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SPATIAL FREQUENCY SWEEP VEP: VISUAL ACUITY DURING THE FIRST YEAR OF LIFE

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Abstract—The grating acuity of 197 infants from 1 week to 53 weeks of age was measured using the visual evoked potential (VEP) in response to counterphase grating stimulation. The gratings were presented as a 10 sec spatial frequency sweep which spanned the acuity limit. The amplitude and phase of the second harmonic response were extracted by discrete Fourier analysis. The VEP amplitude versus spatial frequency function showed narrow spatial frequency tuning with amplitude peaks at one or more spatial frequencies. The phase of the response at medium to high spatial frequencies was generally constant at a spatial frequency peak, followed by a progressive phase lag with increasing spatial frequency. Grating acuity was estimated by linear extrapolation to zero microvolts of the highest spatial frequency peak in the VEP amplitude versus spatial frequency function. This visual acuity estimate increased from a mean of 4.5 c/deg during the first month to about 20 c/deg at 8–13 months of age. The VEP acuities at 1 month are a factor of three to five higher than previously reported for pattern reversal or pattern appearance stimuli. By 8 months VEP grating resolution was not reliably different from adult levels in the same apparatus.

Visual acuity Human infants Visual evoked potential

INTRODUCTION

A variety of psychophysical and electrophysiological techniques have been developed or adapted for measurement of infant visual acuity. Visual acuity can be measured by a number of behavioral techniques [see Dobson and Teller (1978) and Mayer and Dobson (1982) for reviews] but this report will focus on the visual evoked potential (VEP) technique. The VEP represents some part of the activity of the visual cortex in response to visual information passed by the optics of the eye and processed by the retina and geniculo–striate pathway. The presence of a reliable evoked response indicates that the visual pathway has resolved the stimulus information at least up to the point in the visual system where the response is generated. VEP acuity may be defined as the pattern element size at which a VEP can no longer be elicited from visual cortex. In practice, direct measurement of threshold cortical activity is impossible using the VEP since measurements made at the scalp are contaminated by noise sources which originate outside visual cortex, such as muscle spike activity, EEG or EKG.

A cortical acuity threshold may be estimated by extrapolation of measurements obtained above the experimental noise level, employing the assumption that the VEP declines linearly with spatial frequency near the acuity limit. The empirical validity of this assumption has been verified in adults by Tyler *et al.* (1979) and Wiener *et al.* (1985). A second assumption of the extrapolation technique is that the VEP amplitude function is sampled at sufficiently fine intervals to be well characterized by the data. This is considered in detail in the Results section.

It is difficult on *a priori* grounds to establish the relationship between a zero amplitude threshold and an acuity estimate from a psychometric function, since the later involves an arbitrary criterion of percent correct as the "threshold" value. Campbell and Kulikowski (1972) suggest that the zero amplitude threshold corresponds empirically to the 50% point on a frequency of seeing curve. The zero microvolt extrapolation can be taken to represent the cessation of stimulus related activity and thus the theoretical limit up to which spatial information can be resolved by the mechanisms generating the recorded signal. Although further mechanisms may exist which do not generate a detectable signal, the acuity defined by the extrapolation is the *minimum* resolution that should be assigned to the recorded cortical mechanisms and therefore to the retinal *input* and optics of the eye.

A number of studies have shown that the zero microvolt extrapolation results in VEP thresholds which correspond well with psychophysical threshold in adults (usually within about a factor of 2). Such correspondence has been shown for contrast threshold (Campbell and Maffei, 1970; Campbell and Kulikowski, 1972; Cannon, 1983; Sieple *et al.*, 1984), visual acuity (Tyler *et al.*, 1979, Wiener *et al.*, 1985), and stereo acuity (Norcia and Tyler, 1980). These studies suggest that under many conditions the VEP can provide a reasonably accurate representation of the information available to perception in adults. However, the same relationship between the VEP and perception may not hold in the developing visual system if significant development occurs in the *afferent* pathway beyond the point at which the VEP is generated.

Several previous investigators have studied the development of evoked potential pattern resolution in infants. Marg *et al.* (1976) recorded responses to vertical square wave gratings in a group of nineteen 1–7 month infants. Acuity was considered to lie between the highest spatial frequency at which a response could be recorded and a spatial frequency up to 1 octave higher which did not elicit a response. Several responses at 30 c/deg were measured in 14–36 week olds. Marg *et al.* (1976) did not report adult acuity values, so it is unclear whether 30 c/deg represents a fully adult acuity level under their experimental conditions. Nonetheless, they found an increase in acuity by a factor of 20 over the first 5 months of life.

Sokol (1978) measured the amplitude of the steady state evoked potential as a function of check size in forty 2–7 month infants. Acuity was estimated as the zero amplitude intercept of a linear regression on the decreasing portion of a VEP amplitude vs check size plot. Sokol found a roughly linear increase in log acuity over the 2–7 month age range with an adult acuity level being reached by 7 months of age.

Pirchio *et al.* (1978) measured steady-state VEP amplitudes as a function of sine-wave grating spatial frequency in 12 infants tested on 20 occasions. Again acuity was estimated by extrapolation to zero amplitude. They found a rapid increase in acuity from 1.5 c/deg at 1 month to 20 c/deg at 12 months. However, infants 6 months to 1 year of age failed to reach adult levels measured on the same apparatus.

