

Contrast Discrimination in Human Infants

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The ability to detect differences in spatial contrast is crucial to object recognition and identification. This ability is generally examined by measuring the contrast discrimination function. This function represents, for a variety of conditions, the smallest contrast difference required to discriminate otherwise identical patterns. We examined human infants' ability to discriminate patterns on the basis of differences in spatial contrast. The forced-choice preferential looking procedure was used to estimate contrast increment thresholds at a number of background contrasts. The Weber fractions of 6- and 12-week-old infants were about 1 log unit higher than adult values for background contrasts ranging from 0.14 to 0.55. Furthermore, the slopes of infants' discrimination functions were much shallower than those of adults. These age differences in contrast discrimination imply certain changes in the neural mechanisms that underlie contrast encoding. They also aid our understanding of the anomalies observed in early pattern vision.

The perception of spatial contrast is fundamental to vision. Spatial contrast is, in a sense, the stimulus for vision because object boundaries and surface characteristics are defined by differences in brightness (luminance contrast) and by differences in hue (chromatic contrast). The ability to discriminate one contrast from another is an important facet of visual processing. This claim is supported by the central role of contrast discrimination in theories of visual acuity (Carlson, 1983; Klein & Levi, 1985; Wilson, 1986b), pattern discrimination (Bennet & Banks, in press; Braddick, 1981; Burton, 1981), and visual accommodation (Green, Powers, & Banks, 1980).

Contrast discrimination is typically indexed by measurements of the contrast increment threshold. The subject is presented two patterns that differ only in contrast. The luminance profiles of two such patterns are displayed in Figure 1. The pattern on the left contains a fixed level of background contrast (C), and the one on the right contains the background plus a contrast increment ($C + \Delta C$). The subject is asked to indicate which pattern contains the greater contrast. The contrast increment threshold is generally taken as the value of ΔC that corresponds to 75% correct performance. The threshold is often expressed as the contrast increment divided by the background contrast ($\Delta C/C$), which is called the *Weber fraction*.

A complete description of contrast discrimination requires measurements of contrast increment thresholds for a number of spatial frequencies and background contrasts. As shown in Figure 1, adults' discrimination functions are dipper-shaped. From intermediate to high background contrasts, the increment threshold increases monotonically with increasing background contrast. At low background contrasts, however, threshold actually decreases with increasing background contrast; this has been called

the pedestal or facilitation *effect* (Foley & Legge, 1981; Legge, 1979; Nachmias & Sansbury, 1974).

The shape of the discrimination function over its rising portion conforms to a power law; that is, the data are fit well by the equation

$$\Delta C = k * C^n,$$

where ΔC is the contrast increment threshold, C is the background contrast, k is a sensitivity parameter, and n is the slope of the function when plotted in log-log coordinates. The value of the slope of the adult's function has been debated, but most researchers report values between 0.5 and 1.0 for a variety of spatial frequencies and testing conditions (Kohayakawa, 1972; Kulikowski & Gorea, 1978; Legge, 1979, 1981; Legge, & Foley, 1980). A slope different from 1.0 implies that the Weber fraction is not constant. For slopes less than 1.0, the fraction decreases with increasing background contrast.

As with many psychophysical functions, the contrast discrimination function provides insight into underlying physiological mechanisms. In particular, the function reflects the properties of mechanisms involved in contrast coding under threshold and suprathreshold conditions. Most models that link contrast discrimination data to underlying mechanisms posit three processes (e.g., Legge & Foley 1980; Nachmias & Sansbury, 1974): (a) A transducer represents the response of physiological mechanisms as a function of stimulus contrast. The transducer is assumed to be nonlinear (in fact S-shaped); contrast increments at low and high background contrasts produce relatively small response increments, whereas similar contrast increments at intermediate background contrasts produce relatively large response increments. (b) One or more sources of physiological noise are posited. The noise is generally constant and added at a stage

