Vision Res. Vol. 32, No. 11, pp. 2005-2012, 1992
0042-6989/92 $5.00 + 0.00

The Effects of Luminance on FPL and VEP Acuity in Human Infants

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Received 5 October 1987; in revised form 28 June 1989; in final form 6 May 1992

Grating acuity was measured in 16-week-old human infants. Three measurement techniques were used: forced-choice preferential-looking (FPL), and two visual-evoked-potential (VEP) techniques. The stimuli were counterphase flickering sinewave gratings with a space-average luminance of -1.0 or 2.0 log cd/m'. Slightly different luminance-dependent changes occur between FPL and VEP acuities, suggesting that some factor influences the two methods differently as stimulus luminance varies. A comparison between FPL acuities and VEP acuities within infants suggests a quantitative relationship between techniques. Infant's acuity for sinewave gratings with a space-average luminance of -2.0, - 1.0, 0.0, 1.0 and 2.0 log cd/m^2 was also measured using a single VEP paradigm. The results are compared to the same measurements in adults and to infant and adult ideal observers. VEP acuity in this group of infants improves by about 0.5 log units between -2.0 and 0.0 log cd/m^2 and remains asymptotic between 0.0 and 2.0 log cd/m^2. This result suggests that luminance-dependent changes in infant acuity cannot be fully accounted for by immaturities in the optics and photoreceptor spacing and efficiency.

Infant visual development   Acuity   Preferential looking   Visual evoked potentials

INTRODUCTION

Visual acuity in adults improves with increasing stimulus luminance, although little improvement is observed for luminances > 2.0 log cd/m^2 (Patel, 1966; Shlaer, 1937). Several factors contribute to this improvement, including the transition from scotopic to photopic vision at moderate luminances (Hecht, 1927) and the increase in the ratio of signal to photon noise at higher luminances (Banks, Geisler & Bennett, 1987). The state of adaptation of the eye also affects the variation of acuity with luminance (Lythgoe, 1932) so post-receptoral processes are important as well.

The visual performance of human infants at different light levels is of theoretical interest for the following reasons. It is now well established that the spatial vision of young infants is quite deficient relative to that of adults (Banks & Salapatek, 1983; Braddick & Atkinson, 1988) and that the fovea, the retinal region that supports fine resolution in adults, is distinctly immature during the first months of life (Abramov, Gordon, Hendrickson, Hainline, Dobson & LaBossiere, 1982; Youdelis & Hendrickson, 1986). A handful of investigators have pointed out recently that an important consequence of the retinal immaturity is reduced quantum catch among foveal cones (Banks & Bennett, 1988; Brown, Dobson & Maier, 1987; Wilson, 1988). The lower catch is, in a sense, similar to the effect of reducing the retinal illuminance of the stimulus by placing dark glasses in front of the eye. This is the dark glasses hypothesis (MacLeod, 1978), which, when adapted to development, states that the performance of infants and adults can be equated by increasing the light level presented to infants enough to overcome the attenuation of the theoretical glasses. According to this hypothesis, infant spatial vision at a suitably bright level should be similar to adult vision at a lower level. In the context of the current paper, the dark glasses hypothesis would predict that infant grating acuity should approach adult levels of 30-60 c/deg at high light levels.

Using the forced-choice preferential-looking (FPL) procedure, Brown et al. (1987) and Dobson, Salem and Carson (1983) examined this idea by measuring grating acuity in 8-week-old infants at luminances ranging from - 2.6 to 1.5 log cd/m^2. They found that plots of acuity as a function of luminance were slightly different in shape for infants and 4dults and that the infant data were 1.5 log units lower than the adult. The fact that the infant data reached an asymptote at roughly the same luminance as the adult data, but at a much lower acuity value, is clearly inconsistent with the dark glasses hypothesis. Of course, this hypothesis is rather simplistic because it does not incorporate other known differences between infants and adults

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that assuredly affect resolution. For instance, age differences in eye size and photoreceptor spacing affect the sampling frequency of the eye and hence its resolution capacity. To examine the contribution of these differences as well, we compare in this paper acuity as a function of luminance in infants and in an ideal observer with neonatal optics and photoreceptors.

The acuity estimates obtained with various visual-evoked-potential (VEP) techniques are typically significantly higher than those obtained with FPL (Dobson & Teller, 1978; Norcia & Tyler, 1985). This observation raises the concern that the FPL procedure underestimates the resolution capacity of infants. Because the observation of a low asymptote in acuity vs luminance plots is crucial to rejection of the dark glasses hypothesis, it is important to use techniques that yield high acuity estimates in infants. Additionally, it is possible that this difference in acuity between techniques could be more pronounced at some luminances. Given these concerns, it seems premature to reject the dark glasses hypothesis on the basis of data obtained from FPL alone. Perhaps VEP measurements will reveal that infants' resolution performance continues to improve at high light levels. Moreover, finer acuity estimates will be important to comparisons with ideal performance.

There have been no reports of infants' VEP acuity as a function of luminance. Fiorentini, Pirchio and Spinelli (1980) recorded VEPs to sinusoidal gratings of varying contrast and spatial frequency at - 1.2 and 0.8 log cd/M2. One can extrapolate their data to estimate grating acuity. As in the behavioral studies, infants exhibited similar or less improvement in acuity compared to adults with increasing luminance. These data do not really bear on the dark glasses hypothesis, however, because the highest luminance was lower than the level at which adult acuity begins to reach an asymptote.

To test the dark glasses hypothesis more directly, we first measured acuity at two luminance levels with FPL and VEP in the same infants using nearly identical stimuli. To our knowledge, this is the first study to measure acuities in the same infants with the same stimuli using both behavioral and evoked potential techniques. We expected the absolute acuity values to differ between the two techniques, but of more interest were the relative improvements of the acuity estimates with increasing luminance. Similar relative improvements would be consistent with the hypothesis that FPL and VEP estimates of visual resolution are constrained by the same neural mechanisms. A difference in the relative improvements in acuity would suggest that the two techniques are affected differently by some factor.

We then measured acuity in a group of infants at five luminance levels spanning a 4 log-unit range and compared this to the same measurements in adults and to infant and adult ideal observer predictions of the measurements. This comparison allows one to estimate how much of the improvement in acuity can be accounted for by the pre-neural factors incorporated in the ideal observer.

METHODS

Subjects

Twenty-five infants were recruited by letter and phone from county birth records. After receiving informed consent from the parents, the infants were tested between the ages of 15 and 20 weeks. The average age was 16 weeks and 2 days. All infants were free of significant health problems, ocular pathology and strabismus. We also tested four adults with normal corrected visual acuity.

Stimuli

The stimuli were displayed on a Joyce electronics display in an otherwise dark room. The stimuli were vertical sinusoidal gratings of 80% contrast, counterphase flickered at 6 Hz. In the FPL sessions, a grating was presented on the left or right half of the display and a uniform field of the same space-average luminance was presented on the other half. In the VEP sessions, the stimulus filled the entire display. Viewing distances were 40 and 80 cm in the FPL and VEP sessions, respectively, so that equal number of cycles was presented at a given spatial frequency for both techniques.

Forced-choice preferential-looking procedure

The forced-choice preferential-looking technique has been described previously (Teller, Morse, Borton & Regal, 1974;

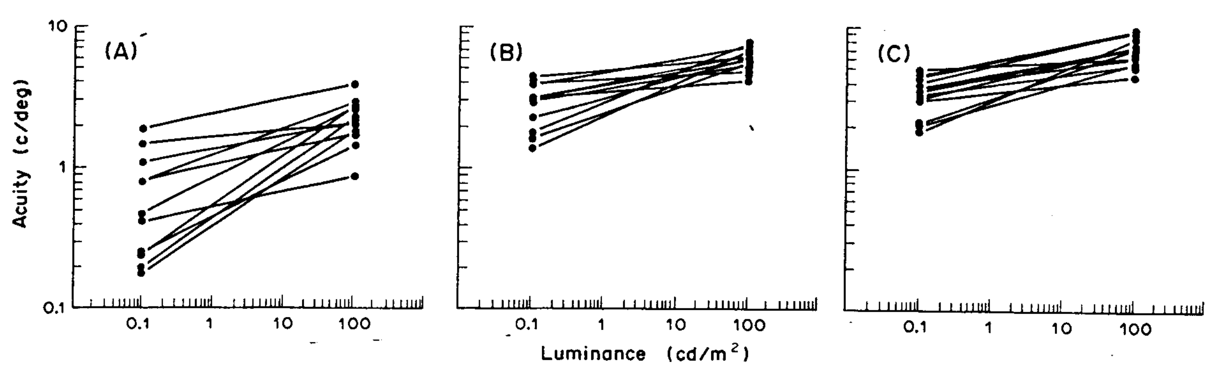

FIGURE 1. Grating acuity of 16-week-old infants at -1.0 and 2.0 log cd/m^2. The acuity was determined using either (A) forced-choice preferential-looking behavior, (B) steady-state evoked-potentials or (C) sweep evoked-potentials. The data from individual infants are connected by straight lines.