De Vries-Khoe and Spekreijse (1982) measured the response to briefly presented checkerboard patterns in large groups of observers from 2 months of age through late adulthood. They found two phases in the development of VEP acuity: one ending at 8 months, coinciding with the time at which the peak in the VEP amplitude vs checksize function reached the adult value, followed by a slow second phase of increasing acuity lasting until approximately the eighth year when adult acuities were attained.

If we assume that these VEP studies were measuring the growth of a similar function, one might ask how measurement of that underlying function could be improved. It is important to determine the normal growth function with a high degree of precision in order to support theoretical modeling of the growth process. Clinically, the degree of precision associated with age norms dictates diagnostic utility (the ability to discriminate normal from abnormal). Moreover, the limited attention span of the infant requires that the desired precision must be obtainable in a short time period.

We report results from a sample of 215 infants under one year of age obtained with an efficient swept spatial frequency technique based on digital filtering of the steady-state VEP. We have found that acuity at 1 month is substantially higher than reported in several previous studies and that approximately adult acuity levels are reached by 8 months.

METHODS

Subjects

215 normal infants were recruited from parent education classes and newspaper announcements. Infants with eye turns and eye pathologies as noted by pediatricians were excluded, as were infants whose birthdate was not within two weeks of term. Five adults, corrected to emmetropia, were also tested.

Experimental procedure

Infants were seated comfortably in their parent's lap. Infants 0–2 months old were placed 65.5 cm from the display; 2–4 month old infants were tested at 131 cm, and infants 5 months and older were usually tested at 262 cm. The infant wore a Velcro headband which held Grass gold cup electrodes to the scalp. A bipolar placement of 1 cm above the inion and 3 cm to the right at the same level was used.

Four experimental conditions varying grating temporal frequency were presented in a loosely randomized order. We attempted to obtain at least three trials in a given condition before testing another condition. Only data taken at 12 contrast reversals per second will be discussed.

Fixation control

The infants' attention was attracted to the screen by a small bell or toy which was dangled 1–2 cm in front of the screen throughout each 10 sec recording. The experimenter judged whether or not the infant was fixating the toy: eye position shifts were noted, along with gross motor activity to reject trials or portions of trials on which these events occurred.

Although this toy might tend to occlude the central fovea, it served to keep the infants fixation and accommodation on the screen for the full length of the trial—beyond the point when the swept grating became invisible.

Apparatus

Recording. The EEG was amplified by either a Grass P15 or P511 EEG amplifier with a gain of 1000 followed by an Analog Devices 284-J isolation amplifier with a gain of 10. Filter corner frequencies were 3 and 100 Hz at −3 dB. The recording system consisted of a hardware interface module and an Apple II + microcomputer. An analog data acquisition board contained an additional self-ranging gain stage providing 1 to 100 times additional gain depending on the ambient EEG level before each trial. A/D conversion of 8 bit accuracy occurred at 200 Hz. A preliminary analysis of the amplitude of the evoked response during the 10 sec trial was presented to an experimenter who also monitored the EEG for artifacts and lost electrodes. The preliminary analysis also included the amplitude of the EEG noise during the trial at a frequency slightly different from the response frequency (see Analysis Techniques). Broadband EEG artifacts such as electrode motion and muscle spikes produced elevations in both noise and signal frequencies, whereas the evoked response elevated only the response frequency.

Display. Vertical sinewave luminance gratings were presented on a TECO 12" video monitor, and were switched in counterphase at 12 contrast reversals per second (rps). Mean luminance was 80 cd/m^2 at a nominal Michelson contrast of 80%. The display maintained the full contrast value to at least 100 cycles per screen (20 c/deg at 262 cm) as measured with the 1.5 arc min slit of a Spectra Pritchard photometer. The display was carefully adjusted so as not to produce changes in mean luminance (flicker) correlated with pattern reversal, which was a temporal square wave. The experiments were conducted in a low ambient illumination.

Spatial frequency sweep. Presentation of a spatial frequency sweep was controlled by the Apple II + software. Every 0.5 sec, for a period of 10 sec, the voltage-controlled frequency input to an Exact 506 function generator was linearly incremented. The spatial frequency was thus changed every 0.5 sec in a linear sweep, with each change of spatial frequency synchronized to the video frame. Sweep ranges could be selected by the experimenter to cover the expected acuity range of the infant being tested, with a 20:1 range being the largest and a 4:1 range the smallest. At 65.5 cm the 20:1 range corresponded to a linear sweep from 0.5 to 10 c/deg; at 262 cm, 2–40 c/deg. Field sizes were 20, 10 and 5 deg at 65.5, 131 and 262 cm viewing distances respectively.

Each trial was preceded with 1 sec of grating reversal at the lowest spatial frequency of the sweep, allowing the visual system to reach steady state before the sweep was started. A linear sweep of spatial frequency was chosen because this results in fine sampling through the high spatial frequencies corresponding to the acuity limit. A linear spatial frequency sweep can also be justified on theoretical grounds inasmuch as Campbell and Green (1965) have shown that log contrast sensitivity falls off linearly with spatial frequency and it is believed that VEP amplitude is linearly dependent on log contrast near threshold (Campbell and Maffei, 1970; Campbell and Kulikowski, 1972). Thus, the VEP should fall off linearly with linear spatial frequency.

