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High Visual Contrast Sensitivity in the Young Human Infant

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The visual evoked potential (VEP) was used to estimate photopic contrast sensitivity of 10-week-old infants over a wide range of spatial frequencies including the acuity limit. Adult and infant VEP contrast sensitivity was compared for sinusoidal luminance gratings reversed in contrast at 6 Hz. Space-average luminance was 220 cd/m^2. Grating contrast was swept from well below the measured thresholds to well above them in 10 sec trials. Contrast thresholds were defined as the zero voltage intercept of the initial rising portion of the VEP amplitude versus contrast function. The VEP contrast sensitivity of 10-week-old infants was close to that of the adults for spatial frequencies below about 1 cycle (c)/deg. Invest Ophthalmol Vis Sci 29:44–49, 1988

Measurements of contrast sensitivity as a function of spatial frequency provide one of the most fundamental descriptions of spatial vision. Contrast sensitivity functions of various types have played a major role both in psychophysical[1] and electrophysiological[2] studies of the visual system. Additionally, the contrast sensitivity function (CSF) is of utility in the understanding and diagnosis of visual disorders.[3–5]

Measurements of the CSF have also been of importance in the study of human visual development. Behavioral data from 2- and 3-month-old infants show their maximum contrast sensitivity to be a factor of 40 to 50 times lower than that of the adult for both stationary[6–9] and moving targets.[6,8] VEP data in some studies,[10–13] however, indicate substantially better sensitivity relative to the adult, while other VEP data[14] have indicated sensitivities in line with the behaviorally obtained thresholds.

It is difficult to evaluate much of the available VEP data. Atkinson et al[14] failed to include an adult comparison group tested under the same conditions as were the infants, so it is hard to judge the infants' relative maturity. The Harris et al study[12] involved only a single 6-month-old who was tested extensively. Two of the VEP studies[10,11] are unsatisfying inasmuch as peak adult performance was well below that to be expected under optimal conditions. The relative maturity of the infant visual system is difficult to assess if methodological limitations have prevented access to the most sensitive mechanisms known to exist in the adult. It is thus desirable that both the method and stimulus conditions used to assess infant sensitivity yield high sensitivities in adults.

Using an efficient sweep VEP technique,[15] we recently reported higher acuity values for very young infants than had been obtained by previous behavioral or VEP studies. This technique has been adapted for measurement of VEP contrast thresholds.[16] The initial application[13] of the swept contrast VEP in infants confirmed the high contrast sensitivity of 6-month-olds first reported by Harris et al.[12] We thus wished to assess whether the swept contrast method would allow us to demonstrate the existence, in much younger infants, of neural mechanisms with high contrast sensitivity.

Materials and Methods

Apparatus and Sweep VEP Technique

Contrast sensitivity was measured using a swept-contrast VEP technique.[13,16] We recorded the second harmonic response generated by sinusoidal luminance gratings reversed in contrast 12 times per sec. The amplitude and phase of the reversal response at 12 Hz and a second, orthogonal frequency of 14 Hz were determined by a Discrete Fourier Transform. The amplitude at 14 Hz was used as an estimate of the uncorrelated background noise during the trial. Grating contrast was incremented in a series of 19 equally spaced logarithmic steps spanning a range of up to eight octaves in trials lasting 10 sec. The contrast sweep started well below threshold and ended well above it. The display (Joyce Electronics, Cam-

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bridge, UK) contrast was linear to within less than 2 percent up to a Michelson contrast of 90% at the space average luminance of 220 cd/m^2 used in the present study.

Contrast thresholds were determined by linear extrapolation of the VEP amplitude versus contrast function to zero microvolts using methods described elsewhere.[13,15-17] Briefly, a range of amplitude values to be used in the extrapolation was selected by an automatic computer algorithm which incorporated both amplitude and phase criteria. The criteria were designed to distinguish driven activity from spontaneous EEG, ensuring that the points used in the extrapolation were all likely to be determined by stimulus-related activity. For all points in the range used for extrapolation, the response phase had to be constant within 20 degrees or gradually leading the stimulus (no more than 90 degrees of phase shift between points) as contrast increased, since the VEP is known to either remain constant or decrease its latency as a function of contrast.[18] For all points within the range, the amplitude at 14 Hz could not exceed 70% of that at 12 Hz, in order to rule out local transients in the EEG. The range had to include at least three points, one having a response amplitude at least 3 times higher than the average amplitude at 14 Hz during the trial, with the other points all exceeding 1.5 times the average amplitude at 14 Hz. The algorithm sought the highest increasing amplitude value exceeding 3 times the noise level as the high contrast limit for the range of extrapolated values. The numerical criteria were set empirically to limit the false alarm rate for spurious detection of signal to less than 2% of the trials run.