Teller, 1979), so only a brief description is given here. Infants were tested while seated on the parent's lap. An observer monitored the infant's eye position using a Panasonic WV-1550 video camera (sensitive to 0.3 lx) and video monitor. The infant's face was illuminated by the light from the stimulus display and by an i.r. light source (60 W incandescent bulb and Wratten 87B filter). The observer initiated a trial when the infant was judged to be fixating the center of the display. On each trial, a grating appeared on either the left or the right side of the screen. The observer guessed the location of the grating based on the infant's behavior. Feedback indicated the accuracy of the response.

At least 25 trials were presented at each of 3-5 spatial frequencies for every luminance level tested. A Probit analysis (Finney, 1971) was performed on each set of psychometric data in order to determine the best fitting cumulative normal function. Acuity was defined as the spatial frequency associated with 75% correct responding.

Visual-evoked potentials

Two VEP paradigms were used. In one, which we will call the steady-state VEP, spatial frequency remained constant during each trial. The EEG was recorded only while the observer judged the infant to be attending to the stimulus. The trial continued until 10sec of data were accumulated. The amplitude and phase of the 12 Hz component (second harmonic of the stimulus frequency) were determined from the EEG using a discrete Fourier transform algorithm (Norcia & Tyler, 1985). The response amplitudes for approximately five trials were averaged together. The mean amplitude for the averaged data was computed and defined as the VEP response amplitude for that spatial frequency. Response amplitude was plotted as a function of spatial frequency. The data for 3-5 spatial frequencies were fit to a line by linear regression. VEP acuity was defined as the spatial frequency corresponding to the x-intercept of the line (Sokol, 1978; Pirchio, Spinelli, Fiorentini & Maffei, 1978).

In the second paradigm, which we will call the sweep VEP (Norica & Tyler, 1985), the spatial frequency of the grating increased from 0.5 to 8 c/deg in nineteen equal linear steps, once every 500 msec. Approximately five 10-sec trials were recorded and averaged together. The VEP amplitude and phase were extracted from the EEG using the same discrete Fourier transform algorithm. A regression line was fit to a plot of response amplitude vs spatial frequency using both a signal-to-noise ratio and a phase consistency criteria. The response signal amplitude had to exceed the noise amplitude by a factor of 3. In portions of the record used for the regression, there could be no local EEG transients which elevated the amplitude of the noise frequency to more than 70% of that at the response frequency. The phase of the response had to be either constant or gradually lagging the stimulus as spatial frequency increased. This constraint was introduced because it is known that evoked response latency is longer for higher spatial frequency stimuli (Parker & Salzen, 1977; Vassilev & Strashimirov, 1979). Intersection of the regression line with 0 It V was taken as acuity threshold. The best acuity from either the vector average or a single trial was chosen as the infant's sweep-VEP acuity.

RESULTS

Experiment 1

Grating acuity was measured in thirteen infants at –1.0 and 2.0 log cd/m^2. These measurements were made using FPL, steady-state VEPs and sweep VEPs. Figure 1(A) shows FPL grating acuities for eleven of the thirteen infants tested. Two infants are not included because their data at –1.0 log cd/m^2 could not be fit by Probit analysis. There was considerable variability between subjects, especially at the lower luminance level. Despite this variability, acuity increased with luminance in all but one infant. Grating acuities measured with the steady-state and sweep VEP techniques are plotted in Fig. l (B, C) respectively. Only twelve infants are included in Fig. l (B) because the data from one could not be fit by linear regression. Again, higher acuities are observed at the higher luminance. Between-subject variability appears to be lower than with FPL.

The group average acuity estimates are plotted in Fig. 2. As expected, the average VEP acuities were higher than the FPL acuities. The sweep VEP acuities and the steady state acuities did not differ significantly from one another ($F_{1,21}$ = 0.03).

The improvement in acuity with increasing luminance was similar for all three techniques but slightly greater for FPL ($F_{2,21}$ = 5.50, P < 0.05). The difference in slopes of the VEP and FPL acuity vs luminance plots can be understood from considerations of the relationship between contrast sensitivity and grating acuity. It is well known that higher contrast sensitivities are observed with the VEP across a wide range of spatial frequencies (Banks & Salapatek, 1978; Norcia, Tyler & Hamer, 1990). Because the high-frequency end of the CSF has an accelerating negative slope, its slope at the acuity cut-off is steeper in VEP than FPL assessments. Thus, any manipulation, such as reducing space-average luminance, should have a larger effect on the FPL than the VEP cut-off.