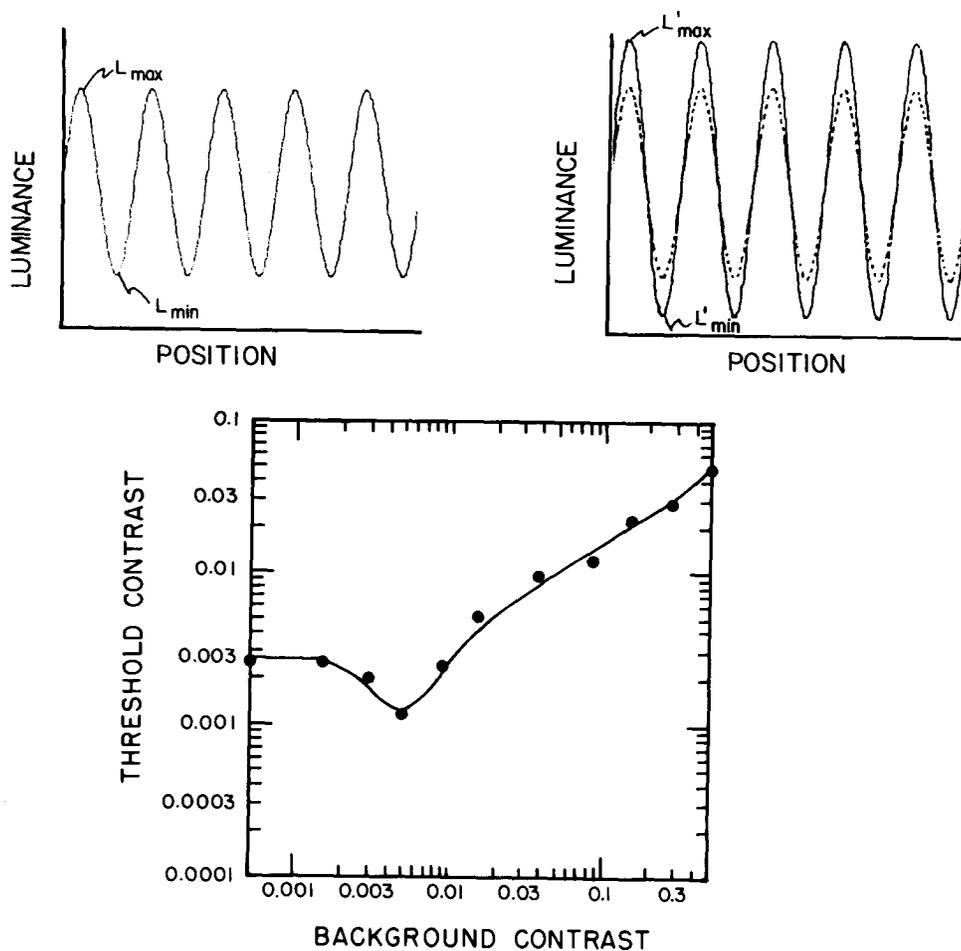


Figure 1. Stimuli and typical adults' data for contrast discrimination task. Top left: The luminance profile of a sinewave grating with the contrast set to the background level. (The maximum and minimum luminances are indicated by the arrows. Contrast is defined by the following equation: $[L_{max} - L_{min}]/[L_{max} + L_{min}]$) Top right: The luminance profile of a sinewave grating with a contrast increment added to the background contrast. (The background contrast is indicated by the broken line and the background plus increment by the solid line. In the text, C refers to the contrast of the background alone and ΔC to the difference in contrast between the incremented grating and the background grating.) Bottom: A typical adult contrast discrimination function. Contrast increment threshold $[\Delta C]$ is plotted as a function of background contrast $[C]$ on log-log coordinates.)

beyond the nonlinear transducer. (c) A simple decision rule is assumed: For each trial, the subject compares the responses with the two stimuli and selects the stimulus associated with the larger response as containing the increment. The decision is correct if the response to $C + \Delta C$ exceeds the response to C .

Under the assumptions of these models, the shape, or slope, of the contrast discrimination function depends directly on the shape of the transducer functions. The dipper of the adult discrimination function implies that the transducer function is S-shaped: accelerative at low contrasts (Foley & Legge, 1981; Nachmias & Sansbury, 1974) and decelerative at high contrasts (Legge, 1979; Legge & Foley, 1980).¹ Within the context of these models, discrimination data from infants may reveal important properties of developing physiological mechanisms.

Despite its importance, there have been no direct measurements of contrast discrimination in infants.

¹Pelli (1985) has given a different explanation of the dipper in adults, contrast discrimination functions. He argues that positional uncertainty rather than an accelerating transducer function is the basis of the dipper.

Contrast discrimination has, however, been discussed in the infant literature. Banks (1980) has shown that accommodation to high-contrast targets can be accurately predicted in 1- to 3-month-old infants if one assumes that infants' Weber fractions are not much higher than adults'. Wilson (1986) has argued that changes in contrast discriminability might underlie infants' dramatic improvements in vernier acuity from 1 to 6 months of age (Manny & Klein, 1985; Shimojo, Birch, Gwiazda & Held, 1984). In both cases, these theoretical claims could not be directly evaluated because no measurements of infant contrast discrimination existed.

