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THE CONTRAST SENSITIVITY OF HUMAN INFANTS TO GRATINGS DIFFERING IN DUTY CYCLE

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Abstract—Human infants' contrast thresholds for rectangular wave gratings differing in duty cycle were measured. The forced-choice preferential looking technique was used to estimate thresholds in fifteen 8to 10-week old infants. The results indicated that contrast threshold varied systematically with duty cycle. Our findings were consistent with the predictions of a linear, multiple channel model and one version of a linear, single channel model but were inconsistent with the predictions of a contour density and another version of a single channel model.

INTRODUCTION

Several aspects of pattern vision change dramatically during the first year of life. Visual acuity and sensitivity to contrast increase (Dobson and Teller, *1978;* Salapatek and Banks, *1978)*. Pattern preferences undergo noteworthy change as well; older infants exhibit stronger preferences for patterns composed of small elements than younger infants do (Fantz *et al.*, 1975).

Three groups of investigators have measured the contrast sensitivity function (the function relating contrast threshold to spatial frequency for sinusoidal gratings) at various ages in an attempt to characterize the manner in which pattern vision capabilities develop early in life (Atkinson *et al., 1977;* Banks and Salapatek, *1978;* Pirchio *et al., 1978).* The emphasis in this line of work has been on characterizing pattern detection thresholds rather than pattern preferences. Infant contrast sensitivity functions (CSFs) reveal numerous age-related changes. The most pronounced change, however, is the steady increase in contrast sensitivity at medium and high spatial frequencies from early to later infancy (Harris *et al., 1976).*

To what extent can the change in various aspects of infant pattern vision be related to changes in the CSP Linear systems theory states that the output of a linear system to any input can be predicted if one knows the system's modulation transfer function. This approach can be used justifiably to model the optical processing of the eye since most optical systems are linear. The optical quality of the young infant's eye exceeds the demonstrable acuity of the system as a whole, however, so the cause of the contrast sensitivity deficit appears to be primarily of neural rather than optical origin*. Thus, the shape of the CSF at a given age and the way in which it changes during infancy is probably mostly dependent on the characteristics of neural interactions rather than optical processing. Since one does not know to what extent linear systems assumptions are violated by neural mechanisms in the infant visual system, it is unclear how successful linear systems approaches might be in predicting thresholds and preferences in young infants.

Banks and Salapatek *(1981)* showed that spatial frequency cut-offs (acuity thresholds) for different types of gratings could be predicted reasonably accurately from infant CSFs and linear theory. Specifically, they reanalyzed two older studies of infant acuity. In one case, they predicted the difference in cut-offs

* The evidence that optical defects are not the primary cause of infants' contrast sensitivity deficits is mostly indirect yet reasonably convincing. Several types of optical defects can affect the contrast sensitivity of a visual system. Three of these-spherical aberration, chromatic aberration, and diffraction-have little effect on adult sensitivity at the spatial frequencies to which the infant visual system is sensitive (0-4c/deg) (Campbell and Gubisch, 1967; Westheimer, 1963). Thus, barring the unlikely possibility that one or more of these three defects is very much larger in infant eyes, they are unlikely to contribute significantly to the sensitivity deficits observed in infants. One optical defect which can constrain sensitivity to 0-4c/deg is cloudiness or the presence of significant opacities in the optic media. This defect can also be ruled out, however, because ophthalmoscopic examinations indicate that the media are relatively free of opacities or cloudiness early in life (e.g. Cook and Glasscock, 1951). Large spherical refractive error or accommodative error are other defects which can affect sensitivity to frequencies in the range of the infant CSF (Green *et el., 1980).* These errors can also be ruled out though because most infants in the age range tested can and do accommodate reasonably accurately to the target distances used in infant CSF experiments (e.g. Banks, 1980).

between rectangular wave and square wave gratings at three ages. In another, they predicted the difference in cutoffs between a square wave grating and a hand-drawn grating whose duty cycle and period varied. Atkinson et al. (1977a) showed that preferences for blurred faces could also be predicted from infants' acuity cut-offs.

