

values (Georgeson & Sullivan, 1975; Hess, 1983). Channels tuned to high frequencies are assumed to have higher gains (that is, their response grows more rapidly with increases in contrast) than channels tuned to intermediate frequencies.

This model is very similar to the Fourier techniques used in computer enhanced imaging. For example, computer processing of photographs taken from satellites uses knowledge of the defocusing effects of the camera's optics and of the earth's atmosphere to "deblur" photographs. The deblurring is accomplished in the following way. First, the defocusing effects of the camera's optics and the earth's atmosphere are represented as a blur function. This function simply describes how much the contrasts of various spatial frequencies are attenuated by the defocusing agents. Then the Fourier transform of the original photograph is computed and the amplitudes of the resulting spatial frequency components are multiplied by the inverse of the blur function. The result is a much improved image that represents the objective structure of objects on the earth more veridically than the original did. Some practical illustrations of this technique are given by Gennery (1973) and Stroke (1971).

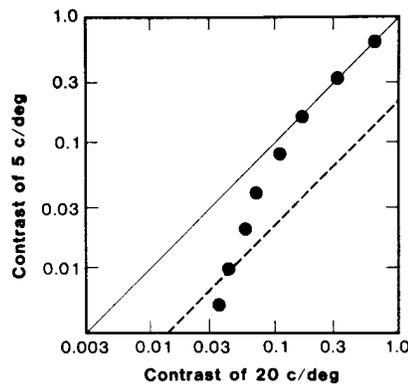


FIG. 6. Contrast matching plot showing contrast matching data and retinal image contrasts. The data points represent adult contrast matching data from Georgeson and Sullivan (1975). The contrast of a 5 c/deg standard grating is plotted on the ordinate and the contrast of a 20 c/deg comparison grating on the abscissa. The solid diagonal line indicates where the data would lie if contrast matches occurred at equal physical contrasts. The broken diagonal line indicates stimulus pairs for which the retinal image contrasts are the same. The data would lie on this line if contrast matches occurred at equal retinal contrasts.

The similarity of the Fourier technique's used in computer-enhanced imaging and the multiple-channel model of adult contrast constancy draws attention to an interesting point. In order to compensate accurately for the defocusing effects of the eye's optics and of peripheral neural summation, the visual system must "know" its own blur function. This point is illustrated in Fig. 6 which displays apparent contrast matches for 5 and 20 c/deg gratings.¹ For simplicity, we treat the blur function of the visual system as though optics were the only source of defocus. Under ordinary viewing conditions, the retinal image contrast of a 5 c/deg grating is 70% of the stimulus contrast while the retinal contrast of a 20 c/deg grating is only 15% of the stimulus contrast (Campbell & Gubisch, 1966). In other words, for equal stimulus contrasts, the retinal contrasts of the two gratings differ by a factor of 4.7. This statement is true for all stimulus contrasts because optics are a linear process. The dashed line represents stimulus pairs for which the retinal image contrasts are the same. As in Fig. 2 and 5, the solid line represents stimulus pairs with equal physical contrasts. Notice that the dashed line is always lower than the solid line by 0.7 log units. The data points represent apparent contrast matches for 5 and 20 c/deg gratings. At low contrasts, the data points fall near the equal retinal contrast line (any discrepancy is probably due to the additional effects of peripheral neural summation) but, as contrast is raised, they approach and finally coincide with the equal stimulus contrast line. This means that at high contrasts adults accepted as equal in apparent contrast two gratings that had quite different retinal contrasts. The most intriguing aspect of these data, however, is the fact that the apparent contrast matches at

¹ Although the example involves only 5 and 20 c/deg gratings, the argument that follows applies to any spatial frequencies with the possible exception of very low ones.

high contrasts coincide almost exactly with the equal stimulus contrast line. Thus, the mechanisms responsible for amplifying the contrast response at 20 c/deg relative to the response at 5 c/deg are adjusted to the exact gains that compensate for the blur function and thereby yield veridical contrast matches. Veridical contrast matching, therefore, implies that the visual system in some sense "knows" its own blur function. It is interesting to consider how such knowledge might be acquired. Three possibilities come to mind.

1. Knowledge of the blur function may be prespecified in some fashion so that once the expected function develops, veridical contrast matching can occur. This explanation is quite unlikely if our finding is correct that 12-week-olds exhibit contrast constancy. This would mean that the 12week-old visual system must also "know", its blur function in order to compensate for it. But the blur function surely differs significantly between 12 weeks of age and adulthood. The eye undergoes considerable growth and becomes less hyperopic (farsighted) with age (Banks, 1980) causing changes in optical quality. The pigmentation of the lens and the macula deepens causing a reduction in the effects of chromatic aberration, one source of optical defocus (Cooper & Robson, 1969; Mann, 1964; Werner, 1982). The morphology and distribution of retinal neurons changes (Abramov et al., 1982). All of these factors and more imply that the blur function changes with age, and it is unlikely that prespecification of the blur function would include information about how the function changes from early infancy to adulthood. Additional evidence against a prespecification model comes from experiments with amblyopes, adults who have had aberrant blur functions (Hess & Bradley, 1980; Hess, Bradley, & Piotrowski, 1983). Despite optical correction, these individuals exhibit degraded vision in one eye. Under suprathreshold conditions, amblyopes exhibit accurate compensation for threshold deficits in contrast sensitivity. According to a prespecification model, the extent of amblyopia would have to be prespecified for compensation to be accurate. This sort of pre specification seems quite unlikely.