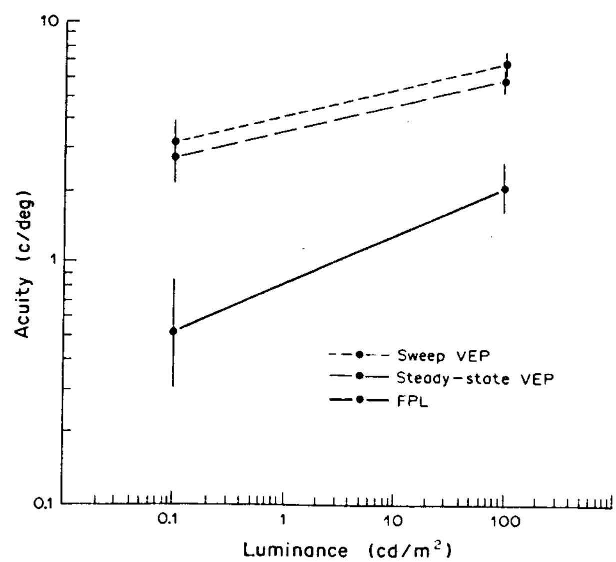

FIGURE 2. Average grating acuities for 16-week-old infants at - 1.0 and 2.0 log cd/m2. The dotted line represents the average acuities obtained with the sweep VEP, the dashed line the average acuities obtained with the

steady-state VEP and the solid line the average acuities obtained with forced-choice preferential-looking. The error bars represent ±2 SENI.

Experiment 2

The variation of acuity with luminance was examined in more detail in the second experiment. Sweep VEP grating acuity was measured in twelve infants using stimuli at - 2.0, - 1.0, 0.0, 1.0 and 2.0 log cd/m^2. For comparison, we measured adults' grating acuity over the same range using the sweep VEP and a two-alternative, forced-choice psychophysical procedure.

Figure 3 displays sweep VEP acuities for twelve infants. Although all infants were tested at each luminance, only five produced reliable signals at the lowest luminance. Acuity for each subject usually increased with increasing luminance, improving most rapidly at the lowest luminances tested.

In order to compare these findings with adults, we would like to plot the average acuities for the twelve infants. One may be concerned that only five of the twelve infants yielded usable data at the lowest luminance and therefore a comparison with adults should be limited to these five infants. In order to determine whether the different number of subjects at each luminance level biases the data in some way, we plot in Fig. 4 the mean acuity values for the five infants who yielded data at all five luminances and for the entire group of twelve infants. This graph shows that there is no significant difference in the means of the two groups. Therefore, the data do not appear to be biased by the manner in which we computed mean acuities and it seems justifiable to use the entire data set from twelve infants for the comparison.

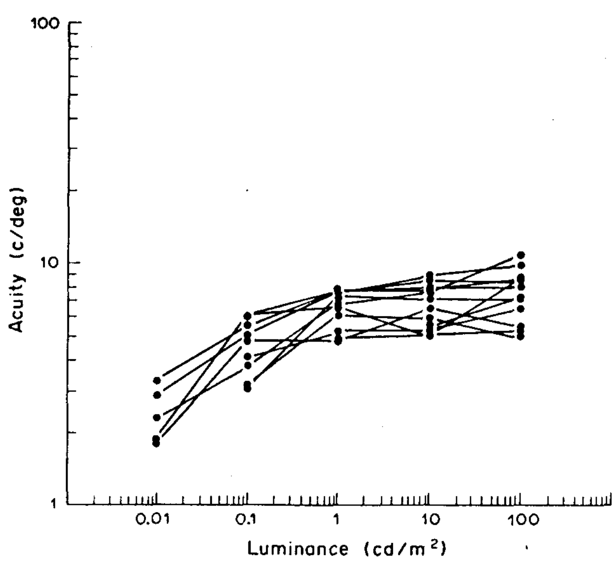

FIGURE 3. Sweep VEP acuities of 16-week-old infants as a function of luminance. All infants were tested at live luminance levels over a 4 log-unit range. Only five infants produced reliable signals at the lowest luminance.