The alternative strategy of sampling spatial frequencies in random order would tend to stimulate different spatial channels (cf. Blakemore and Campbell, 1969) for each test spatial frequency, requiring extra time per sample to allow the system to reach steady-state. In a linear sweep, the stimulus is likely to activate channels in smooth succession, remaining within the same channel for considerable periods, particularly at the acuity limit. It might be argued that a logarithmic sweep would be preferable since the sweep would spend a more equal amount of time in each channel if the channels have equal bandwidths on a log scale (e.g. Wilson, 1978; De Valois *et al.*, 1982). Although the log sweep may more adequately address the time-per-channel issue, it is hard to justify theoretically as discussed above. Empirically, the log sweep sacrifices resolution near the acuity limit and small amounts of noise contaminating the points used in the regression will produce greater variability in the acuity extrapolations.

ANALYSIS TECHNIQUES

Detection of the evoked response: Fourier analysis of response and noise frequencies

The amplitude and phase of the evoked response were determined using a discrete Fourier transform algorithm. The raw EEG was multiplied by sine and a cosine waves whose frequency was equal to the reversal rate of the pattern (i.e. twice the modulation frequency). These products were then accumulated over a 1 sec epoch. The stimulation frequency was an integer sub-multiple of the analysis epoch. The mean sine and cosine coefficients were computed by dividing the accumulated product by the number of reversals per sec. We have plotted the amplitude and phase obtained in this manner at the mean spatial frequency during each 1 sec epoch. This has the advantage of making the filtering insensitive to the direction of the sweep. Any hysteresis observed would then be due to neural mechanisms. With analog devices (e.g. Regan, 1975; Tyler *et al.*, 1979; Nelson *et al.*, 1984) the data is effectively plotted at the *end* of the analysis epoch with a resulting instrumental hysteresis. The same analysis was applied to a second Fourier frequency of 14 Hz which was also an integral multiple of the analysis epoch and hence orthogonal to the 12 Hz response frequency. The amplitude during the trial at 14 Hz was used in forming a signal to noise ratio criterion and for artifact rejection as described below.

The 1 sec analysis window moved through the 10 sec trial record in 1/2 second increments, yielding 19 datum points. Each point plotted thus contained 50% of the data from the previous data window (see Fig. 1). The 50% overlap provided reasonable smoothing of the VEP amplitude vs spatial frequency function without excessive computation. Phase values are plotted modulus 2π in the lower panels in Figs 1–5. Phases run from $-\pi$ at the bottom to $+\pi$ at the top. Thus, at the modulus boundaries, phases are plotted as both $+\pi$ and $-\pi$. A continuous phase contour can be visualized by shifting a segment of the phase contour by 2π so that the contours match.

Signal vs noise discrimination and acuity extrapolation

Three types of criterion had to be met to regard a signal as representing a scorable VEP response. The

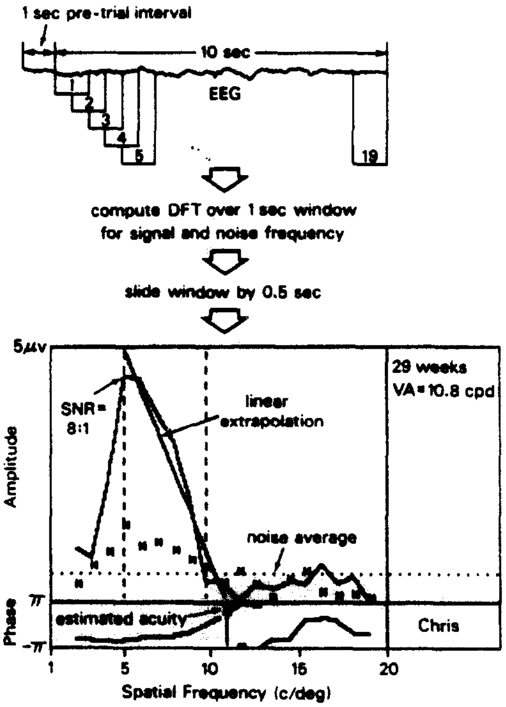

Fig. 1. Evoked potential analysis. The amplitude and phase of the response at the pattern reversal rate were extracted from the raw EEG over the 10 sec of the spatial frequency sweep by a discrete Fourier transform. The transform was calculated over a sliding rectangular data window 1 sec in duration, with each window overlapped 50% with the previous window. Each 1 sec analysis epoch contained the average of 0.5 sec of response from two linearly placed spatial frequencies presented during each 1 sec window. The EEG was processed for the amplitude of the 2nd harmonic of the modulation frequency (pattern reversal frequency) and an adjacent noise frequency (full line and N's respectively in the upper panel. Phase is plotted from $-\pi$ to $+\pi$ on the ordinate of the lower panel. The signal to noise ratio was calculated by comparing the amplitude at the response frequency with the average noise amplitude (dotted line). Acuity was estimated as the zero microvolt intercept (arrow) or a linear regression (slanting line) on amplitude versus spatial frequency.

amplitude had to be sufficiently large relative to the mean noise at the auxiliary frequency, the phase of the response had to conform to certain criteria to be discussed, and there had to be no evidence of local artifacts at the acuity limit.

Empirical sampling distribution for the signal to noise ratio criterion

A convenient response amplitude measure to calculate is the signal to noise ratio (SNR), that is, the power present at the response frequency vs that present during the test at the adjacent "noise" frequency. In order to determine a significance criterion for evoked potential SNR an empirical sampling distribution was constructed for a large number of samples of EEG noise as follows.