2. The visual system may "know" the spatial frequency distribution of information in the environment and deduce its blur function from differences between that distribution and the visual pathway's representation of it.² This explanation also seems unworkable. Switkes, Mayer, and Sloan (1978) have sampled the spatial-frequency distribution of pattern information in the normal visual environment and found that it is quite variable from scene to scene. Thus, the visual system could only "know" the objective distribution of the environment in the average sense. Comparison of the objective and subjective distributions would, therefore, require considerable averaging of the moment to moment subjective distributions that a person encounters. It is not clear how accurate averaging without loss of information could occur.

3. Perhaps the visual system "learns" its blur function by noting the change in contrast responses at different spatial frequencies that accompanies a change in an object's distance. As an object recedes from the viewer, its spatial-frequency components shift to higher and higher values. Of course, the objective pattern information in an object remains the same across distances, so any changes in the nervous system's contrast responses would have to be caused by the blur function. The system could in principle deduce its own blur function by tracking these response changes for a given object. The memory requirements would not be nearly as demanding as those required by the second model.

No matter how the visual system acquires the information about its blur function needed to "deblur" pattern information, the perceptual consequence should be advantageous to infants. When contrast constancy is observed, the contrast that defines an object and its features would be perceived as roughly invariant despite changes in the object's distance. This property of distance invariance should facilitate the learning of cues that allow the infant to recognize and eventually identify objects. What those cues might be (e.g., distinctive features, Gibson, 1969; Fourier components, Pollen, Lee, & Taylor, 1971) depends on one's theoretical orientation. Nonetheless, the acquisition of any cue would be made easier if distance invariance held under normal viewing conditions.

² Georgeson and Sullivan (1975) proposed that the spatial frequency distribution might be assumed to be flat on the average, but samples of environmental information clearly show that this proposal is false. The spatial-frequency distribution of the visual environment is not flat on average. Rather low spatial frequencies predominate (Switkes, Mayer, & Sloan, 1978).

Our data have fairly clear implications for models of infant pattern preferences. Recall that the linear systems models (Banks & Ginsburg, 1985; Banks & Salapatek, 1981; Gayl et al., 1983) assume that infants prefer patterns that contain the greatest contrast once filtered by the peripheral stages of visual processing. The models assume further that the CSF is the appropriate filter to use in determining filtered contrast. An implication of these assumptions is that the CSF, a threshold function, determines the relative salience of different spatial frequencies whether they are near or well above threshold. Our data suggest that this implication is correct for 6-week-olds: the ratio of F and $3F$ contrasts at the equal preference point was always predictable from the ratios of contrast thresholds. Thus, the CSF appears to be the appropriate filter to use in determining relative salience at this age for both near-threshold and suprathreshold contrasts. The implication of the models' assumptions appears to be incorrect for 12-week-olds. At low contrasts, the ratio of F and $3F$ contrasts at equal preference was predictable from threshold data. At high contrasts, this ratio was not predictable from threshold data. This suggests that different filters should be used at different contrast levels to model 12-week-olds' pattern preferences; the CSF is appropriate at low contrasts, but functions flatter than the CSF should be used at high contrasts.

Finally, we would like to emphasize an implication common to both this and the companion paper. We have observed a reasonably distinct change in the manner by which pattern information is processed between 6 and 12 weeks of age. At 6 weeks, the visual system does not seem to possess multiple narrowband mechanisms. Six weeks later narrowband mechanisms are present and they allow the segregation of pattern information into coarse, intermediate, and fine grain information. It also appears that contrast constancy does not operate at 6 weeks and that it does at 12 weeks. Both of these age changes imply that the manner in which pattern information is represented by the visual system changes fundamentally between 6 and 12 weeks of age.