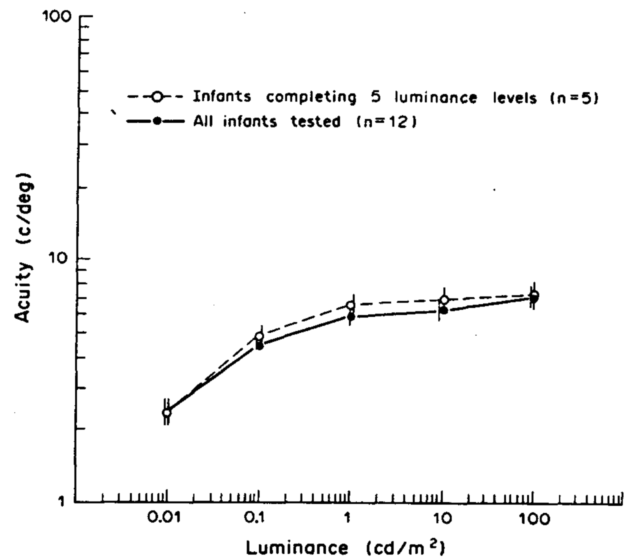

FIGURE 4. Mean sweep VEP acuities for the five infants who provided data at all five luminance levels and for the entire group of twelve infants. Error bars are ± 1 SEM. There is no significant difference in the means of the two groups.

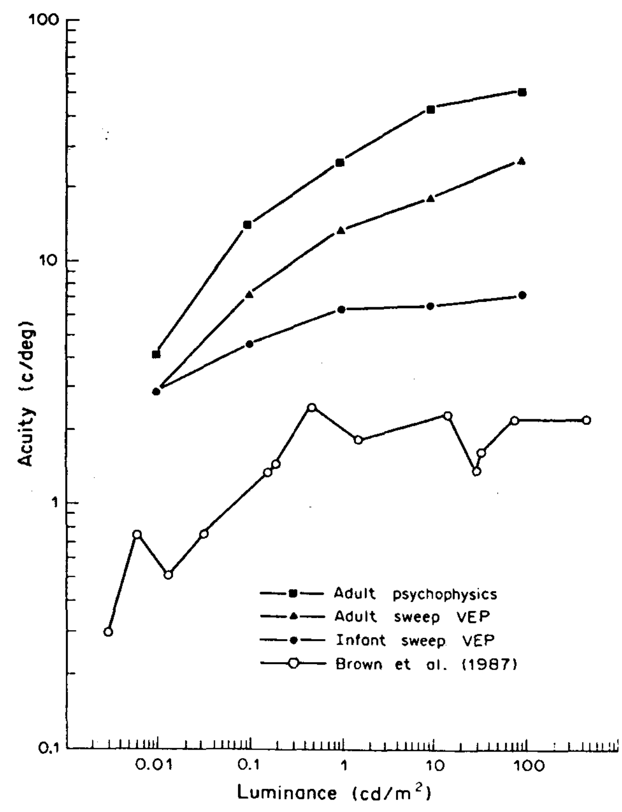

FIGURE 5. Comparison of adult and infant grating acuity. In each case, mean acuities are plotted as a function of luminance. The squares are adult data measured using a two-alternative forced-choice psycho physical procedure. The triangles are adult data measured using the sweep VEP. The solid circles are the mean acuities of twelve infants replotted from Fig. 4. The open circles are data from 26 8-week-old infants reported by Brown et al. (1987).

The average acuities for all twelve infants are shown in Fig. 5 along with the average acuities measured psychophysically and with VEPs in four adults. The behavioral infant data from Brown *et al.* (1987) are also plotted. The two adult functions do not superimpose because higher acuities were observed psychophysically, but the shapes are quite similar. The infant functions are also similar in shape, but shallower than the adult functions, particularly at the higher luminances.

DISCUSSION

FPL and VEP acuities

Using nearly identical stimuli and a within-subject design in the first experiment, we have measured the luminance dependence of infants' grating acuity using FPL, steady-state VEP and sweep VEP. As expected, VEP acuity estimates are higher than behavioral estimates. The difference from infant to infant varies from I to 2 octaves. The relative improvement in performance with increasing luminance is slightly greater for FPL acuity than for VEP, an observation that can be understood from the relationship between contrast sensitivity and grating acuity. We offer no explanation for the difference between FPL and VEP acuities. However, concerns that the FPL procedure underestimates the resolution capacity of infants are rendered less plausible when similar results are observed with an entirely different technique.

Because this study measured FPL, sweep VEP and steady-state VEP acuities within-infants, it is of interest to compare the acuities obtained between techniques. Figure 6 is a scatter plot in which VEP acuity for each infant is plotted as a function of FPL acuity. Different symbols represent different conditions; low and high luminance levels and sweep and steady-state VEPs. The entire data set has been fit using simple linear regression. The equation for this line is $y = 1.39x + 3.00$ ($R = 0.70$, SE of $x = 0.215$). Keeping in mind the fact that these are not completely independent samples, since each infant provides four data points, the fit of the data to the regression line suggests a strong, quantitative relationship between FPL and VEP acuity. This correlation also reflects the effects of error from various sources and the extent to which the techniques are influenced differently by variation in light level. The correlation within luminance level is much lower. For the data at the high luminance level alone, $R = 0.42$ while for the data at the low luminance level, $R = 0.10$. The variation - between individual infants is greater at the lower luminance level for all three techniques. The low correlations within luminance level, especially at the lower luminance, suggest that individual differences within either or both techniques may be due to measurement error.

