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Research Note

Temporal Contrast Sensitivity in Human Infants

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Temporal contrast sensitivity was measured in 1.5- and 3-month-old infants using the FPL procedure. Stimuli were 0.1 c/deg counterphase-flickering sinewave gratings. Temporal rates ranged from 1 to 20 Hz. Because the spatial sinewave underwent phase shifts of 180°, the target could not be seen unless the observer was able to resolve it temporally. Adults were tested with the same temporal stimuli using a 2-alternative forced-choice procedure and a spatial frequency of 0.5 c/deg. Adult temporal CSFs were bandpass with peak sensitivity at 10 Hz. Infant temporal CSFs were lowpass at 1.5 months and bandpass at 3 months. The infants' contrast sensitivity was over a log-unit lower than adults'. Unlike spatial CSFs, infant sensitivity was closest to adult sensitivity at the highest flicker rate.

Infant vision   Infant temporal vision   Temporal contrast sensitivity

INTRODUCTION

The temporal contrast sensitivity function (CSF) represents an observer's sensitivity to sinusoidally flickering stimuli as a function of temporal frequency. In adults, this function varies with stimulus conditions, but is generally bandpass. At photopic luminances, sensitivity rises smoothly from low frequencies to a peak at about 10 Hz and then falls smoothly to the high frequency cut-off at about 60 Hz (also referred to as the critical flicker frequency or CFF). Temporal CSFs represent a general index of the visual system's ability to process time-varying information, because, in conjunction with linear systems analysis, they can be used to predict sensitivity to a wide variety of flickering stimuli (e.g. De Lange, 1958). It is also well-known that temporal contrast sensitivity varies with the spatial properties of a stimulus. For example, the spatiotemporal CSF in which temporal and spatial frequency are changed independently reveals that temporal sensitivity varies in bandpass fashion at low spatial frequencies and in lowpass fashion at high spatial frequencies (Kelly, 1969).

The CFF of human infants has been estimated electrophysiologically and behaviorally. The most informative of the electrophysiological studies have used the electroretinogram (ERG). In adults, a measurable ERG can be obtained at quite high flicker frequencies. Indeed, adult CFFs measured in this way are similar to those measured psychophysically (Dodt & Wadensten, 1954; Heck, 1957). Heck and Zetterström (1958) and Horsten and Winkelman (1961, 1964) used ERGs to measure CFFs in 1-day-old to 2-month-old infants. They used large, unpatterned fields flashed at varying temporal rates. Both groups observed ERGs at all ages tested. According to Heck and Zetterström, CFF increased with age from 15 Hz at 1 day to adultlike values of 56 Hz by 2 months. Horsten and Winkelman observed nearly adultlike values at all ages tested. The discrepancy between these two studies is probably due to variations in methodology, particularly adaptation state of the subjects. Nonetheless, the ERG studies suggest that the retina is able to signal rapid temporal changes with adultlike precision by 2 months of age or earlier. ERG measurements, however, do not tell us what the visual system as a whole is able to resolve.

Infant flicker perception has also been studied with behavioral methods (Nystrom, Hansson & Marklund, 1975; Regal, 1981; Mercer & Adams, 1989). Nystrom *et al.* (1975) presented unpatterned flickering stimuli side by side to 1.5-month-old infants. Although their paired-comparison technique does not allow an estimation of threshold, their findings indicate that infants as young as 1.5 months have the ability to distinguish flicker at rates as high as 20 Hz. Regal (1981) estimated CFF in 1-, 2- and 3-month-old infants using the forced-choice preferential looking (FPL) paradigm (Teller, 1979). Average CFF estimates were 41 Hz for 1-month-olds, 50 Hz for 2-month-olds, 51 Hz for 3-month-olds and 53 Hz for adults. Regal concluded that CFF is essentially adultlike by 2 months. Mercer and Adams (1989) used

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FPL to estimate CFFs in 3-month-old infants for blue and red isochromatic stimuli. Infant CFFs were about 22 Hz for both stimuli while adult values were about 38 Hz. These findings appear to contradict Regal's, because infant CFFs were much lower than adult.