Method

Subjects

Full-term infants were recruited by letter and telephone. Twenty 6-week-olds and twenty-four 12-week-olds were tested. Of these, five 6-week-olds and seven 12-week infants completed all of the experimental conditions. Another four 6-week-olds and four 12-week-olds provided partial data sets (two or more thresholds). The other infants did not

produce more than one threshold because of fussiness, sleepiness, failure to return for a subsequent session, equipment malfunction, or experimenter error. This high attrition rate is not unusual, given the lengthy (30-50 min) and numerous (3-6) testing sessions needed to collect all the data.

Apparatus and Stimuli

The stimuli were sinewave gratings (see Figure 1) generated on a large-screen cathode-ray tube (Hewlett-Packard 1317A with P31 phosphor), using the method of Campbell and Green (1965). At the 35-cm viewing distance, the display subtended $32^\circ \times 42^\circ$ of visual angle. The luminance and contrast of the targets used in this experiment were measured by using a photometer calibrated with a standard source. Average luminance was 10.6 cd/m^2 and the luminance response of the display was linear up to a contrast of 0.81. Simultaneous presentation of two gratings, one on the left and one on the right side of the screen, was accomplished by splitting the display electronically at midline. The gratings filled the screen, were adjacent, and were equal in average luminance, hue, and size. There was a uniform interstimulus separation of about 0.5 cm that was equal to the average luminance of the display.

Sinewave gratings of 0.3 and 0.5 cycles per degree (c/d) of visual angle were presented to the 6- and 12-week-olds, respectively. These spatial frequencies were chosen because they are near the peak of the contrast sensitivity function (CSF) for the two ages (Atkinson, Braddick, & Moar, 1977; Banks & Salapatek, 1978), and thus they provide the largest possible range of visible contrasts for both age groups. The contrast sensitivities of the two age groups are similar for these frequencies, too. The same spatial frequency was presented on both sides of the display, and the contrast on both sides was set to the appropriate background value. During a trial a contrast increment was added to the background on one side.

Four background contrasts were presented. The lowest was 0.0; thus this condition was a detection threshold measurement. The other background contrasts were 0.14, 0.28, and 0.55. The 0.14 value is, on average, just above detection threshold for infants in this age range (Atkinson et al., 1977; Banks & Salapatek, 1978). An infant's data were not considered complete unless thresholds were obtained for all four background contrasts.

Procedure

A modified version of Teller's (1979) forced-choice preferential looking procedure was used with the method of constant stimuli. Infants were seated in their parent's lap and centered in front of the display. The parent's view of the display was occluded by a curtain. The observer was behind and above the face of the display and was unaware of the location of the increments. The logic of the procedure is straightforward: If the observer is able to judge the location of the pattern increment reliably, the infant must be able to discriminate the background and the

increment from the background contrast alone because the infant's behavior is the only source of information available to the observer.

Experimental trials were conducted in the following fashion. Before presentation of the test stimulus, both sides of the display contained the background grating. The observer lowered a noise-making toy to the middle of the display to attract the infant's attention to midline. When the infant was judged to be fixating centrally, the observer lifted the toy from view and pressed a button to begin the trial. A contrast increment was added suddenly to one side of the display while the other side remained at the background level.² The increment remained present until the observer responded. On a small number of trials, infants' responses were ambiguous, because either no eye movements were observed or the parent seemed to distract the infant. In such cases, the observer could restart the trial; the increment was extinguished and then reappeared on the same side. Using any cue from the infant, the observer scored a trial by judging the location of the increment. The observer was provided feedback as to the accuracy of that judgment.

The testing sessions consisted of two phases: practice and test. In the first phase, the observer practiced scoring the infant in the experimental situation. The contrast increment was always large and presumably detectable. Once the observer felt that he or she could judge the infant's behavior accurately, the second, or test, phase began. For each background contrast, three different contrast increments were presented with the method of constant stimuli. The increment values used were chosen to bracket 70% correct performance. The three increments were presented in blocks of 5 trials until 20 trials were presented for each increment. If performance did not bracket 70%, another 20 trials were presented at another increment value. Therefore, each estimate of contrast increment threshold was based on at least 60 trials.

An adult was tested in the same apparatus. His contrast discrimination function was estimated at two spatial frequencies. For the 0.5-c/d stimulus, the testing conditions were identical to those of the 12-week old infants. For the 6.0-c/d stimulus, the testing conditions were similar to the infant's conditions, but the viewing distance was increased to 210 cm. Thus the stimulus on the screen was identical to the one used for the 12-week-olds; only the viewing distance, and hence the spatial frequency, differed.