Despite the reasonably good optics of the young eye, spatial frequency cut-offs are more likely to be influenced by optics than are contrast thresholds for lower frequency stimuli. Consequently, the present report investigates whether linear theory can be used to predict contrast thresholds for relatively low frequency rectangular wave gratings. The experiment is similar conceptually to an adult psychophysical experiment conducted by Campbell and Robson (1968). They showed that adult CSFs and linear theory could be used to predict the visibility of a variety of waveforms. In one experiment they measured contrast thresholds as a function of the duty cycle of an 11 c/deg rectangular wave grating. The luminance distributions of three rectangular wave gratings differing in duty cycle are shown in Fig. 1. Duty cycle is defined as the ratio of the width of a light bar to the combined widths of a light and dark bar. The amplitudes of the first, second, third and successive harmonics of a rectangular wave of contrast m and duty cycle r are respectively (4 m sin pr)/p, (4 *m* sin 2pr)/2p, (4 *m* sin 3pr)/3p and so on. Thus, the amplitudes of all the higher harmonics are less than that of the fundamental (first harmonic). However, when duty cycle is very small or approaches unity, the amplitudes of the first few higher harmonics are nearly as great as that of the fundamental. Campbell and Robson observed that contrast sensitivity for the 11 c/deg rectangular wave grating was highest at a duty cycle of 0.5 and fell symmetrically for lower or higher values. They noted that the relation observed between sensitivity and duty cycle would be obtained if only the fundamental component of the rectangular wave grating contributed to its visibility. Other experiments revealed that this relation held only for spatial frequencies higher than 5-6 c/deg, the peak of the adult CSF. At lower frequencies, contrast sensitivity could not be predicted so easily presumably because the rectangular wave grating's higher harmonics influenced its visibility in those cases. Thus, linear systems theory and a multiple-channel model predicted their results accurately for spatial frequencies above the peak of the adult CSF. Campbell and Robson also examined the predictions of a single-channel model. They found that the model did not predict contrast sensitivity for rectangular wave gratings accurately except at very high spatial frequencies approaching the acuity cut-off. At those frequencies multiple- and single-channel models yielded identical predictions simply because the higher harmonics of the grating were beyond the acuity cut-off and, consequently, could not influence its visibility.

We have conducted an experiment analogous to Campbell and Robson's in 8- to 10-week old infants. Contrast thresholds were measured as a function of the duty cycle of a 1 c/deg rectangular wave grating using the forced-choice preferential looking technique (Teller, 1979). The reasons for choosing I c/deg rather than some other spatial frequency are described below.

METHODS

Infants between 8 and 10 weeks of age were recruited by letter and telephone. Those with known ocular or general pathology were excluded. Fifteen of the 21 infants who participated provided complete data sets. The others did not complete the experiment due to fussiness, sleepiness, or scheduling difficulty. Multiple sessions were required to complete testing. The longest time between the first and last session for any infant was seven days. The average was four days.

Stimuli were generated on a large-screen CRT (Hewlett-Packard 1317A with P31 phosphor) using the method of Campbell and Green (1965). Viewing distance was always 40cm because 8- and 10-week olds are most likely to accommodate accurately to this distance (Banks, 1980; Haynes et al., 1965). At the 40cm distance the display subtended 48 x 37. The surround was dark. Space-average luminance was 10.6 cd/m' for all stimuli regardless of duty cycle. The forced-choice preferential looking paradigm was employed (Teller, 1979). Simultaneous presentation of a vertical rectangular wave grating and a uniform field was accomplished by splitting the screen electronically at midline. Thus, the grating and blank field were adjacent and equal in space-average luminance, hue, and size*. The spatial frequency of the rectangular wave was I c/deg. This frequency was chosen because at the ages tested it is about 3 times lower than the acuity cut-off yet 2 times higher than the peak of the CSF (Atkinson et al., 1977; Banks and Salapatek, 1978). Based on Campbell and Robson's (1968) results, this frequency should have been low enough to allow multiple- and single-channel models to be distinguished yet high enough to insure that multiple-channel predictions could be calculated unambiguously. Five different duty cycles were presented: 0.15, 0.30, 0.50, 0.70 and 0.85. Contrast at each duty cycle was varied in 6-dB steps according to a two-alternative, forced-choice version of the method of constant stimuli. Step sizes of 5-dB were used for adults. Contrast (defined as $(L_{max} - L_{min})/2L$) was measured using a Photo Research Spectra Brightness Spot Meter for each combination of duty cycle and dB employed.

* To hold space-average luminance constant, the d.c. level for each duty cycle was adjusted by eye so as to match the luminance of the adjacent, uniform field. This was accomplished by presenting a high-frequency grating of the appropriate duty cycle at the highest contrast to be used. The experimenter, who was far enough from the screen to be unable to resolve the grating. then adjusted the grating luminance to match that of the uniform field. Adult increment thresholds are significantly lower than infant (Peeples and Teller, 1975), so the match should have been more than adequate.