The mean amplitude of the narrow band EEG was calculated for 100 samples of the 10 sec recording periods and a probability distribution was formed for deviations from the mean of 1 sec samples, expressed in terms of multiples of the mean amplitude for the 10 sec epoch. It was found that the probability of the noise in an individual 1 sec bin exceeding an SNR of 2:1 over the mean of a 10 sec sample was 4.5%. At an SNR of 3:1 the probability of a false signal alarm to 0.3%. The 1 sec samples used were 50% correlated with their neighbors, as are the samples in the actual analysis. A 0.3% false alarm rate provides an adequate protection level for multiple tests when combined with the phase consistency criteria below.

Phase characteristics of the VEP vs those of narrow-band EEG noise

By definition, the phase distribution of Gaussian noise is uniform over the interval of 0 to 2π. In the narrowband noise which results from the Fourier filtering of the EEG the phase varies continuously. An evoked response however is characterized by its phase locking or synchronization with the stimulus. Thus, a constant phase is inconsistent with noise but is characteristic of an evoked response.

The phase of an evoked response may also progressively lag as spatial frequency increases due to visual system latency changes (Parker and Salzen, 1977a,b; Vassilev and Strashmirov, 1980). Thus physiologically consistent response phases are either constant over a considerable period or gradually lagging the stimulus as spatial frequency increases. No part of the record which showed a progressive phase lead was therefore scored for visual acuity. Phase lags are indicated by an upward movement on the phase plots for the VEP tuning functions in Figs 1–5.

Artifact rejection

If the EEG spectrum is locally flat, the EEG amplitude at an adjacent frequency can be used as an indicator of the background noise at the response frequency *during* the trial (see Empirical Sampling

Table 1. Analysis of variance for the difference in amplitude between response (12 Hz) and noise (14 Hz) frequencies in the absence of an evoked response

Age group (weeks)	Amplitude at 12 Hz (μV)	Amplitude at 14 Hz (μV)	F
6–10	0.93	0.71	$F_{1,17} = 1.72$ ($P > 0.05$)
16–30	2.06	1.93	$F_{1,18} = 0.14$ ($P > 0.05$)
31–52	2.17	2.13	$F_{1,25} = 0.4$ ($P > 0.05$)

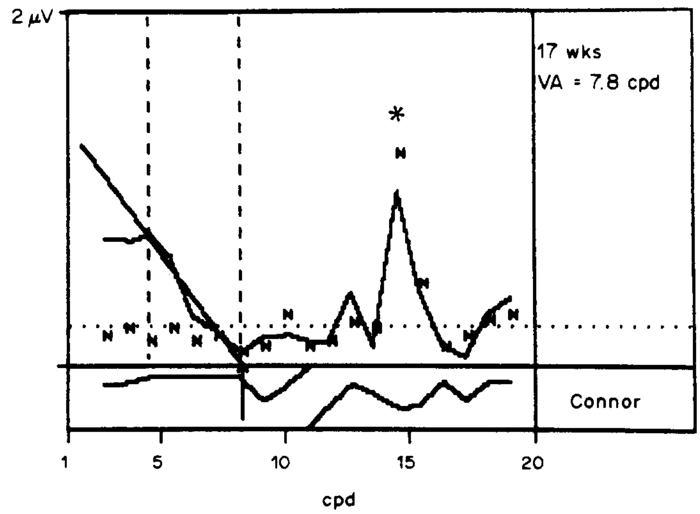

Fig. 2. Example of a broad-band EEG movement artifact at 7 sec (asterisk), which elevated both response and noise frequencies. The earlier spatial frequency peak at 5 c/deg was used for the acuity estimate.

Distribution section). The noise frequency was not allowed to be closer than 1 Hz, since the full bandwidth of the 1 sec rectangular data window is ± 1 Hz around the response frequency. The response and noise frequencies are independent in the analysis, and should have the same mean amplitude in the absence of a signal. This was verified empirically for 12 and 14 Hz by calculating the power at 12 vs 14 Hz at the end of the 10 sec sweep trial. Table 1 presents 3 one way analyses of variance of the amplitude at the two frequencies performed for groups of 4–10, 16–30 and 31–52 week-old infants. Amplitudes were calibrated in reference to a 1 V synchronous sine-wave and are expressed as the modulus of the sine/cosine vector. In no case was there a significant difference in the amplitude at the response and noise frequencies. The comparability of amplitudes at 12 and 14 Hz can also be seen in the portions of the records above the estimated acuity limit in Figs 1–5. In frequency regions of the EEG which are not locally flat (below about 10 Hz in infants, Sterman *et al.*, 1977, Moskowitz and Sokol, 1980) it may be advisable to use two noise frequencies placed symmetrically about the stimulus frequency.

Figure 2 shows a broad-band artifact (asterisk) which elevated both the response and noise frequencies. The peak in the neighborhood of the artifact was rejected for scoring and the estimate of acuity was made on the initial portion of the record which showed no artifact.

Acuity extrapolation

For our acuity estimate the spatial frequency of the grating was swept well beyond the putative acuity for the infant's age. The highest spatial frequency peak meeting all our SNR and phase criteria was chosen for extrapolation. A linear regression line was calculated on the data between the spatial frequency of the last peak and the spatial frequency at which the signal crossed the noise level [Fig. 5(B) and (D)]. These points and the regression line were determined automatically from the amplitude function but could be adjusted by the experimenter if other signal criteria were not met. The spatial frequency at which the regression line crossed zero microvolts (arrows Figs 1–5) was taken as the estimate of VEP acuity.