Results

Probit analysis was used to estimate the contrast increment threshold associated with 70% correct for

² The method of increment presentation was chosen on the basis of pilot testing. Two types of increment presentation were tried initially: flickering increments and sudden-onset, steady increments. Temporal flickering increments were inferior to the steady increments because many infants would not preferentially fixate the temporally modulated field. The steady increments elicited consistent preferential fixations.

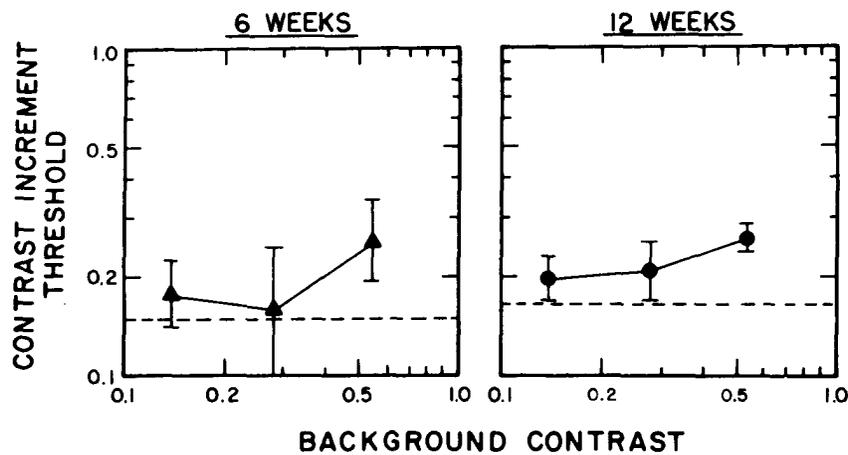


Figure 2. Average infants' contrast discrimination functions. (Average contrast increment thresholds of 6- and 12-week-olds are represented by triangles and circles, respectively. The error bars represent $\pm 1 SE_M$. The horizontal dashed lines represent the average contrast thresholds [0.0 background contrast].)

each experimental condition. We were primarily interested in two aspects of the infant contrast discrimination data: the value of the Weber fraction and the slope of the discrimination function (when plotted as in Figure 1).

Figure 2 displays the geometric means of the contrast increment thresholds as a function of the background contrast for 6 and 12-week-old infants. The horizontal dashed lines represent contrast thresholds (0.0 background contrast). The vertical bars represent ± 1 standard error. The average functions for the two age groups were quite similar, although the 6-week-olds' data were more variable.

Figure 3 shows the infants' data of Figure 2 along with the adult's data. The slope of the adult's function, estimated by linear regression, was 0.67, a value similar to slopes previously reported for similar conditions (Legge, 1979; Pelli, 1985). Thus our stimuli and procedure yielded conventional results for an adult.

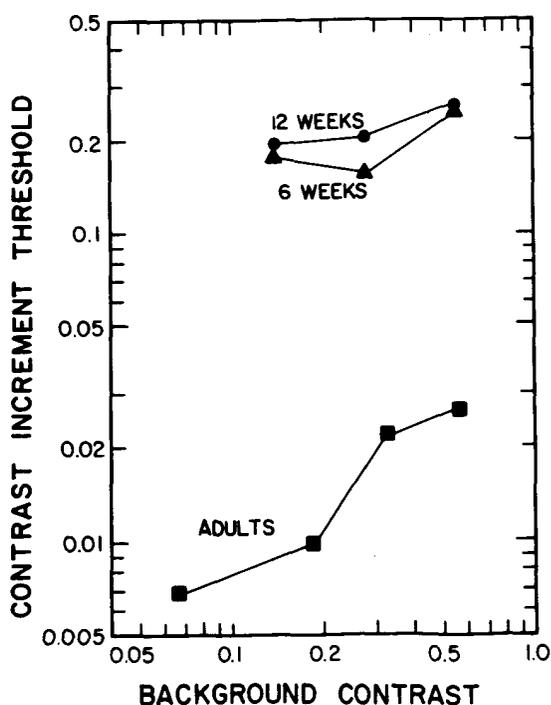


Figure 3. Infants' and the adult's contrast discrimination functions. (The infants' data of Figure 2 are replotted along with the data of an adult tested with a grating of 6 cycles per degree.)

Both groups of infants exhibited high increment thresholds and shallow slopes in comparison with those of the adult. The average thresholds expressed

as Weber fractions are plotted in Figure 4. The 6- and 12-week-olds' data are combined. With increasing background contrast, infants' Weber fractions decreased much more than the adult's fractions. Consequently, infants' and the adult's Weber fractions were most similar at high contrasts.