Subjects and Procedure

A group of ten infants between 7 and 11 weeks of age (mean age 9.5 weeks, SD 1.5 weeks) and a group of five normal adults were studied. The goal of the study and the experimental procedure was explained to the parents and informed consent was obtained. Infants were seated in the parent's lap 88 cm from the display, which subtended 10 × 20 degrees of visual angle. For the lowest spatial frequency tested (0.25 c/deg) the viewing distance was 44 cm and the field size was 20 × 40 degrees. Different field sizes were used for the different spatial frequencies due to the limited size and resolution of the video monitor; it was not possible to produce adequate high spatial frequency gratings at the shortest viewing distance, nor was it possible to maintain a large number of cycles on the screen at low spatial frequencies and long viewing distances. As a compromise, the viewing conditions were such that at least ten grating periods were displayed. Adults were tested with the same distances and field sizes up to 4 c/deg, but were tested at 177 cm and 355 cm over the spatial frequency range above 4 c/deg. The VEP was recorded from two bipolar placements, midline to 0_1 and midline to 0_2. For the infants, we attempted to complete at least two measurements at each of a series of spatial frequencies. For the adults, six trials were obtained at each spatial frequency, with these blocks of trials being presented in random order. For both infants and adults, threshold for each spatial frequency was taken as the best sensitivity value demonstrated on a single 10 sec sweep trial from either recording channel or on the vectorial average, within a recording channel, of all sweep trials taken at that spatial frequency and contrast range.

Results

Examples of the VEP contrast response functions used to estimate threshold are shown in Figure 1 for an adult observer (RDH) and a 9-week-old infant (Jacob). VEP response profiles for three spatial frequencies spanning the range between 0.5 and 2 c/deg are shown. The solid curve in the upper portion of each panel indicates the amplitude of the VEP at the contrast reversal rate of 12 reversals per sec, as determined by a Discrete Fourier Transform. The open squares plot the EEG amplitude during the trial at 14 Hz. The horizontal dotted line indicates the average amplitude at 14 Hz over the 10 sec of the trial. This was used as the noise baseline for the evoked potential. The solid curves in the lower panels plot response phase running from π at the top to $-\pi$ at the bottom. Phase lead of the response with respect to the stimulus is indicated by a downward trend in the phase plot. The range of VEP amplitude values selected by the computer to estimate threshold is indicated by the vertical dashed lines. VEP contrast thresholds obtained by extrapolation to zero amplitude are indicated by the vertical arrows.

VEP contrast sensitivity in this 9-week-old infant (arrows in Fig. 1) is comparable to that of the adult at 0.5 and 1 c/deg but is substantially lower at 2 c/deg. The best sensitivities (reciprocal of threshold contrast) were equal at 250 for the adult and the infant. Peak sensitivity occurred at 1 c/deg for the adult and at 0.5 c/deg for the 9-week-old infant. The records presented in Figure 1 were chosen for their high signal-to-noise ratio and are from an infant with above-average sensitivity and an adult with below-average VEP sensitivity.

The conclusion that the adult and infant sensitivities are similar at low spatial frequencies is not particularly dependent on the method of estimating con-

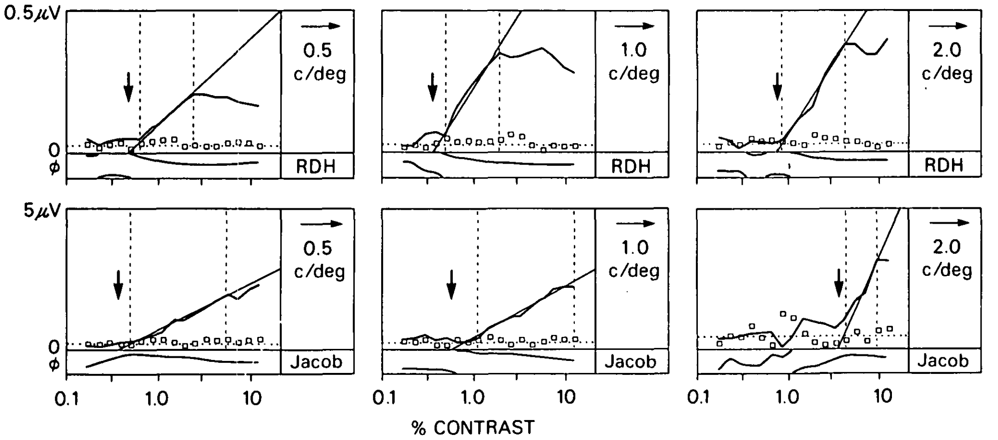

Fig. 1. Each panel shows VEP amplitude and phase as a function of contrast for an adult (RDH) and a 9-week-old infant (Jacob). The amplitude scale is linear and phase is plotted from $+\pi$ at the top of the lower panels to $-\pi$ at the bottom. The slanting line indicates the regression line fit to the data between the vertical dashed lines. VEP contrast thresholds for 0.5, 1 and 2 c/deg are indicated by vertical arrows.