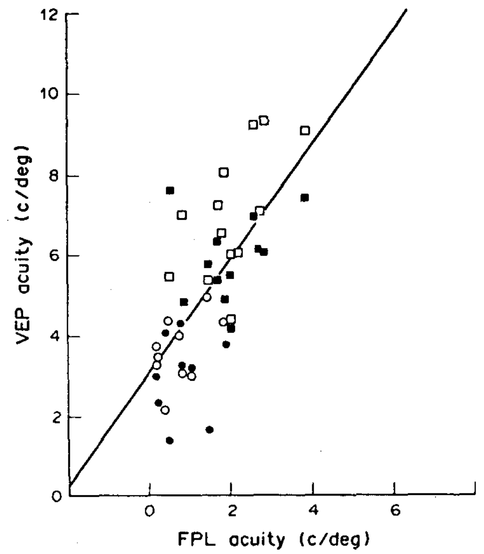

FIGURE 6. VEP acuity plotted as a function of FPL acuity for the twelve infants in Expt 1. Squares represent acuities at 2.0 log cd/m^2 and circles represent acuities at - 1.0 log cd/m2. Open symbols are sweep VEP acuities and solid symbols are steady state VEP acuities. A line is fitted to the total data set by simple linear regression. The equation for the line is $y = 1.39x + 3.00$ ($R = 0.7$, SE of $x = 0.215$).

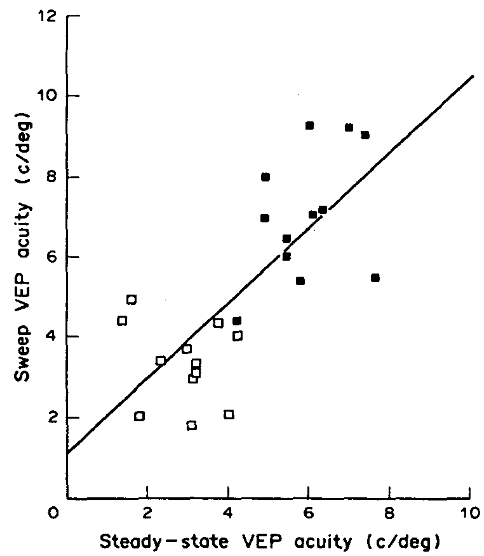

FIGURE 7. Sweep VEP acuity plotted as a function of steady state VEP acuity. Solid symbols represent acuities at 2.0 log cd/m^2 and open symbols represent acuities at - 1.0 log cd/m^2. A line is fitted to the total data set by simple linear regression. The equation for the line is $y = 0.94x + 1.03$ ($R = 0.75$).

In order to compare acuities measured with different VEP techniques, Fig. 7 shows sweep VEP acuities as a function of steady-state VEP acuities for both luminance levels tested. As expected, the acuities between VEP techniques are similar. There is a small but systematic difference, with sweep VEP producing slightly higher estimates of acuity. However, this difference is not statistically significant. The total data set has been fit by linear regression. The equation for this line is y = 0.94x + 1.03 (R = 0.75). This correlation suggests that VEP estimates of infant acuity thresholds are reasonably repeatable despite differences in the details of the techniques used. It also supports the use of the sweep VEP technique because of tile advantages in reduced recording time it offers over steady-state.

Comparison with other studies

The acuities measured here are somewhat lower than those in previous reports. The average FPL acuity at 2.0 log cd/m2 was 2.2 c/deg. Others have reported average FPL acuities of 3-4 c/deg for infants of similar ages (Allen, 1979; Gwiazda, Brill, Mohindra & Held, 1978; Teller *et* al., 1974). The differences in estimated acuities may be due to the different stimuli used. All of the above-mentioned studies used squarewave gratings with contrasts of 82-95%. This means that the contrast of the fundamental sinewave component (which is 27% higher than the contrast of the grating itself) was 104-121% compared to 80% in the present study. Because the high-frequency slope of the infants contrast sensitivity function estimated by FPL is shallow (Atkinson, Braddick & Braddick, 1974; Banks--& Salapatek, 1978) the differences in fundamental contrast could account for the differences in observed acuities. It is also worth noting that numerous other studies have measured acuity in human infants using FPL (Atkinson *et* al., 1974; Banks & Salapatek, 1978; Dobson, Teller & Belgum, 1978; Fantz, Ordy & Udelf, 1962) and the mean acuities reported vary by as much as two octaves.