To assess the statistical reliability of these data, we conducted a 2 X 3 (Age X Background Contrast) analysis of variance (ANOVA), with age as a between-subjects factor and background contrast as a within-subjects factor. We observed a main effect of background contrast, $F(2, 22) = 20.7, p < .05$, but no reliable age differences between the 6- and 12-week-olds' data. The differences between infants' and the adult's Weber fractions were also evaluated. The infants' Weber fractions were significantly higher than the adult's fractions at low, medium, and high background contrasts, $t(11) = 9.7, 5.5, \text{ and } 6.6$, respectively; $ps < .05$.

To estimate the slope of the contrast discrimination functions (and thereby the exponent, n , of the infant power function), we fit each infant's discrimination function by linear regression. Figure 5 displays the mean slope estimates based on data from infants who provided complete data sets (C), partial data sets (P; fewer than four thresholds), and both (C + P). The estimates of n based on complete data sets at 6 and 12 weeks of age were 0.27 and 0.21, respectively. These estimates did not differ reliably, $t(10) = .027, ns$. The estimates based on partial data were similar to those based on complete data. Infants' slopes were combined and compared with the adult's value of 0.67. The infants' values were reliably lower than the adult's, $t(11) 3.53, p < .05$.

For theoretical reasons, it is useful to examine the psychometric characteristics of the infant data. Specifically, we examined the slope of the psychometric functions, which relate percentage of correct performance to increment contrast, for all of the infants' data. (The slope referred to here is different from the slope of the contrast discrimination function itself.) We began by determining the standard deviation of the cumulative normal function fit by probit analysis to each infant's data. This parameter is sensitive to changes in the level of physiological noise; an increasing standard deviation

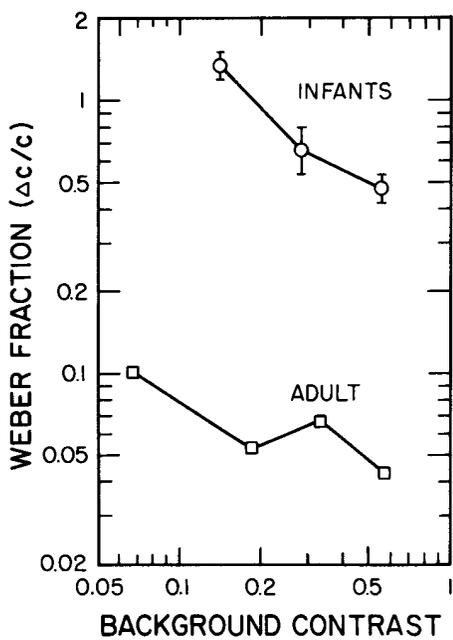


Figure 4. Infants' and the adult's Weber fractions as a function of background contrast. (The Weber fractions are the contrast threshold increment $[\Delta C]$ divided by the background contrast $[C]$. The infant data represent the average of both age groups. The error bars are $\pm 1SE_M$).

corresponds to increasing noise. Table I presents the mean standard deviations of the infants' psychometric functions for the 0.0, 0.14, 0.28, and 0.55 background contrasts. We conducted a 2 X 4 (Age X Background Contrast) ANOVA with these data. We observed no significant main effects or interaction ($F_s < 1.20$ in all cases). Therefore, the slopes of infant psychometric functions did not vary reliably with age or background contrast.

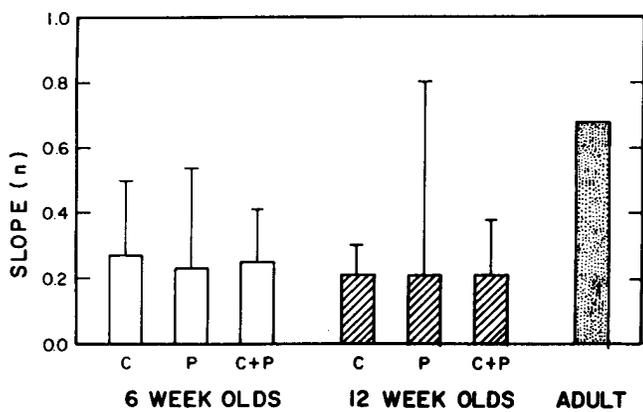


Figure 5. Slopes of infants' and the adult's contrast discrimination functions. (Average slope estimates are plotted separately for 6-week-olds, 12-week-olds, and the adult. For the infants, the various slope estimates are based on the data of those infants who provided complete data sets [C], those who provided partial data [P], and those who provided both [C + P]. The error bars are $\pm 1SE_M$.)