Temporal CSFs have also been estimated in infants. Recently, Swanson and Birch (1990) measured temporal CSFs in 4-, 6-, and 8-month-old infants using an FPL procedure. Their stimuli were localized grating patches. They estimated thresholds at two spatial frequencies (1.0 and 0.35 c/deg) and four temporal frequencies (2, 4, 8, and 17 Hz). Temporal CSFs were bandpass at 1.0 c/deg at 6 and 8 months, but lowpass at 4 months. At 0.35 c/deg, CSFs were bandpass at all ages. Perhaps more importantly, temporal contrast sensitivity was much reduced at both 4 and 8 months relative to adults. Swanson and Birch could not account for their results by modeling developmental changes in photoreceptors, i.e. either changes in photoreceptor spacing or reductions in quantal catch, or both (Banks & Bennett, 1988; Wilson, 1988). Hence, their data imply changes in spatio-temporal mechanisms and temporal tuning functions from 4 months to adulthood.

The purpose of the present study was to estimate temporal CSFs in younger infants. We presented a very low spatial frequency, counterphase-flickering sinewave grating to 1.5- and 3-month-old infants and estimated detection thresholds at various flicker rates.

METHODS

Subjects

Subjects were recruited by letter and phone. A total of 12 1.5-month-olds and 27 3-month-olds were tested. Contrast thresholds were measured at five temporal frequencies. Twelve of the 1.5-month-olds and 17 of the 3-month-olds provided at least one threshold. Six infants from each age group provided three or more thresholds. Data from these 12 subjects are reported here. Slightly more than five sessions were required for the 1.5-month-olds to complete three or four threshold measurements and slightly more than six sessions were required for the 3-month-olds. The average age at the midpoint of testing was 41.8 days (SD = 1.5) for the 1.5-month-olds and 83.5 days (SD = 3.8) for the 3-month-olds. Three adults were tested in the same apparatus. All adults were emmetropic or corrected to normal vision.

Stimuli

The stimuli were counterphase-flickering sinewave gratings. Because the spatial sinewave underwent phase shifts of 180°, the target could not be seen unless the observer was able to resolve it temporally.

The signals were generated by a combination of function generators and a custom pattern generator. Stimuli were displayed on a Hewlett–Packard 1371A CRT (P31 phosphor). The display was $64 \times 44°$ at the infants' viewing distance of 32 cm. Time-average luminance was 10.6 cd/m^2. The linearity of the display and stimulus contrast were measured *in situ* by a calibrated photometer. The display was the only source of illumination in the testing room. The spatial frequency of the target was always 0.1 c/deg and the temporal frequency of the counterphase modulation was varied from 1 to 20 Hz. All infants were tested at 1, 5, and 20 Hz; some were tested at 2 and 10 Hz as well.

The display was split electronically at midline in order to present the flickering stimulus on one side, while a non-flickering uniform field of the same time- and space-average luminance was presented on the other side. Stimulus contrast was varied by means of a programmable attenuator. Side of presentation and contrast were controlled by PDP-11/04 minicomputer, which also recorded the observer's responses.

Procedure

Contrast thresholds were estimated using the FPL procedure. An adult observer (author EEH) held the infant in front of the display screen at a distance of 32 cm. The observer's view of the display was occluded by a curtain. The observer could see the infant's face in a mirror that was suspended above the display.

A trial consisted of the following sequence of events. An assistant attracted the infant's attention to the center of the screen by holding a small toy at midline. At a signal from the observer, the assistant lowered the toy from view. Simultaneously, the observer depressed a foot switch to begin a stimulus presentation. The infant was allowed to look at the screen as long as required for the observer to make an FPL judgment of the position of the flickering stimulus. The observer responded by depressing one of two additional foot switches. Feedback was provided after each trial. Individual trials could be discarded if the infant became fussy or inattentive before the observer made an FPL judgment.