RESULTS

Data acceptance criteria

In order for a sweep response to be scored, the infant had to have attended to at least 7 sec of the 10 sec trial. Only those portions of the trial to which the infant was attending were scored. Sections of the trial record with EEG artifacts were also eliminated.

Amplitude and phase as a function of spatial frequency

Several spatial frequency sweep records are shown in Fig. 3. The simplest form (panel A) consists of a response which is largest at the lowest spatial frequency, decreasing monotonically with increasing spatial frequency. Another common form (panels B and C) is a response that peaks at a single spatial frequency with declining amplitudes on either side of the peak, as reported by Sokol and Dobson (1976) and Sokol (1978) for reversing checkerboards. Phase is constant at the peak, as has been reported by Tyler *et al.* (1979), but generally lags progressively as spatial frequency increases to the acuity limit (Fig. 3, lower segment of each panel).

Multiple spatial frequency peaks

The third common form of spatial frequency tuning contains multiple spatial frequency peaks as has been reported in adult human (Tyler *et al.*, 1978; Tyler *et al.*, 1979; Apkarian *et al.*, 1981) and monkey (Nakayama and Mackeben, 1982). Figure 4 shows several examples of multiple peak functions for our

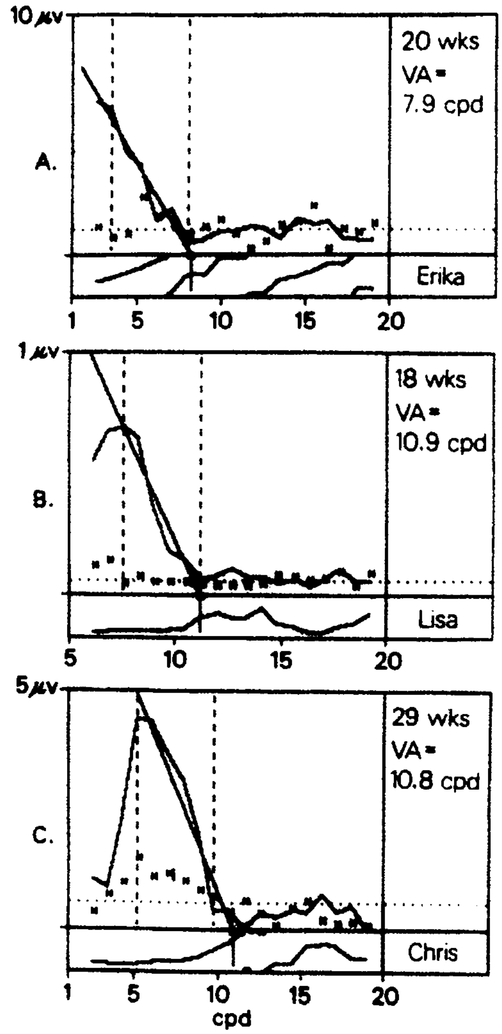

Fig. 3. Prototypical spatial frequency sweep records for three infants who showed a single response peak in the VEP amplitude versus spatial frequency function. Phase is constant at the peak, but generally shows a progressive phase lag with increasing spatial frequency.

pattern reversal stimulus from 3 infants. The first two records for each infant are individual 10 sec sweeps, while the third is the vector average of all trials obtained under the same stimulus conditions. In a vector average the amplitude and phase of the response are calculated based on the mean of the sine and cosine coefficients for the individual trials comprising the average. This is in contradistinction to an average of the amplitudes of the individual trials. Vector averaging (with the same phase reference on each trial) has the advantage of narrowing the effective bandwidth of the analysis in direct proportion to the number of trials averaged. Multiple spatial tuning has been observed in the present population at all ages and spatial frequency ranges, although it is more common in older infants.

Multiple peaks and the estimation of visual acuity

The occasional presence of more than one spatial frequency peak leads to a reconsideration of Sokol's (1978) extrapolation technique and shows the need for fine sampling of the spatial frequency response function when reversing gratings are used. Sokol obtained widely placed spatial frequency samples (check sizes) assuming a reciprocal inverted V-shaped tuning function with a linear fall-off of VEP amplitude towards smaller check sizes. The highest spatial frequency (7 c/deg Fourier fundamental) used by Sokol (1978) was a factor of 5 below the highest acuity estimated. Inappropriate sampling of either the single peak or multiple peak functions obtained with reversing gratings can lead to erroneous acuity estimates (Fig. 5).

Figure 5(A) shows a single broadly tuned peak in the VEP amplitude vs spatial frequency function. To the left of the hatched area is the portion of the response below 8 c/deg. An extrapolation on the decreasing portion of this curve would lead to an acuity estimate of 24.3 c/deg. This is a considerable over-extrapolation since it is apparent that the measured response falls away much more rapidly above 8 c/deg than it does between 1 and 8 c/deg. Figure 5(B) shows how our approach to the extrapolation would avoid this overestimation problem.

Figure 5(C) shows an example of how sampling a limited portion of the VEP amplitude vs spatial frequency function could lead to an underestimation of acuity. If samples were obtained between 1 and 7 c/deg, only the first peak in the amplitude versus spatial frequency function would have been observed, yielding an apparent acuity of 7.9 c/deg. Sampling the tuning function to 20 c/deg as in Fig. 5(D) leads to an acuity estimate of 13.4 c/deg based on the existence of a second amplitude peak at 10 c/deg.

VEP Grating acuity as a function of age

Of the 215 infants tested at 12 rps, 197 (92%) yielded records satisfying all the SNR and phase consistency criteria. Each infant's VEP acuity estimate is shown in Fig. 6 as the highest value obtained by extrapolation on either an individual sweep or on the vector average of all sweeps at 12 rps. Figure 7 shows the 95% confidence band for mean VEP acuity in one month bins. Datum points are plotted at the mean age for the bin (e.g. the first bin covers 1–4 weeks, with the mean age being 2.5 weeks). VEP acuity gradually increases from 4.5 c/deg at 2.5 weeks to 22.0 c/deg at 50.5 weeks.

Note that the extrapolated acuity typically fell only about one quarter to one half octave above the highest spatial frequency at which a significant SNR was obtained (Figs 1–5). Even if this frequency had been taken as the acuity estimate, the qualitative conclusions we have reached would still hold.

Sweep VEP acuity in adults

VEP acuity in the 5 adults tested averaged 24.3 c/deg (geometric mean, −1 SE = 20.76 c/deg, +1 SE = 26.67 c/deg). Infant acuities starting at

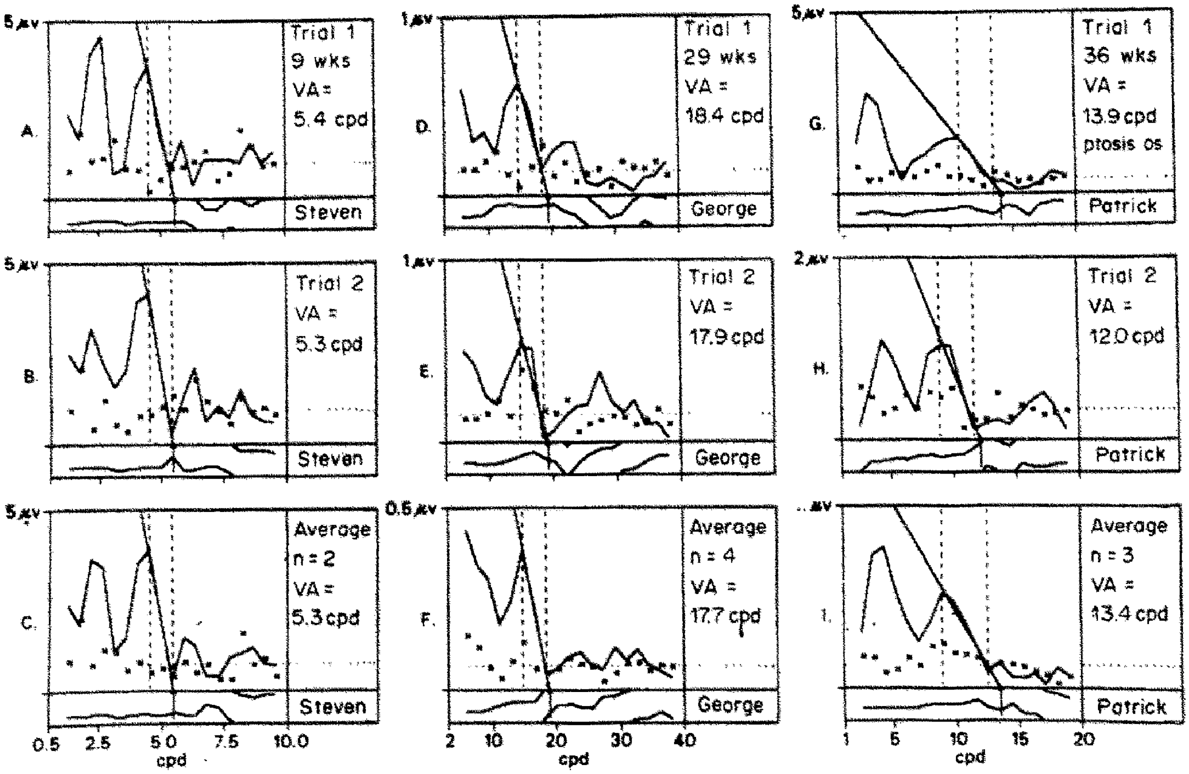

Fig. 4. Prototypical spatial frequency sweep records for three infants who showed multiple response peaks in the VEP amplitude versus spatial frequency function. Phase is roughly constant at each peak, but may differ between peaks. Upper two panels show individual 10 sec sweep records; the lower panel shows the vector average of all trials obtained under the same condition.