Table 1
Mean Standard Deviation (in Log Units) of Infant Psychometric Functions

Age	Background contrast			
	0.0	0.14	0.28	0.55
6 weeks	0.28	0.59	0.66	0.82
12 weeks	0.52	0.61	0.35	0.55

Discussion

These results indicate that the infant contrast discrimination function differs from the adult function in two important ways. First, Weber fractions are greater in infants than in adults tested under the same conditions. Second, slopes of the contrast discrimination function are lower in infants. We discuss three general implications of these age-related changes in contrast discrimination: (a) physiological processes that might be inferred from the data, (b) the validity of models of infant vision containing assumptions about contrast discriminability, and (c) effects on pattern discrimination, recognition, and identification.

Let us first consider the physiological implications. To guide the interpretation of these results, one can consider the factors that were previously described for adult models of contrast discrimination. Recall that these models posit three processes: a transducer, physiological noise, and a decision rule.

According to the models of Legge and Foley (1980) and Nachmias and Sansbury (1974), the value of Weber fractions and the slope of the contrast discrimination function could be influenced by changes in physiological noise and the transducer function. Changes in either of these factors could account for the developmental differences that we observed.

Table 2
Log of Infant/Adult Threshold Ratios

Threshold	Age of infant	
	6 weeks	12 weeks
Peak contrast sensitivity ^a	1.7	1.5
Low-frequency contrast sensitivity ^a	1.3	1.1
Grating acuity ^a	1.3	1.1
Contrast discrimination	1.1	1.1
Absolute threshold ^b	1.8	1.2
Increment threshold ^c	1.7	1.4

a Adapted from original data in "Acuity and contrast sensitivity in 1-, 2-, and 3-month-old human infants" by M. S. Banks and P. Salapatek, 1978, *Investigative Ophthalmology and Visual Science*, 17, p. 262-263. Copyright by the Association for Research in Vision and Ophthalmology. Adapted by permission.

b Adapted from original data in "Spectral sensitivity of human infants at absolute visual threshold" by M. K. Powers, M. Schneck, and D. Y. Teller, 1981, *Vision Research*, 21, p. 1015. Copyright 1981 by Pergamon Press. Adapted by permission.

c Adapted from original data in "The development of light adaptation in infants" by J. L. Dannemiller and M. S. Banks, 1983, *Vision Research*, 23, p. 604. Copyright 1983 by Pergamon Press. Adapted by permission.

There is another possibility, however: Perhaps nonsensory factors are primarily responsible for the observed differences in contrast discrimination. Stated another way, infants may be as able as adults to discriminate stimuli on the basis of contrast, but they appeared to be much poorer because they did not attend consistently in our experiment. Examples of such nonsensory factors are insufficient motivation to respond to a barely visible target, distraction resulting from irrelevant external (or 3 internal) events, and so on.³ In evaluating this possibility, it is interesting to

³ The shape of the infants' psychometric functions suggests that such nonsensory factors frequently intrude. Specifically, infant psychometric functions commonly reach asymptote at 85-95% rather than at 100%, which implies that perfectly reliable responses are not always observed even at suprathreshold levels.

note that our infants' performance relative to adults' performance was quite similar to that observed in other behavioral experiments. This is illustrated by Table 2, which compares infant and adult thresholds in several psychophysical tasks. These tasks are low-frequency (0.3-0.5 c/d) contrast detection, peak-frequency contrast detection (0.3-0.5 c/d for infants, 6.0- 10 c/d for adults), grating acuity, intensity discrimination at absolute threshold, and photopic intensity discrimination. (Note that these tasks involve manipulations of different stimulus dimensions, but presumably all of them involve contrast- or intensity-coding mechanisms.) The differences between infants' and the adult's performances were surprisingly similar across tasks, particularly in view of the procedural variety of these experiments. Infant performance was, in all cases, 1.1- 1.8 log units poorer than that of the adult. This observation is consistent with two explanations of the developmental differences. First, infant deficits in contrast/intensity detection and discrimination may be caused by inefficiencies among anatomical structures and physiological mechanisms. Second, the infant deficits may be caused by general nonsensory deficits that affect performance in a wide range of visual tasks. We are unable to reject either of these explanations because both appear to be partially correct. In regard to the anatomical/physiological inefficiency hypothesis, there is considerable evidence that ocular, retinal, and central nervous mechanisms are inefficient early in life (see Banks & Salapatek, 1983, for a review). For example, the newborn's fovea and parafovea are distinctly immature (Abramov et al., 1982; Yuodelis & Hendrickson, 1986). Photoreceptive inefficiencies must adversely affect contrast/intensity detection and discrimination (for further details, see Banks, Geisler, & Bennett, in press), but it is unknown whether they alone can account for the 1.1- 1.8 log-unit performance deficits observed.