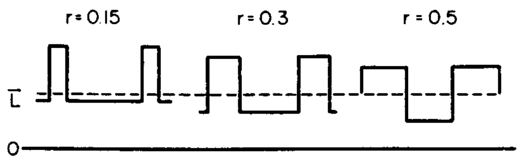

Fig. 1. Luminance distributions of rectangular wave gratings differing in duty cycle. Duty cycle is the width of a light bar divided by the combined width of a light and dark bar. Duty cycles of 0.15, 0.30 and 0.50 are displayed from left to right. Space-average luminance is indicated by dashed lines. The contrast of each grating is defined by $(L_{max} - L_{min})/2L$ where L is the space-average luminance and is given by $r \cdot L_{max} + (1 - r) \cdot L_{min}$.

During testing the parent held the infant on the lap or over the shoulder. The parent's view of the display screen was occluded by a curtain. An observer who also could not see the stimuli viewed the infant through a 1 cm peephole just to the right of the CRT. Between trials the display screen was uniformly illuminated. To attract the infant's attention, the observer lowered a noise-making toy to the middle of the screen. Once he judged that the infant was fixating midline, the observer lifted the toy from view and initiated stimulus presentation with a button press. A rectangular wave grating appeared immediately on either the left or right half of the screen. Unless the infant simply did not attend to the display, the observer guessed which side the grating had appeared on based on the infant's eye and head movements. A TRS-80 microprocessor recorded the observer's responses and provided feedback. A trial was terminated when the observer responded which was usually 5-15 sec after stimulus onset. Generally three contrast levels were presented at each duty cycle although four were presented in a few cases. Twenty trials were presented at each level in blocks of five. Presentation order was random and the observer was unaware of the contrast being presented in any given block of trials.

Four of the infants completed testing at all five duty cycles. For these infants three to six 45-min sessions were required. Five completed testing at 0.15, 0.30 and 0.50 only and six completed testing at 0.50, 0.70 and 0.85 only. For these infants two to four 45-min sessions were required.

One emmetropic adult was also tested using the same apparatus and the two-alternative, forced-choice version of the method of constant stimuli. This subject viewed the stimuli binocularly with natural pupils from a distance of 280 cm. The gratings were the same frequency expressed in c/cm as presented to the infants. Thus, the spatial frequency was 7 c/deg, a frequency roughly five times lower than the adult's acuity cutoff, yet two times higher than the peak of the adult's CSF measured in this apparatus.

RESULTS AND DISCUSSION

For both the infant and adult data, the observer's percent correct was plotted as a function of log contrast for each duty cycle. Probit analysis (Finney, 1971) was used to find the contrast associated with 70% correct and this value was taken as the contrast threshold.

Figure 2 displays individual subject data for the four infants who completed testing at all five duty cycles. Contrast sensitivity, the reciprocal of contrast threshold, is plotted as a function of duty cycle. Despite considerable variability, sensitivity is generally higher at a duty cycle of 0.5 and lower for duty cycles of 0.15 and 0.85. Once the results from all 15 infants are averaged, the relation between duty cycle and contrast sensitivity is more apparent. Figure 3, which shows mean contrast sensitivity as a function of duty cycle, illustrates this. Because some infants were tested at three duty cycles and the others at all five (see Methods), the plotted points at duty cycles of 0.15 and 0.30 are the geometric means of nine individual sensitivity values; points at 0.70 and 0.85 are the geometric means of 10 values and the point at 0.5 is the geometric mean of 15 values. The error bars are standard errors of each point once overall subject differences in sensitivity are partialled out[*].

One might expect the adult results at 7 c/deg to be similar to the infant results at I c/deg because those spatial frequencies are about twice the peak frequencies of the adult CSF and infant CSF respectively. Thus, Fig. 3 also displays the contrast sensitivity values for the adult tested at 7 c/deg. The adult results exhibit the same relation between sensitivity and duty cycle that Campbell and Robson (1968) observed at I 1 c/deg and hence replicate their findings.

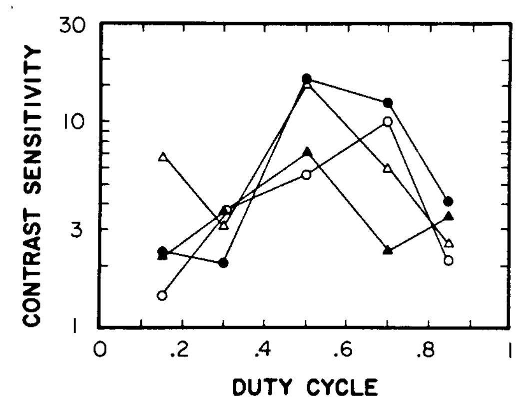

Fig. 2. Contrast sensitivity as a function of the duty cycle of I c/deg rectangular wave gratings. The results from the four infants who completed testin'9 at all five duty cycles are shown.