The VEP acuities reported here were only slightly lower than previous estimates in similar experimental situations. The average acuities at 2.0 log cd/m^2 with the sweep VEP were 6.9 and 7.2 c/deg in Expts 1 and 2. Norcia and Tyler (1985) report a mean acuity of 9.0 c/deg at 16 weeks of age.

In order to test the relationship we found between FPL and VEP acuities, we applied our regression equation to FPL acuities from one group of infants (Allen, 1979) to see how well it predicts sweep VEP acuities in another set of infants (Norcia & Tyler, 1985). The mean acuities for both sets of data are shown in Fig. 8 as a function of age. The FPL data have also been scaled using the above equation and replotted. One can see from Fig. 8 that the adjusted FPL data are in reasonable agreement with the VEP data. The regression equation slightly underestimates the VEP acuities at the youngest age and slightly overestimates it at the oldest age in the comparison. Agreement is best at 16 weeks, the average age of the infants in our test population. Thus, to a first approximation, acuity measured with one technique can be predicted from the acuity measured with the other technique.

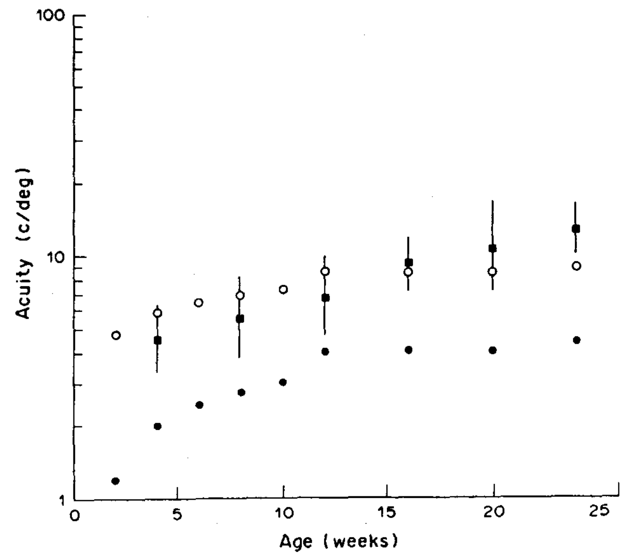

FIGURE 8. Infant's sweep VEP acuities from Norcia and Tyler (1985) are plotted as solid squares. Error bars represent 1 SD of the mean acuity at each age. Average FPL acuities from Allen (1979) are plotted as solid circles. The equation for the relationship between FPL and VEP acuity, which was determined by the regression line in Fig. 6, has been applied to the FPL acuity data and the predicted VEP acuities are plotted as open circles. To a first approximation, the predicted VEP acuities are in close agreement with the measured VEP acuities.

Dark glasses hypothesis

The dark glasses hypothesis in its simplest form states that infant and adult spatial vision can be rendered identical if infants are tested at a brighter light level than adults in order to overcome the attenuation of the theoretical glasses. As pointed out previously by Brown *et al.* (1987), this hypothesis predicts that infant acuity-vs-luminance plots, once shifted leftward by a suitable amount, will superimpose with adult plots. To examine the contributions of reduced quantum catch along with eye size, optics and photoreceptor spacing, we used the method of Banks and Bennett (1988) to compute the best resolution performance possible at various luminances given infant optics and photoreceptors. We constructed two ideal observers (Geisler, 1984), one with the properties of the adult fovea and one with the properties of the neonatal fovea. The appropriate posterior nodal distance, pupil size, ocular media transmittance, optical transfer function and the size, shape and spacing of the photoreceptors are included in each of these ideal observers (for details, see Banks & Bennett, 1988). Thus, the calculated acuities, which are shown in Fig. 9, are the grating acuities of an ideal machine if it had the optics and receptors of the human adult or neonatal fovea.