Stimulus contrast was varied according to a modified method of constant stimuli. Generally, 20 trials were presented at each of three contrast levels that differed by 0.3 log-units. The computer randomly selected, without replacement, one of the three levels at the beginning of each block of three trials. The computer was programmed to inspect the data after the first 30 trials, 10 at each contrast level. The purpose of this check was to determine if the 70% point on the psychometric function had been encompassed. If it had not, we presented a new contrast level in the remaining trials. If performance at all contrast levels was above 70% in the first 30 trials, the new contrast level was 0.3 log-units below the lowest initial level. If performance at all levels was below 70%, the new level was 0.3 log-units above the highest previous one. If we decided not to change stimulus contrast, 30 more trials were run at the original levels. This second set of trials was again 10 blocks, 3 trials per block. However, if we decided to change contrast level, we presented 20 trials at the new level and 10 trials at each of two adjacent initial levels. In this case, each block consisted of four trials, two at the new level and one at each of the previous levels. Again, a total of 10 blocks was presented.

Probit analysis (Finney, 1971) was used to estimate the 70% point on the resulting psychometric function. If the probit routine could not estimate a threshold, the data were discarded.

Adults were tested in the same apparatus. The stimuli on the screen were the same as those presented to the infants. The viewing distance was increased to 175 cm, so the spatial frequency was 0.5 c/deg. The purpose of changing the viewing distance was to test a spatial frequency that fell roughly at the same position relative to the peak of the adult spatial CSF, as 0.1 c/deg did relative to the infant peak. Thresholds were estimated using a 2-down/1-up staircase procedure with 18 reversals. Threshold was the average of the contrasts at the last 16 reversals, which corresponds to the 71% point on the psychometric function (Wetherill & Levitt, 1965). Adults initiated trials and judged target locations themselves. Feedback was provided at the end of each trial. The adults were tested twice on all five temporal frequencies. Thresholds were averaged across the two sessions for each observer.

RESULTS

Individual temporal CSFs are shown in Figs 1 and 2 for the 1.5- and 3-month-olds, respectively. Contrast threshold estimates from 6 infants are plotted by temporal frequency of the stimulus for each age group. The data from the younger infants are quite variable: some of these infants exhibited apparently lowpass functions and some apparently bandpass functions. The older infants' data are less variable: all but one of them exhibited an apparently bandpass function.

The average contrast sensitivity values for the adults and both groups of infants are shown in Fig. 3. The adult data are bandpass, as expected, and exhibit much higher sensitivity than the infants. The average 1.5- and 3-month sensitivities are similar at 1 Hz, but 3-month sensitivity is about two times higher at both 5 and 20 Hz. As a consequence, the average temporal CSF for the 3-month-olds appears bandpass, while that for the 1.5-month-olds does not, at least for the range of frequencies tested.

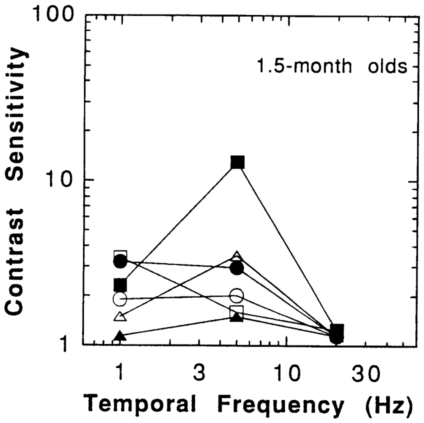

FIGURE 1. Temporal CSFs at 1.5 months. Contrast sensitivity is plotted against flicker rate.

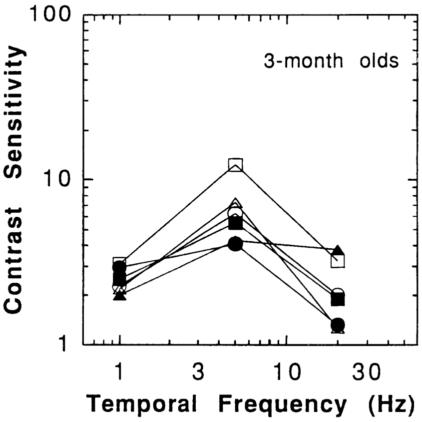

FIGURE 2. Temporal CSFs at 3 months. