Scotopic contrast sensitivity in infants evaluated by evoked potentials

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The contrast sensitivity function of infants 2½ to 6 months old has been obtained at mean luminances of 6 and 0.06 cd/m² by recording visual evoked potentials in response to sinusoidal gratings of various spatial frequencies alternating in phase at 8 Hz. The scotopic contrast sensitivity develops earlier than the photopic contrast sensitivity, reaching values very close to those of the adult between 4 and 5 months of age. This suggests that mechanisms responsible for adaptive changes of receptive field organization from night to day vision are not yet mature at this age.

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

The sensitivity of the human visual system to spatial luminance modulation is fully described by the contrast sensitivity function, relating contrast sensitivity (reciprocal of contrast threshold) for sinusoidal gratings to the spatial frequency of the grating. In adult subjects, the shape of the contrast sensitivity function varies with the level of light adaptation; that is, decreasing the mean luminance of the stimulus leads to progressive decreases of spatial resolution and of the optimal contrast sensitivity while the peak of the curve moves towards lower spatial frequencies.[1-6] Thus the visual system has different spatial properties at high and low luminances.[7]

The problem of how contrast sensitivity and spatial resolution develop with age in the first year of life has been tackled recently by a number of investigators,[8-16] and information is now available on the photopic contrast sensitivity function of infants of various ages. At 2 months of age contrast sensitivity is very low, and resolution does not exceed 2 to 3 cy/deg. The photopic contrast sensitivity function at this age is similar to the contrast sensitivity function obtained from adults at a scotopic luminance level. There is then a progressive increase of optimal contrast sensitivity with age that is accompanied by an increase of visual acuity and of the optimal spatial frequency. The infant contrast sensitivity function closely approaches that of the adult during the second half of the first year of life.

All these findings have been obtained at photopic luminance levels. Very little is known about the scotopic performance of the infant visual system.

The aim of this work is to investigate the scotopic contrast sensitivity of infants of various ages and to compare it with that of a normal adult subject. To do this we have used the visual evoked potential (VEP) technique introduced by Campbell and Maffei[17] and previously applied to estimate the photopic

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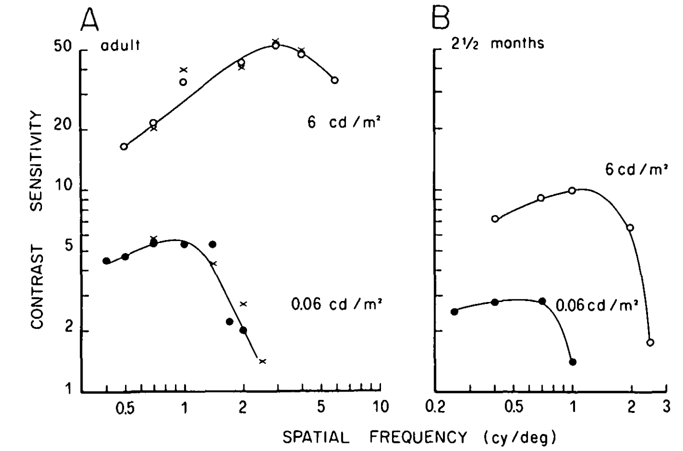

Fig. 1. A, Contrast sensitivity evaluated from VEP recordings in an adult subject at two luminance levels plotted as a function of spatial frequency (crosses). The circles represent relative amplitudes of VEPs recorded at a fixed contrast (0.20 and 0.50 for the higher and lower luminance, respectively). For further explanation see text. **B,** Relative amplitudes of VEPs recorded in a 2½-month-old infant at two luminance levels and two stimulus contrasts (0.35 at the higher and 0.70 at the lower luminance) plotted as a function of spatial frequency. The points at 1 cy/deg (upper curve) and 0.7 cy/deg (lower curve) coincide with the infant's contrast sensitivity evaluated by extrapolating to zero amplitude the regression line between VEP amplitude and log grating contrast.

contrast sensitivity of infants[8, 14, 16] and its development during the first year of life.[14]

Methods

The stimuli were vertical gratings of sinusoidal luminance profile, electronically generated on a display monitor (HP 1300A). The phase of the grating was reversed at 8 Hz. The mean luminance was 6 or 0.06 cd/m^2. The lower luminance was obtained by neutral-density filters covering all the screen surface. The viewing distance was 57 cm for 2½-months-old infants and 114 cm for all other subjects. The stimulus subtended 25° by 20° and 12.5° by 10° of visual angle at the two distances, respectively, and was viewed binocularly with natural pupils. At the lower luminance the color of the screen (phosphor P31) appeared very much desaturated, indicating that vision was largely dominated by rods. During recording no other light sources were present in the room except for the monitor and a very dim reddish light.