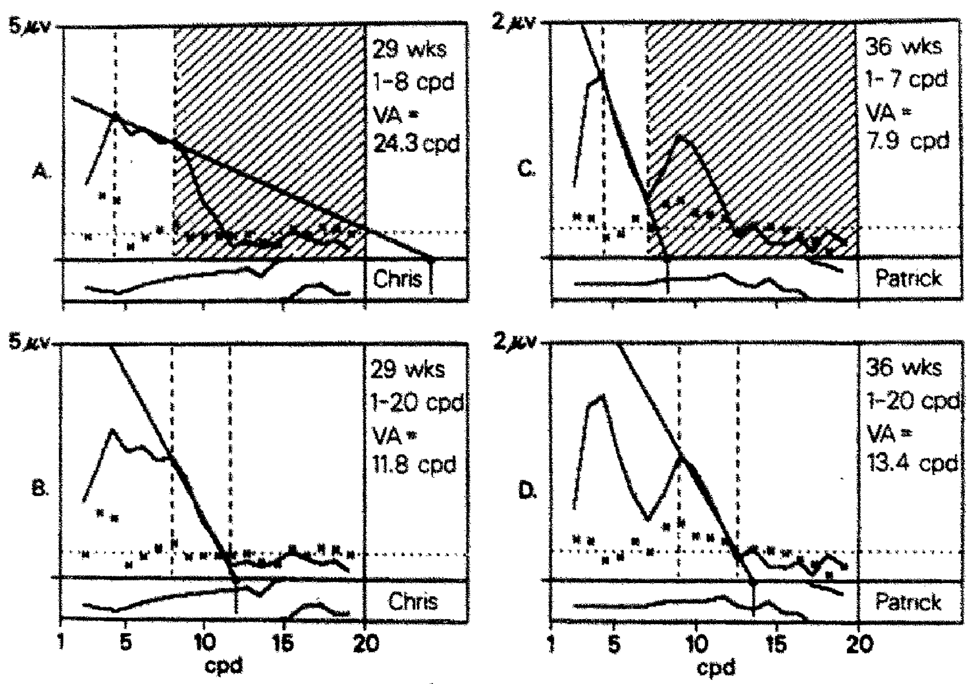

Fig. 5. Example of possible errors in VEP acuity extrapolation caused by undersampling the VEP amplitude versus spatial frequency function. In panel (A) extrapolation of the response only between 1 and 8 c/deg would lead to an overestimation of acuity. Panel (B) shows the appropriate acuity estimate made based on sampling from 1 to 20 c/deg. In panel (C) sampling only between 1 and 7 c/deg would lead to an underestimate of acuity due to a lack of information regarding a second response peak. Panel (D) shows the appropriate acuity estimate made based on sampling from 1 to 20 c/deg.

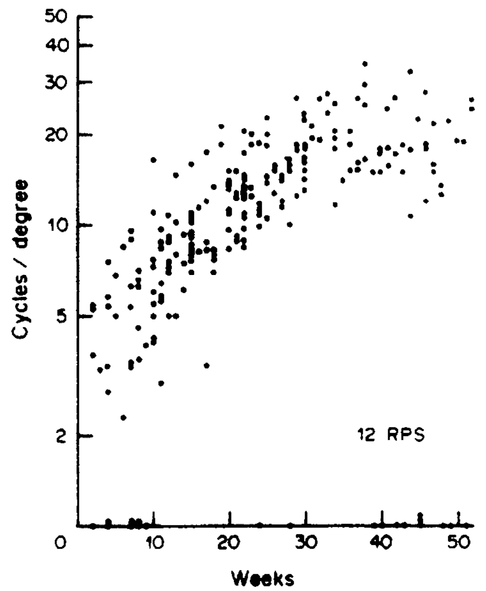

Fig. 6. Individual infants' sweep VEP acuities in relation to natal age in weeks. Datum points represent the highest extrapolated acuity value obtained from each of 197 infants on either a single 10 sec trial or from the vector average of all trials at 12 rps. Points plotted along the abscissa are from infants who did not produce a criterion response in 3 or more attempts.

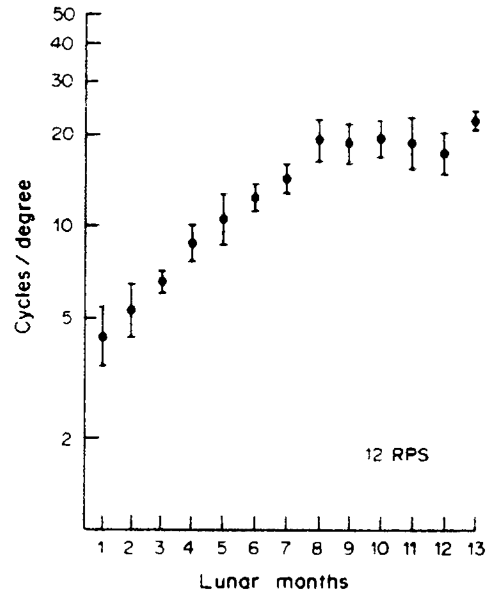

Fig. 7. The mean sweep VEP acuity with 95% confidence bands in 1 month (lunar) increments for the data of Fig. 6.

30.5 weeks are not reliably different from the adult value, with the exception of the group at 46.5 weeks ($n = 11$).

Sweep VEP cross-sectional variability

Cross-sectional variability for our sample is given in Table 2 as the population standard deviation as a function of age, along with the number of infants successfully tested at each age. The cross-sectional variability remains roughly constant across age at an average standard deviation of 0.44 octaves (0.1328 log units). Adult cross-sectional variability was similar at 0.29 octaves.

DISCUSSION

During the first year of life VEP acuity measured with swept spatial frequencies increased from 4.5 c/deg in the first month to about 20 c/deg by the end of the first year. Infant VEP acuities approach adult levels within the measurement error for the first time at 8 months. The 17–22 c/deg mean acuities for 8–13 month old infants however do not quite reach the adult mean of 24.3 c/deg, although many older infants were found to have VEP acuities at or above the adult mean. The small difference in mean acuity between the infant acuity asymptote and the adult acuity value may represent only the difficulties of recording from infants vs cooperative adults who can be expected to comply to the experimenter's instructions regarding fixation, accommodation and attention. The infant value should be regarded as a lower bound on performance rather than as a clearly defined maximum.