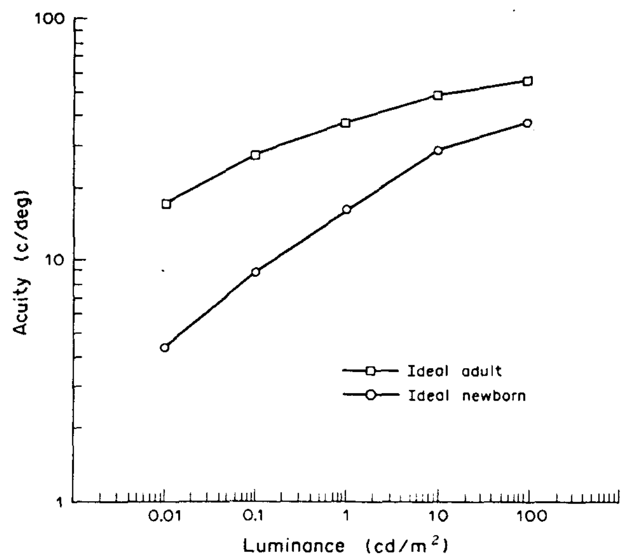

FIGURE 9. Grating acuities as a function of luminance for ideal observers with the optical and photoreceptor properties of the adult and neonatal fovea. The ideal observers are described in Banks and Bennett (1988). Pupil sizes were 2.5 and 1.7mm for the adult and neonatal observers, respectively. Eye sizes were from Larsen (1971). Optical transfer functions were from Campbell and Gubisch (1966), Photoreceptor properties were from Youdelis and Hendrickson (1996). The stimuli were Gabor patches with a contrast of 80%, SID of 3, SF (where SF=spatial frequency), and a duration of 100msec. The gratings were in sine phase.

Banks and Bennett (1988) estimate that the quantum absorption rates of adult and newborn foveal cone lattices differ by a factor of about 350. The diameter of the newborn's inner segments in the fovea is more than three times that of adults (Yuodelis & Hendrickson, 1986). Their large size prevents them from functioning as wave guides, funneling light into the outer segments, and prevents the outer segments from being tightly packed together. Banks and Bennett (1988) estimate that the effective light collecting area covers about 65% of the adult central fovea and about 2016-of the neonatal central fovea. Thus, the vast majority of the difference in quantum absorption rates is probably due to the large inner segments of neonatal cones.

The dark glasses hypothesis would mandate that a leftward shift of the ideal infant function by an amount similar to this difference in quantum absorption rates should superimpose the curves. Indeed, if one shifts the neonatal ideal function leftward by approx. 2.0 log units the ideal observer curves superimpose. Therefore, much of the difference between neonatal and adult ideal acuity can be understood in terms of the difference in quantum catch and, to a first approximation, the dark glasses hypothesis predicts the difference in neonatal and adult ideal observer acuity. However, it does not predict the data. Notice that the slope of the ideal neonatal function is steeper than that of the ideal adult function, which is opposite to the empirical result. Infant acuity reaches a low asymptote at roughly 0.0 log cd/m' while the ideal neonatal function does not reach an asymptote by even 2.0 log cd/m^2. Clearly, no shift of the infant acuities in Fig. 5 can superimpose the infant and adult curves because the data reach asymptotes at different acuity values. (See also Brown *et al.*, 1987.) Therefore, our data are inconsistent with the simplistic version of the dark glassed hypotheses. We conclude that the reduced quantum catching ability of the infantile fovea cannot by itself explain the observed differences in acuity as a function of luminance. This failure of prediction suggests that other processes such as receptor and retinal adaptation and the analysis of spatial patterns at higher neural levels are important determinants of visual resolution in human infants, particularly at higher luminances.

CONCLUSION

We have shown that human infants exhibit similar luminance-dependent changes in grating acuity when measured behaviorally or electrophysiologically. However, FPL acuity improved slightly more with luminance than did VEP acuity. This latter finding can be understood from the relationship between contrast sensitivity and grating acuity. VEP acuities did not differ by the technique, steady-state or sweep, used to measure them.

We have quantified the relationship between infant acuity measured behaviorally and electrophysiologically and shown that one can predict the acuities measured with one technique from the acuities measured with the other technique.

We have shown, as others have (Brown *et al.*, 1987; Dobson *et al.*, 1983), that the resolution performance of infants and adults is influenced differently by changes in stimulus luminance. Our ideal observer analyses support the idea that this developmental difference cannot be explained by age related changes in pre-neural factors alone. A better understanding of the maturation of receptor and retinal adaptation and of convergence of receptors onto higher-order neurons will be required before we can adequately pinpoint the causes of low visual resolution in the human infant.

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Acknowledgements — This research was supported by NIH training grant EY 07043-09, by an American Optometric Foundation Ezell Fellowship to the first author and by NIH research grant HD-12572 (to MSB). We thank Anthony M. Norcia and Christopher W. Tyler for the equipment used to record evoked potentials.