The large difference in Fig. 3 between infant and adult contrast sensitivity is similar to that observed previously (Atkinson *et al.*, 1977; Banks and Salapatek, 1978; Pirchio *et al.*, 1978). However, both sets of data exhibit the same relation between sensitivity and duty cycle. If multiple-channel

[*] Overall subject differences in mean contrast sensitivity were partialled out in the following manner. Each subject's mean contrast sensitivity, averaged across duty cycles, was calculated. This value was then compared to the group's mean contrast sensitivity. also averaged across duty cycles, in order to estimate a vertical shift factor. The shift factor was then applied to each of the subject's data points so as to equate the subject's mean sensitivity to the group's. The standard error bars shown in Fig. 3 were calculated on these shifted data.

processing obtained at 8-10 weeks of age, one would expect the fundamental of our gratings to be more visible than the higher harmonics because infant CSFs exhibit greater sensitivity at I c/deg than at higher frequencies. One would, of course, expect the same for the adult since 7 c/deg is above the peak of the adult CSF. The solid lines in the Figure represent multiple-channel predictions; that is, the sensitivity values that would be obtained if only the fundamental component of the rectangular wave grating contributed to its visibility. The two lines are identical in shape; they have been shifted vertically to obtain the best least squares fits. The multiple-channel predictions match both data sets quite well.

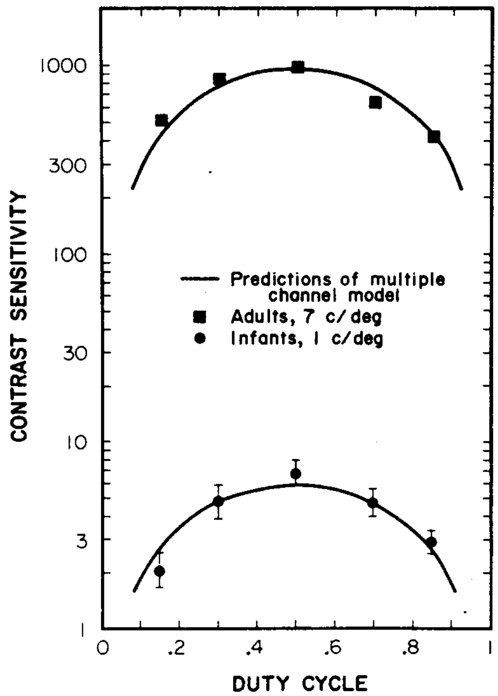

Fig. 3. Average contrast sensitivity for infants and the adult as a function of duty cycle. The infant data are rep resented by filled circles. The sensitivity values are for I c/deg rectangular wave gratings. The error bars represent the standard errors of each point once overall subject differences in contrast sensitivity are partialled out. The adult data are represented by filled squares. Those sensitivity values are for a 7 c/deg grating. The two curves represent the predictions of the multiple-channel model. They are identical in shape but have been shifted vertically for best fit.

Figure 4 shows the same data expressed in terms of relative sensitivity. The adult data have been shifted vertically by a constant factor to match the infant data. The predictions of the multiple-channel model are represented by the solid line. Again, the fit between the predictions and the infant data (r' = 0.96) and the adult data (r' ='0.88) is quite good. We have investigated whether multiple channels must be assumed to account for the results of Figs 3 and 4. Specifically, we have calculated the predictions of two single-channel models which have appeared previously in the psychophysical literature. Campbell and Robson (1968) considered the behavior of a linear, single-channel model in which threshold is determined by the peak or trough value (whichever deviates most from the DC level) of the grating waveform once it has been filtered by the CSF. For the infant calculations, the grating waveforms were filtered according to the 2-month CSF of Banks and Salapatek (1978). The relation between duty cycle and sensitivity ratio for such a "peak or trough detector" is shown by the dotted line in Fig. 4*. For simplicity, only predictions for infants are displayed but the adult predictions are quite similar. The "peak or trough" function is clearly inconsistent with both the infant data (r' = 0.66) and adult data (r' = 0.61) and, consequently, does not account for our findings.