The infants sat on their mothers' lap, and their attention was maintained onto the screen with sounds and moving objects. An operator watched the infant from behind the screen and used a switch to stop the VEP recording whenever the infant's eyes were not directed to the screen.

VEPs were differentially recorded with one electrode 2 cm over the inion and the other on the vertex. The ground electrode was on the forehead. The signals were amplified and filtered by a passband filter 2 to 20 Hz (12 db/octave).

The filtered signal was fed into an analog input channel of a PDP11/10 computer, which performed on-line the following operations: elimination of single sweeps disturbed by artifacts; on-line averaging of the VEP over 70 single reversal periods; storage of VEP for off-line analysis; Fourier analysis of averaged VEP; plotting the VEP by an X-Y plotter; and typing the amplitude of the second harmonic of the averaged VEP.

In an adult subject no differences in the amplitude of the scotopic VEP were observed when the period of preadaptation to the dark was prolonged beyond 1 to 2 min. Therefore the infants were given only a short period (4 min) of preadaptation to the lower luminance level before starting the recording session. The photopic VEPs were recorded after the scotopic VEPs in the same session. At least two sessions were held for each infant with a few days' interval. Usually four to six records were taken for each spatial frequency and/or contrast of the stimulus. The 280 to 350 single sweep responses were averaged off-line at the end of the session.

Five infants took part in the experiments.

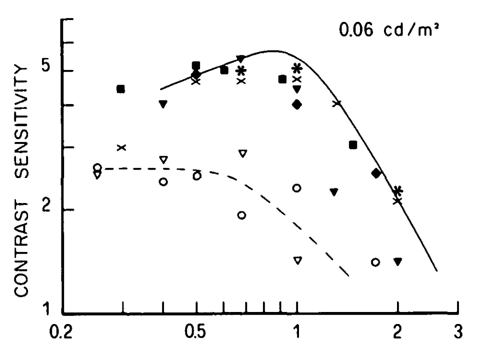

Fig. 2. Scotopic contrast sensitivity in the infant at various ages: 2½ months (open symbols); 4 months (filled symbols); 6 months (crosses); 7 months (asterisks). Different symbols indicate different infants (circles, squares, diamonds, and crosses) or data from one infant tested at 2½ months (open triangles), 4 months (filled triangles), and 7 months (asterisks). Experimental points represent the relative amplitudes of VEPs obtained at a fixed contrast level (0.70) for the various spatial frequencies and normalized with respect to the infants contrast sensitivity evaluated by extrapolation at either 0.5 or 0.7 cy/deg. The broken curve interpolates data from two infants of 2½ months of age. The continuous line is the adult scotopic curve replotted from Fig. 1, *A*.

Dynamic retinoscopy indicated that they were emmetropic or slightly hyperopic. Four infants were tested only at one age. Their ages were 2½, 4, 4½, and 6 months. One infant was tested at the ages of 2½, 4, and 7 months.

Results

The waveform of the scotopic VEPs recorded from an adult subject was approximately sinusoidal, as is the photopic waveform, but the scotopic VEPs were much smaller in amplitude.

Fig. 1, *A*, shows the contrast sensitivity functions for one adult subject obtained by recording VEPs with gratings of various spatial frequencies at two different levels of mean luminance (6 and 0.06 cd/m^2). The crosses represent reciprocals of VEP contrast thresholds evaluated by extrapolating to zero amplitude the regression line between VEP amplitudes and log grating contrast.[17] Each cross also coincides within ±0.1 log units, with the psychophysical contrast threshold measured in the same stimulus conditions as for VEP recording. Circles represent relative amplitudes of the VEP measured at two fixed contrast levels (0.20 and 0.50 at the higher and lower luminance, respectively) and normalized to the contrast sensitivity at 0.7 cy/deg for the lower luminance and at 3 cy/deg for the higher luminance.

Note the good agreement between the two sets of points at both luminance levels. The curves fitting the two sets of data therefore can be taken to represent with good approximation the psychophysical contrast sensitivity functions of the subject at the two different luminances.