trast sensitivity. Taking the intercept of the regression line with the noise level gives estimates 1.2 and 1.3 times the zero amplitude estimate for the adult and infant, respectively. Taking the lowest contrast at which a significant signal was present on the basis of amplitude alone (signal to noise ratio of 3:1) gave threshold 1.5 and 2 times higher than the zero amplitude estimate. Such changes in the estimation procedure affect the contrast sensitivity estimates by at most a factor of two, indicating that the threshold is quite robust with respect to response criterion. Furthermore, the changes in estimated threshold are of similar magnitude for the infant and adult. The slopes of the regression lines seen in the other infants and adults were similar to those shown in Figure 1.

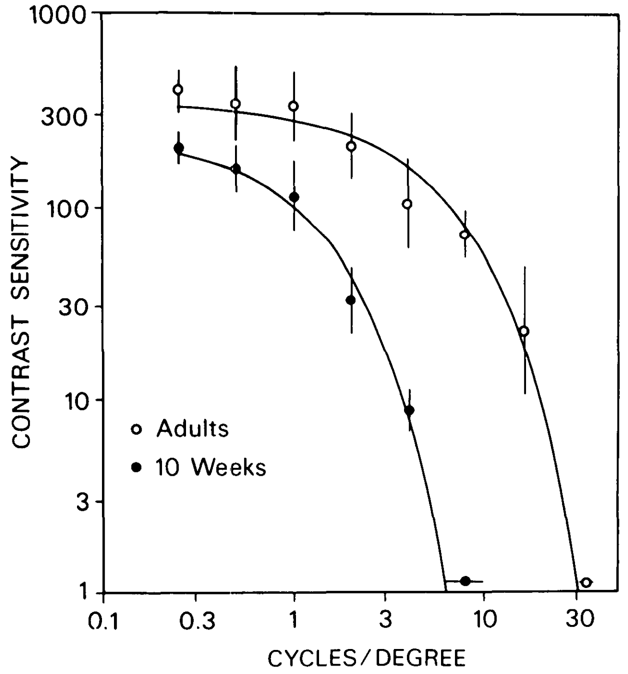

Fig. 2. Group contrast sensitivity functions for ten 10-week-old infants and five adults. The data have been fit by the function $ce^{-a\nu}$. Error bars indicate 95% confidence limits for the mean sensitivity at each spatial frequency.

The functions for the infant and adult in Figure 1 differ in the suprathreshold region, with the adult functions saturating earlier; however, this was not consistently noted in other observers.

Figure 2 plots the contrast sensitivity functions obtained from the ten 10-week-olds (closed circles) and the five adults (open circles). Both the infant and adult CSF exhibit decreasing sensitivity with increasing spatial frequency (ν), but the infant function falls off 4.5 times faster. Smooth curves of the form $ce^{-a\nu}$ have been fit to the contrast sensitivity estimates following Campbell and Green.[19] Maximum sensitivity (c) for the infants was 203 compared to 340 for the adults. Values of a were −0.72 and −0.16 for the infants and adults respectively (r^2 values for the fits were 0.98 for the infant curve and 0.94 for the adult curve). Low spatial frequency attenuation is not seen due the use of 6 Hz square-wave temporal modulation.[20] The highest spatial frequency point in each function was determined by sweeping the spatial frequency of the grating at a fixed contrast of 80% (sensitivity level of 1.25) rather than by sweeping contrast. The threshold obtained in this fashion constitutes an estimate of grating acuity.[15] For both infants and adults the acuity value obtained by sweeping spatial frequency is consistent with the x-axis intercept of the exponential that best fit the swept contrast measurements. For the infants, the predicted value was 6.4 c/deg versus a measured value of 7.4 ± 1.7 c/deg. For the adults the predicted value was 31 c/deg versus a measured value of 33.9 ± 1.0 c/deg.