REFERENCES

- Abramov, I., Gordon, J., Hendrickson, A., Hainfine, L., Dobson, V. & LaBossiere, E. (1982). The retina of the newborn human infant. *Science (Washington, D.C.)*, *217*, 265-267.
- Atkinson, J., Braddick O., & Moar, K. (1977). Development of contrast sensitivity over the first three months of life in the human infant. *Vision Research*, *17*, 1037-1044.
- Banks, M. S. (1980). Infant refraction and accommodation. *International Ophthalmology Clinics*, *20*, 205-232.
- Banks, M. S., & Ginsburg, A. P. (1985). Infant pattern preferences: A review and new theoretical treatment. In H. W. Reese (Ed), *Advances in child development and behavior*. New York: Academic Press.
- Banks, M. S., & Salapatek, P. (1978). Acuity and contrast sensitivity in 1-, 2-, and 37 month-old human infants. *Investigative Ophthalmology and Visual Science*, *17*, 361365.
- Banks, M. S., & Salapatek, P. (1981). Infant pattern vision: A new approach based on the contrast sensitivity function. *Journal of Experimental Child Psychology*, *31*, 145.
- Banks, M. S., with Salapatek, P. (1983). Infant visual perception. In M. M. Haith & J. J. Campos (Eds.), *Infancy and developmental psychobiology*. In P. Mussen (Ed.), *Handbook of child psychology (Vol. 2)*. New York: Wiley.
- Banks, M. S., Stephens, B. R., & Hartmann, E. E. (1985). The development of basic mechanisms of pattern vision: Spatial frequency channels. *Journal of Experimental Child Psychology*, *40*, 501-527.
- Blakemore, C., Munccey, J. P. J., & Ridley, R. M. (1973). Stimulus specificity in the human visual system. *Vision Research*, *13*, 1915-1931.
- Campbell, F. W., & Green, D. G. (1965). Optical and retinal factors affecting visual resolution. *Journal of Physiology*, *181*, 576-593.
- Campbell, F. W., & Gubisch, R. W. (1966). Optical quality of the human eye. *Journal of Physiology*, *186*, 558-578.
- Cooper, G. F., & Robson, J. G. (1969). The yellow color of the lens of man and other primates. *Journal of Physiology*, *203*, 411-417.
- Comsweet, T. N. (1970). *Visual perception*. New York: Academic Press.
- Dobson, V., & Teller, D. V. (1978). Visual acuity in human infants: A review and comparison of behavioral and electrophysiological studies. *Vision Research*, *18*, 1233-1238.
- Fantz, R. L., & Fagan, J. F. (1975). Visual attention to size and number of pattern details by term and pre-term infants during the first six months. *Child Development*, *16*, 318.
- Finney, D. J. (1971). *Probit analysis*. Cambridge: The Univ. Press.
- Gayl, J. E., Roberts, J. D., & Wemer, J. S. (1983). Linear systems analysis of infant visual pattern preferences. *Journal of Experimental Child Psychology*, *35*, 30-45.
- Georgeson, M. A., & Sullivan G. D. (1975). Contrast constancy: Deblurring in human vision by spatial frequency channels. *Journal of Physiology*, *252*, 627-656.
- Gennery, D. B. (1973). Determination of optical transfer function by inspection of frequency domain plot. *Journal of the Optical Society of America*, *63*, 1571-1577.

- Gibson, E. J. (1969). *Principles of perceptual learning and development*. New York: Appleton-Century-Crofts.
- Harris, L., Atkinson, J., & Braddick, O. (1976). Visual contrast sensitivity of a 6-month-old infant measured by the evoked potential. *Nature (London)*, 274, 570-571.
- Hess, R. F. (1983). Contrast coding in amblyopia. 11. On the physiological basis of contrast recruitment. *Proceedings of the Royal Society of London*, 217, 331-340.
- Hess, R. F., & Bradley, A. (1980). Contrast perception above threshold is only minimally impaired in human amblyopia. *Nature (London)*, 287, 463-464.
- Hess, R. F., Bradley, A., & Pirowski, L. (1983). Contrast-coding in amblyopia. 1. Differences in the neural basis of human amblyopia. *Proceedings of the Royal Society of London*, 217, 309-330.
- Karmel, B. Z., & Maisel, E. B. (1975). A neuronal activity model for infant visual attention. In L. B. Cohen & P. Salapatek (Eds.), *Infant perception: From sensation to cognition: Vol. 1. Basic visual processes*. New York: Academic Press.
- Kulikowski, J. J. (1976). Effective contrast constancy and linearity of contrast sensation. *Vision Research*, 16, 1419-1431.
- Mann, I. C. (1964). *The development of the human eye*. London: British Medical Association.
- Nathan, R. (1968). Picture enhancement for the moon, mars, and man. In G. C. Cheng, R. S. Ledley, D. K. Pollock, & A. Rosenfeld (Eds.), *Pictorial pattern recognition*. Washington, DC: Thompson.
- Pollen, D., Lee, J. R., & Taylor, J. H. (1971). How does the striate cortex begin the reconstruction of the visual world? *Science (Washington, D.C.)*, 173, 74-77.
- Stockham, T. G. (1972). Image processing in the context of a visual model. *Proceedings of the IEEE*, 60, 828-842.
- Stroke, G. W. (1971). Sharpening images by holography. *New Scientist*, 51, 671-675.
- Switkes, E., Mayer, M. L., & Sloan, J. A. (1978). Spatial frequency analysis of the visual environment: Anisotropy and the carpentered environment hypothesis. *Vision Research*, 10, 1393-1399.
- Watanabe, A., Mori, T., Nagata, S., & Hiwatashi, K. (1968). Spatial sinewave responses of the human visual system. *Vision Research*, 8, 1245-1263.
- Werner, J. S. (1982). Development of scotopic sensitivity and the absorption spectrum of the human ocular media. *Journal of the Optical Society of America*, 72, 247-258.

RECEIVED: June 7, 1984; REVISED: February 20, 1985.