In agreement with previous psychophysical data, lowering the mean luminance produces a loss of contrast sensitivity and spatial resolution while the peak of the curve moves to lower spatial frequencies. The viewing distance in the present experiment was 114 cm, the same used for the older infants. The highest spatial frequency available was therefore 6 cy/deg. Previous experiments on the same and other adult subjects have shown that at 6 cd/m^2 the VEP contrast sensitivity function has a cut-off frequency of about 30 cy/deg.[14, 17] Thus at 0.06 cd/m^2 spatial resolution is reduced about 10 times.

These findings have been obtained with gratings alternating in contrast at 8 Hz, a temporal frequency that optimizes the photopic VEP amplitude. We also recorded from the same adult subject scotopic VEPs in response to gratings alternating at lower temporal frequencies (4 and 6 Hz). In agreement with psychophysical data, the extrapolated contrast thresholds were somewhat lower (about 0.6 and 0.3 log units, respectively), and the extrapolated visual acuities were somewhat higher than at 8 Hz, but the shape of the scotopic contrast sensitivity functions was approximately the same. For this reason and for shortening the time required to accumulate responses, we used gratings alternating at 8 Hz when recording from infants.

VEPs were recorded from five infants at ages of 2½ to 7 months. Already at 2½

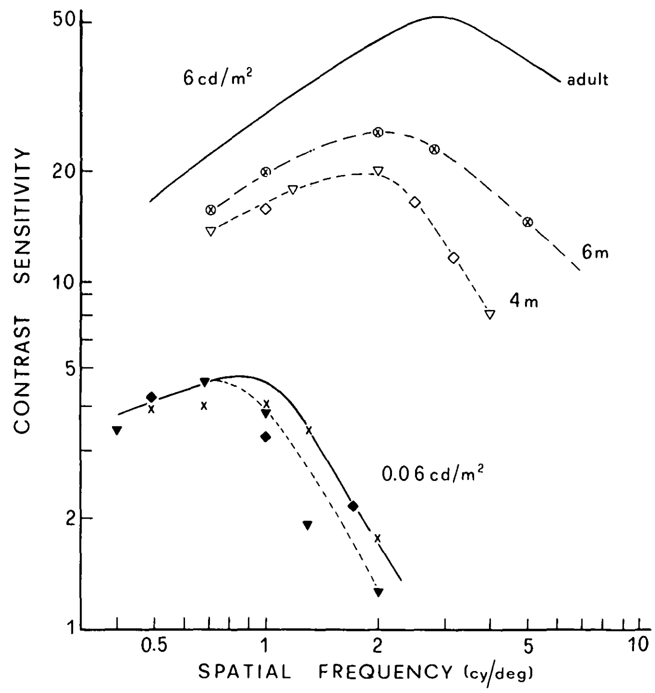

Fig. 3. Contrast sensitivity functions at two luminance levels for two infants of 4 (triangles and diamonds) and one infant of 6 months of age (crosses and encircled crosses). The continuous lines are the adult contrast sensitivity curves replotted from Fig. 1. The photopic experimental points represent the relative amplitudes of VEPs obtained at a fixed contrast level (0.35) and normalized to the infants' contrast sensitivity evaluated by extrapolation at 1 cy/deg (diamonds), 1.2 (triangles), and 2 (crosses). The scotopic points have been replotted from Fig. 2.

months of age the responses at the higher luminance were very different from those at the lower luminance, as with adults. At this age the scotopic contrast sensitivity was about half that of the adult for a spatial frequency of 0.7 cy/deg.

Fig. 1, *B*, shows the contrast sensitivity curves obtained from an infant 2½ months old by recording VEPs at 6 cd/m² (open circles) and 0.06 (filled circles). The two curves are well differentiated. At the lower luminance contrast sensitivity was poorer, and the range of spatial frequencies from which a response could be obtained was narrower than at the higher luminance. Spatial resolution was reduced approximately by a factor of 3.

Let us now compare the results reported in this figure with those obtained from the adult subject (Fig. 1, *A*). It is clear that neither the photopic nor the scotopic contrast sensitivity was fully developed at 2½ months of age.

Information about the development of scotopic sensitivity in the earlier months of life is given in Fig. 2.