Discussion

The average maximum contrast sensitivity of 200 (0.5% contrast) at 10 weeks is less than a factor of two lower than that of the average adult. Contrast sensitivity, however, falls off much more rapidly with increasing spatial frequency in 10-week-old infants than it does in the adult, consistent with their measured acuity and several earlier findings of reduced VEP acuity in young infants.[10,15,21-23] Under our conditions, 10-week-olds have grating acuities of 7.4 ± 1.7 c/deg compared to adult values of 33.9 ± 1.0 c/deg.

Comparison With Previous Work

The maximum photopic sensitivities for luminance contrast we have measured are substantially higher in both relative and absolute terms than has been seen in previous VEP studies.[10,11,14] Infant sensitivity at 10 weeks has been reported to be reduced by a factor of ten relative to the adult,[10,11] as opposed to the factor of two seen in our data. At scotopic luminances, on the other hand, it has been reported[11] that infant contrast sensitivity measured by the VEP equals that of adults tested on the same apparatus.

Our measurements indicate photopic contrast sensitivities 20–25 times higher than has been reported in behavioral tests of contrast sensitivity.[6–9] The average acuity we obtain for 10-week-olds from the VEP contrast sensitivity function is about a factor of three higher than the reported behavioral acuity for this age[24,25] and is consistent with our previous measurements.[15] A difference in acuity of this magnitude is, to a first approximation, consistent with the 20-fold difference in sensitivity between our data and previous behavioral data, at all spatial frequencies above the peak of the behavioral CSF.[6–9] At the behavioral acuity limit which is in the range of 2 to 4 c/deg at 10 weeks,[24,25] we found sensitivities ranging from 30 at 2 c/deg to 8 at 4 c/deg. Since the acuity limit corresponds to a contrast sensitivity of 1.0, our results indicate that the threshold for cortical activity occurs at contrasts 8 to 30 times below previously measured behavioral thresholds.

In adults, our method and/or stimulus conditions have resulted in VEP contrast sensitivities which are about 3 times higher than those obtained by Cannon,[26] Sieple et al[27] and Tyler and Apkarian,[28] although they are comparable to the psychophysical thresholds obtained in those studies. The present VEP sensitivities are lower by a factor of 1.6 than both the VEP and psychophysical sensitivities for single observers reported in the original Campbell and Maffei[29] and Campbell and Kulikowski[30] reports. Adult sensitivity in the present study conducted at 220 cd/m^2 is about a factor of 1.85 higher than that measured by Allen, Norcia and Tyler[16] using the same VEP technique at 80 cd/m^2.

Differences in stimulus conditions between the various VEP and behavioral studies could all have affected the absolute values of infant contrast sensitivity and acuity. Factors such as luminance,[29] temporal frequency[20] and field size[29] could affect the shape, as well as level of the infant and adult CSFs.

Atkinson et al[14] reported a maximum VEP contrast sensitivity of 5 (20% contrast at threshold) in a 7-week-old at 10 cd/m^2, which is a factor of 40 lower than we have measured for 10-week-olds. However, comparable adult sensitivity data were not reported, so it is unclear how much of a relative difference this threshold would represent.

Pirchio et al[10] measured both infant and adult contrast sensitivity at 7 cd/m^2. Our maximum sensitivities are about 10 times higher for adults and 50 times higher for 10-week-olds than measured by Pirchio et al. Some of the difference in absolute sensitivity is no doubt due to the higher luminance used in the present study. However, we find a much smaller difference in relative sensitivity between infants and adults. It is difficult to say whether the differences in results between our study at high luminance and previous results at lower luminance are due to intrinsic differences in the infant and adult contrast sensitivity versus luminance function or are simply due to methodological differences between studies.

Temporal factors may also play a role in determining infant contrast sensitivity, perhaps in a different fashion than they do in adults. Temporal frequency differs widely across studies, especially since the behavioral studies have usually employed static targets and the VEP studies have used temporally modulated targets. Atkinson et al[8,31] found as much as a factor of 2.2 improvement in behavioral maximum sensitivity in young infants when the targets were drifted at 3 Hz rather than being presented statically. The Atkinson et al[14] results were obtained at 20 rps which, along with the difference in luminance, may have accounted for their lower sensitivity. The Pirchio et al results,[10] however, were obtained at 16 rps and it is unlikely that a 2 Hz difference in temporal frequency could account for the differences between their and the present study. It is quite possible, however, that our temporally modulated targets are more optimal for very young infants than the stationary or more slowly modulated targets used in previous behavioral studies.