Visual evoked potential (VEP) experiments provide important data for evaluating these two explanations (inefficiency of sensory mechanisms and nonsensory deficiencies; for discussions of the issues, see Banks & Dannemiller, 1987; Dobson & Teller, 1978). Presumably, the sensory factors affecting VEP and behavioral measurements are similar, at least at the retinal level. It is believed, however, that the early components of the VEP are affected little, if at all, by nonsensory deficits (Regan, 1972). Thus comparisons of behavioral and VEP results yield some insight into the relative contributions of sensory and nonsensory factors to the visual performance deficits of young infants. In VEP experiments, infants' thresholds are higher than adults, but the infant/adult threshold difference is generally somewhat smaller than in behavioral experiments (e.g., Norcia, Tyler, & Allen, 1986; Pirchio, Spinelli, Fiorentini, & Maffei, 1978; but see Atkinson, Braddick, & French, 1979, and Harris, Atkinson, & Braddick, 1976, for evidence of similar VEP and behavioral estimates). If one accepts the assumption that VEP measurements are much less affected than behavioral measurements by nonsensory deficits, then one can argue that the performance deficits that infants exhibit in behavioral

experiments are caused by both sensory and nonsensory constraints. Sensory constraints are evidenced by the fact that infant VEP thresholds are still higher than adult thresholds. Nonsensory constraints are evidenced by the smaller infant/adult difference observed in VEP experiments as compared with behavioral experiments.

A related possibility is that in infants, nonsensory constraints may operate more in the low-background conditions than in high-background conditions. Artifactual threshold elevation in the low-contrast conditions would lower the estimates of the discrimination function slopes. One can assess this possibility indirectly by examining the psychometric functions. If nonsensory factors were more pronounced in some conditions, the psychometric functions might be shallower in those conditions, all other factors being equal. Inspection of Table I reveals that the slopes, as indexed by the standard deviations of the psychometric functions, were not shallower at low-background contrasts. Thus there is no evidence for differential nonsensory effects in the different background conditions. However, other physiological factors, such as noise and/or the transducer function, could vary with contrast and mask the presence of differential nonsensory factors. Consequently, our standard deviation data are at best suggestive evidence that nonsensory factors alone cannot explain the decrease in slopes of infant contrast discrimination functions.

These arguments imply that the age differences in contrast discrimination are caused in part by differences in sensory factors such as the transducer function and/or physiological noise. We conducted computer simulations of contrast discrimination in order to evaluate the sorts of physiological changes that could produce the observed age effects.⁴

First we considered the effects of three possible immaturities in the infant's transducer function:

1. Infants' transducer functions may be shallower than those of adults. If all sensory factors except transducer functions were the same in infants and adults (e.g., the locus and magnitude of physiological noise, the decision rule), both would require the same change in response level to discriminate contrasts. In that case, if the infant's transducer function increased more slowly than that of the adult, the infant would require a larger contrast increment to discriminate the stimuli. In other words, the infant's Weber fractions would be higher, which is our finding.

⁴ The effects of different transducer functions and noise levels on the contrast discrimination function were identified through computer simulations. The model of contrast discrimination was based on Legge and Foley's (1980) model of adults' contrast discrimination. The transducer function that we used was identical to theirs. Gaussian noise was added both before and after the nonlinear transducer. We simulated performance in a contrast discrimination task by using a three-down, one-up staircase procedure, generating 400 estimates of increment threshold for each contrast discrimination function. The following parameters were varied in the simulation: the dynamic range of the transducer, the exponent of the transducer, the location of the transducer's inflection, the standard deviation of noise added after the transducer, and the standard deviation of the noise added before the nonlinear transducer.

2. Infants' transducer functions maybe shifted to higher contrasts than those of adults. This alternative has some face validity because infants do not respond to low contrasts, which suggests that their visual mechanisms are responsive to intermediate and high contrasts only. If the infant's transducer function were shifted to higher contrasts (all other factors being equal), the infant's discrimination function would be shifted rightward and upward in relation to the adult's function. This is also consistent with our results.

3. Infants' transducer functions may be less compressive than those of adults. Such a difference would, in fact, predict lower slopes for infants than for adults, but unless it was combined with other assumptions about physiological noise (to be described) or decision criteria, it would also predict lower Weber fractions. In fact, infants' Weber fractions are significantly larger than adults' fractions, and so a less compressive transducer function cannot by itself predict the age changes that we observed.