The figure summarizes the results obtained at 0.06 cd/m² from four infants of various ages (circles, squares, diamonds, and crosses) and those of one infant tested at 2½, 4, and 7 months of age (open triangles, closed triangles, and asterisks, respectively). The continuous line represents the adult scotopic contrast sensitivity function replotted from Fig. 1, *A*. Note the considerable improvement in contrast sensitivity and spatial resolution between 2½ months (two infants, open symbols) and 4 months of age (three infants, filled symbols). The latter very closely approach the adult data at least for spatial frequencies below 1 cy/deg. The experimental points obtained from two infants at 6 and 7 months of age (crosses and asterisks, respectively) practically coincide with the adult data even above 1 cy/deg.

Previous experiments have shown that the maximum photopic contrast sensitivity of infants does not reach that of the adult until after the sixth month from birth.[14] We have confirmed this finding in all the infants tested in the present experiment. In Fig. 3, the contrast sensitivity functions of the adult (continuous lines) at 6 and 0.06 cd/m^2 are compared with data from two infants of 4 months (triangles and diamonds) and of one infant of 6 months (crosses). The scotopic points have been replotted from Fig. 2.

It is evident that at 4 and even 6 months from birth the photopic contrast sensitivity is still poorer than that of the adult, especially at the higher spatial frequencies. The difference between the adult's and infants' contrast sensitivity functions was certainly much more evident at the higher than at the lower luminance.

Discussion

The present experiments have shown that development of scotopic contrast sensitivity is practically accomplished at the age of 4 to 5 months. In younger infants the scotopic contrast sensitivity is not as good as in the adult, but the difference is not very large and is largely independent of spatial frequency. Contrast sensitivity improves with luminance in very young infants, though less than in the adult.

These findings have been obtained with gratings alternating at 8 Hz. For the photopic conditions there are good reasons to believe that the temporal modulation of the stimulus is not a very serious source of error in a study of the development of spatial contrast sensitivity starting from the third month of life. Indeed, the contrast sensitivity function determined behaviorally with stationary gratings in infants 2 to 3 months old[10, 12] is very similar to that obtained from VEP recordings with gratings alternated at 8 Hz.[14] For the scotopic conditions there are no behavioral data on the infant contrast sensitivity with stationary patterns.

It is possible that the scotopic contrast sensitivity of infants is relatively more impaired at 8 Hz than that of the adult in comparison with stimuli alternating at a lower rate. This cannot be the case for our older infants, whose scotopic contrast sensitivity at 8 Hz equals that of the adult, but it might be true for the younger infants. We cannot exclude therefore the fact that the development of scotopic contrast sensitivity occurs even earlier than we have found. However, according to a very recent report, the behavioral temporal resolution for flickering light of a 2-month-old infant is very close to that of the adult, both at high and low luminances.[18] This makes it rather unlikely that the temporal modulation at 8 Hz is responsible for the poor scotopic sensitivity of our youngest subjects.

It is interesting to compare the scotopic with the photopic contrast sensitivity functions at various ages. In the adult the two curves are very different in shape. When luminance is increased, the contrast sensitivity improves much more at the higher than at the lower spatial frequencies, so that the peak moves from less than 1 to 3 cy/deg and spatial resolution improves by 1 log unit. In the infants contrast sensitivity also improves with increasing luminance, but the shape of the contrast sensitivity function varies much less than in the adult. Spatial resolution did not improve more than three times from 0.06 to 6 cd/m^2 in any of our infants of 4 to 4½ months or younger.

The change in increment luminance sensitivity of the visual system with increasing luminance has been interpreted according to the signal detection theory in terms of an increase in the signal-to-noise ratio in the retinal stimulus.[7] When the mean luminance increases, the noise due to quantum fluctuations increases as the square-root of luminance, whereas the signal (in our case the peak-to-peak luminance modulation of the grating) increases in proportion to the mean luminance (for a given grating contrast). The adult visual system takes advantage of the increased signal-to-noise ratio in part to improve its optimal contrast sensitivity and in part to expand the bandwidth of the resolvable spatial frequencies.[6] These changes are likely to be subserved by changes of the spatial response characteristics of the receptive fields of visual neurones with the level of light adaptation that are known to occur in the retinal ganglion cells[7] and in cells of the lateral geniculate nucleus and visual cortex.[19]

The fact that the scotopic contrast sensitivity develops almost completely within the fifth month of life suggests that at this age cells tuned at low spatial frequencies and having relatively large receptive fields already behave like cells in the adult under stimulus conditions that are favored by spatial integration. At this time, however, finer receptive fields and adaptive changes of receptive field organization suitable for a consistent improvement of spatial resolution with luminance must still be immature.

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