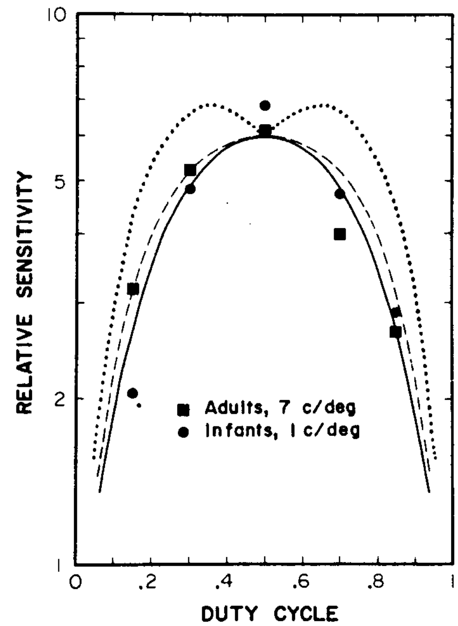

Fig. 4. Relative contrast sensitivity for infants and the adult at various duty cycles. Average relative sensitivity for infants is represented by filled circles. Average sensitivity for the adult is represented by filled squares. The predictions of a linear, single-channel model assuming a "peak or trough detector" are indicated by the dotted line. The line represents the predictions for infants but the adult predictions are quite similar. Predictions of a linear, single channel model assuming a "peak minus trough detector" are represented by the dashed line. Predictions of a linear, multiple-channel model are indicated by the solid line.

Campbell et al. (1969) investigated a linear, single-channel model in which threshold is determined by the arithmetic difference between the peak and trough values of the grating waveform once filtered by the CSF. The predictions of this "peak minus trough detector" are represented by the dashed line in Fig. 4. Again only the infant values are shown but the adult values are very similar. The "peak minus trough" function

* We have not included the effects of probability summation between a peak detector and a trough detector in the calculation of this function. Probability summation would have the effect of increasing the predicted sensitivity ratio for a duty cycle of 0.5 relative to the other duty cycles. Thus, this model with probability summation incorporated would be somewhat more consistent with our results.

is quite close to the multiple-channel function and, consequently, is consistent with both the infant results (r' = 0.94) and adult results (r2 = 0.88). At this point then the relation between duty cycle and contrast sensitivity can be accounted for equally well by a linear, multiple-channel model (which assumes that only the most visible component contributes to the rectangular wave grating's visibility) and by a linear, single-channel model (which assumes that visibility is governed by the peak-to-trough difference in the grating waveform once filtered by the CSF).

It is interesting to note that Campbell and Robson (1968) did not investigate the behavior of a peak-minus-trough detector mechanism in their single-channel simulations. We have reanalyzed their four detection experiments and found that such a single-channel model predicts quite accurately the results of their rectangular wave experiments (their Figs 5 and 6) and their sawtooth wave experiment (p. 559)* The predictions for their square wave experiment do not depend on the detector mechanism chosen, so a peak-minus-trough model yields the single-channel predictions shown in their Fig. 3.

Several models of infant pattern perception have appeared in the child development literature (reviewed by Banks and Salapatek, 1981). The only one which is sufficiently quantitative to test is the contour density model of Karmel and Maisel (1975). We have also investigated the ability of this model to predict our results. The contour density model states that infants' preferential looking is governed by the pattern's contour density (total length of contour divided by stimulus area) and that optimal contour density increases with age. Thus, Karmel and Maisel claim that a pattern whose contour density is close to optimal for the age tested will be preferred over a pattern whose contour density is lower or higher. Likewise, patterns of equal contour density will be equally preferred. The contour density model was originally proposed to account for suprathreshold pattern preferences, so it has not been extended to pattern detection thresholds previously. The number of light and dark bars in a rectangular wave grating does not vary with duty cycle so long as its spatial frequency is constant. In other words, contour density does not vary with duty cycle. A contour density model would thus predict that contrast threshold does not vary with duty cycle. This prediction would yield a horizontal line in Fig. 4. Clearly the data are inconsistent with the contour density prediction. Therefore, we conclude that contour density is not a useful metric for modeling infants' thresholds for periodic patterns.

We have shown that linear systems theory enables one to predict young infants' contrast sensitivity to I c/deg periodic patterns differing in duty cycle. The result is non-trivial because infants' contrast sensitivity at I c/deg probably reflects mostly neural rather than optical processes. The result does not necessarily imply, however, that the neural processes in-the immature system are approximately linear. Different sorts of systems with highly nonlinear stages could yield results similar to those of Figs 3 and 4. For example, consider a linear filtering stage followed by bandpass mechanisms whose responses are highly non-linear functions of the filter output. The system's relative thresholds among gratings differing in duty cycle would be identical to our observations and Campbell and Robson's as well.

In summary, we have shown that linear theory can be used to predict human infants' contrast thresholds for gratings varying in duty cycle. The contrast sensitivity of young infants appears to be constrained more by neural processes than by optical processes, so linear theory's utility extends to situations in which optics are unlikely to be a major constraint.

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