Comparison with previous results

The present data for growth of acuity are in qualitative agreement with other studies (Marg *et al.*, 1976; Sokol, 1978; Pirchio *et al.*, 1978; de Vries-Khoe and Spekreijse, 1982) which have found that log acuity is a rapidly increasing linear function of age during at least the first semester.

A correction to a common spatial resolution metric is necessary for accurate quantitative comparison of our results with data obtained with checkerboards. Sokol (1978), Harter *et al.* (1977) and de Vries-Khoe and Spekreijse (1982) defined resolution based on the angular subtense of single checks in their checkerboard patterns. The Fourier fundamental spatial frequency of a checkerboard is 1.4 × 30/(check size in arc min) and is oriented obliquely rather than horizontally and vertically as are the sides of the checks (Kelly, 1976). Thus, Sokol's (1978) acuity values, when corrected to their Fourier fundamental frequency, are in agreement with the present data at 2, 3 and 4 months when acuity is relatively low, and when the extrapolated acuity is near the range of spatial frequencies actually measured. Above 4 months Sokol's estimated acuities lie considerably above his last measured Fourier fundamental of 7 c/deg and progressively depart from those reported here. De Vries-Khoe and Spekreijse, (1982) found acuities of 14 c/deg Fourier fundamental over the 8–12 month age range where our acuities have asymptoted to about 20 c/deg.

The acuity of about 5 c/deg that we estimate for neonates is higher by a factor of 3–5 than that reported in several previous evoked potential studies (Marg *et al.*, 1976; Atkinson *et al.*, 1979; Beraldi

Table 2. VEP acuity and its standard deviation as a function of age. The number of infants successfully tested is indicated in the rightmost column

Lunar months	Log acuity (c/deg)	Standard deviation (log units)	Linear acuity (c/deg)	*n*
1	0.6545	0.1427	4.5	9/12
2	0.7370	0.1775	5.45	15/19
3	0.8276	0.1649	6.72	25/25
4	0.9547	0.1148	9.0	21/21
5	1.0329	0.1779	10.78	21/21
6	1.1001	0.1095	12.63	27/28
7	1.1650	0.0937	14.62	17/18
8	1.2903	0.1219	19.5	13/13
9	1.2800	0.1121	19.0	11/11
10	1.2901	0.1957	19.5	12/13
11	1.2740	0.1375	18.8	10/12
12	1.2362	0.1135	17.2	11/15
13	1.3421	0.0645	22.0	5/7
	Mean	0.1328		197/215

et al., 1981; Pirchio *et al.*, 1978; Fiorentini *et al.*, 1984; Porciati, 1984). Harter *et al.*'s (1977) results indicate that a 3.8 c/deg flashed checkerboard produces a larger response than a flash alone over this age range. Since the flashed patterns also contained luminance modulation it is not clear what the corresponding acuities were as smaller patterns were not tested.

The most likely explanation for our high acuities in young infants may lie in the speed with which our acuity estimates are made. State changes, which are rapid and pronounced in the very young infant, may lead to serious problems with stationarity of the response. Very young infants are more likely to be in a constant state over the 10 sec trial required for sweep acuity measurements than for the longer periods needed when conventional signal averaging of discrete spatial frequencies is used.

Our acuity estimates establish minimum levels of resolution rather than clearly defined limits. It is conceivable, for example that higher acuities could have been obtained by using more than one electrode placement to sample the brain response (Tyler *et al.*, 1981) or a fixation control technique which allowed consistent stimulation of the central fovea. It should also be noted that the infants were tested without optical correction, so our results reflect the functional acuity of the infant population rather than potential neural acuity. Differences in stimulation and analysis techniques as well as contrast and luminance conditions vitiate more detailed quantitative comparisons between the available VEP acuity studies, although infants in the second semester are consistently found to be receiving and at least partially processing information over an adult-like spatial bandwidth.

Clinical implications

The high level of pattern resolution found in infants using the VEP has rather strong implications for the magnitude of optical defocus which would result in deprivation of patterned input to visual cortex. VEP acuity measurements provide a *conservative* estimate of the spatial bandwidth of the input to cortex and of the optical bandwidth of the eye. From the present VEP data and that of others, it is clear that the cortical pattern threshold and thus the optical bandwidth of the eye is at least 20 c/deg by 8 months.

Unequal refraction between the two eyes or between meridians is believed to cause amblyopia if the error is "large" and present during the critical period (Jampolsky, 1978). Since VEP acuities are adult-like by 8 months one might expect that the presence of relatively modest amounts of anisometropia during the second semester could lead to amblyopia. Gwiazda *et al.* (1984) have recently reported a prospective study of acuity development in infants with a history of large astigmatic errors early in life. They presented data from a group of children who were astigmatic at age 6 months but had lost most of their refractive error during early childhood. Several of these children were found to be amblyopic when tested at age 6 although they had not shown evidence of meridional amblyopia when tested behaviorally at age 6 months (Held, 1978). Since our results show near adult cortical resolution by the age of 6–12 months, it is reasonable to assume that the meridional amblyopia had developed in this period, when the astigmatism was present, at spatial frequencies above the behavioral threshold. This interpretation would place the start of the critical period for meridional amblyopia within the first year of life, rather than after it as suggested by Held (1978).

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