While the differences in stimulus conditions prevent direct comparisons of absolute sensitivity with previous studies, it is possible to compare the ratio between infant and adult sensitivity in the studies which took infant and adult data under the same stimulus conditions. In each of the previous studies in which infant photopic sensitivity was compared directly to adult sensitivity in the same apparatus,[6,8,10] large differences in relative sensitivity—on the order of 1 to 1.3 log units—were found between infants and adults. This is in distinct contrast to the small difference in relative sensitivity we have demonstrated. Differences in scoring criteria between the present and previous studies are not likely to explain the differences in relative sensitivity, since the same criteria were used to score the infant and adult data, both in the present study and in previous studies[6,8,10] where infants and adults were tested on the same apparatus.

Implications For Early Neural Processing of Contrast in Infants

Both behavioral and electrophysiological tests may underestimate the performance of the early portion of the visual system if there are significant losses in attentional, motivational or motor mechanisms required to attend to the stimulus or to perform the threshold task. One possible explanation for the difference between the present and previous findings lies in the speed with which the present technique arrives at an estimate of threshold. We have shown that it is quite possible to make measurements based on 10 sec episodes of infant fixation. The behavioral procedures and older VEP techniques are quite laborious and may have been more affected by changes in the infants' state occurring over the long time period involved in measuring thresholds.

In addition to state-control problems, a discrepancy between behavioral and VEP thresholds may also arise if the VEP is generated early in a chain of visual processing whose later stages are immature, or if information is lost in the additional mechanisms involved in the performance of the behavioral task.

Using the VEP, it is possible to set a lower bound for the spatial bandwidth of the normal input to visual cortex during the developmentally critical period of cortical plasticity. The present VEP data represent a conservative estimate of neural contrast sensitivity since it is possible that optical factors, such as uncorrected refractive errors or poor accommodation, may have reduced infant acuity relative to that of the adult. However, lack of proper focus is unlikely to have affected our estimates of maximum sensitivity since the highest sensitivities were obtained at very low spatial frequencies, where even substantial amounts of defocus would not affect retinal image contrast.[19]

The high sensitivity and acuity which we have demonstrated suggest that unequal input to cortex due to refractive error differences between the two eyes must occur at substantially smaller degrees of anisometropia than indicated by previous results. We have shown that a grating of 3–12% contrast is at threshold for the VEP at a spatial frequency which typically requires 100% contrast to elicit a behavioral response.[24,25] The depth of focus of an eye, and thus its tolerance to blur, depends upon pupil size as well as visual acuity.[32] Visual acuity, defined at some early cortical stage by the VEP, is substantially higher than that observed behaviorally. Consequently, these early cortical mechanisms would receive unbalanced input at proportionally smaller degrees of anisometropia. Since retinal image contrast is reduced by scattering as well as defocus, it would also be expected that congenital cataracts or other scattering media opacities should affect the input to cortex to a greater degree than indicated by either the earlier behavioral or VEP results.

The high sensitivity of young infants also indicates that the efficiency of the retina in transducing small fluctuations in intensity is nearly comparable to that of the adult, and that synaptic transmission to cortex is also quite mature early in life, consistent with Regal's[33] finding of an adult-like CFF at 12 weeks. It is possible that the CFF task and our temporally-modulated grating task are tapping mechanisms with higher sensitivity than those addressed with temporally unmodulated targets. Consistent with this notion is the two-fold increase in behavioral contrast sensitivity found with drifting targets over that obtained with static targets.[8,31]

Relationship to Retinal Anatomy

The present results indicate, to a greater degree than previous studies, that the major growth in visual function after 10 weeks can be described as a progressive increase in spatial resolution rather than in contrast sensitivity. It is reasonable to assume that this development occurs mainly in small receptive-field mechanisms, either in the retina or in cortex, which mediate the processing of high spatial frequency information. Abramov et al[34] have reported that extrafoveal receptors appear to be structurally adult-like at 8 days, while the foveal cones appear relatively less developed. Thus, it is possible that the projection to cortex from extrafoveal retina is functionally more mature in early infancy, reflecting the state of anatomical development of the retina, and that it is the extrafoveal projection which gives rise to the exquisite VEP contrast sensitivities which we find in young infants at low spatial frequencies. This notion receives support from the finding[11] that young infants' VEP contrast sensitivity equals that of the adult at scotopic luminances, where the fovea no longer contributes to the response. It would follow that the relatively lower sensitivities measured at high spatial frequencies reflect the immaturity of the projection from infant's fovea, which continues to develop anatomically throughout infancy into early childhood.[35]

Key words: contrast sensitivity, infant vision, visual development, visual evoked potentials

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