Next we considered the effects of differences in the magnitude of infant and adult physiological noise. Greater levels of noise (added before or after the nonlinear transducer) would lead to increases in contrast increment threshold. In addition, large levels of noise attenuate, or "flatten out," the dipper of the discrimination function. Thus the infant's function may be analogous to the dipper portion of the adult's function, with the dipper attenuated by large levels of noise.⁵

These hypotheses may be combined in different ways to explain the age changes that we observed. Yet other hypotheses may be consistent with the age changes (see, for example, footnote 5). Our data do not allow us to distinguish these possibilities.

The differences that we observed between adults' and infants' contrast discrimination have implications for models of infant vision. For example, Wilson (1986a) hypothesized that improvements with age in contrast discriminability (and in sampling rate) underlie the development of vernier acuity. Specifically, Wilson argued that vernier offsets are detected by response changes among oriented, spatial-frequency-selective mechanisms. Contrast discrimination is an index of the sensitivity of these mechanisms. Our data are qualitatively consistent with this hypothesis. Contrast discrimination appears to be poor early in life, and so Wilson would predict that the vernier acuity of young infants is rather coarse.

⁵ The effects of different transducer functions and noise levels on the contrast discrimination function were identified through computer simulations. The model of contrast discrimination was based on Legge and Foley's (1980) model of adults' contrast discrimination. The transducer function that we used was identical to theirs. Gaussian noise was added both before and after the nonlinear transducer. We simulated performance in a contrast discrimination task by using a three-down, one-up staircase procedure, generating 400 estimates of increment threshold for each contrast discrimination function. The following parameters were varied in the simulation: the dynamic range of the transducer, the exponent of the transducer, the location of the transducer's inflection, the standard deviation of noise added after the transducer, and the standard deviation of the noise added before the nonlinear transducer.

Another example is Banks's (1980) model of the development of visual accommodation. Banks argued that accommodative accuracy is limited by the visual system's ability to detect defocus and that defocus detection relies on contrast discrimination. He assumed a Weber fraction of 0.20 for infants and adults and was able to predict accommodative accuracy at different ages quite accurately. Our data suggest that Banks's assumed Weber fraction was incorrect. Infants' fractions vary rather substantially with background contrast, but the lowest average value that we observed was about 0.50. The ability to detect defocus varies with the square root of the Weber fraction (Green et al., 1980), and so even at high contrasts (like those used in infant accommodation experiments), predicted accommodative accuracy would be somewhat lower than the values reported by Banks (1980). It is also important to note that if contrast discrimination is in fact important to accommodative control, then infants' accommodation should vary substantially with contrast. At high contrasts, where contrast discrimination is fairly good, accommodation should be more accurate than at low contrasts, where discrimination is poor. The implications of our findings for understanding early pattern discrimination, recognition, and identification are less clear because there are as yet no good theories of how to link those perceptual skills to basic visual mechanisms. It is interesting, however, that relative position (or phase) information seems to be more important to adults' pattern recognition and identification than contrast (or amplitude) is. This point has been elegantly demonstrated by Oppenheim and Lim (1981) and Piotrowski and Campbell (1982). Piotrowski and Campbell computed the two-dimensional Fourier transform of two images, a tank and a face. The Fourier transform has two parts: the amplitude spectrum, which represents the amplitude or contrasts of the image's constituent sinewave components, and the phase spectrum, which represents the phases or relative positions of the constituent sinewaves. Piotrowski and Campbell examined the relative importance of amplitude and phase information by creating two new images—one with the amplitude spectrum of the tank and the phase spectrum of the face, and the other with the amplitude spectrum of the face and the phases of the tank. Adults consistently identified the image with the face's phases as a face, and the image with the tank's phases as a tank. This demonstration suggests that pattern recognition and identification do not suffer greatly when amplitude information is corrupted. If one assumes that pattern perception in infants is subject to the same phenomenon, then one would conclude that deficits in contrast discrimination should not be severely detrimental. Unfortunately, this conclusion is probably unwarranted because pattern perception from birth to 2 months of age may not be subject to the Piotrowski and Campbell phenomenon. Banks and Ginsburg (1985) have shown, for example, that young infants' preferences for one stimulus over another are determined primarily by differences in contrast in particular ranges of spatial frequency. Kleiner (1987)

substantiated this observation by demonstrating that neonates' preferences are governed more by contrast than by phase information. Braddick, Atkinson, and Wattam-Bell (1986) made a similar observation regarding neonates' visual discriminations. Interestingly, the preferences and discriminations of infants older than 2 months are strongly influenced by phase.

Thus the deficits that we observed in infants' contrast discrimination capabilities may impose substantial constraints from birth to 2 months of age on their abilities to discriminate, recognize, and identify visual patterns. After 2 months, infants' increasing sensitivity to phase information may lessen the severity of these constraints.

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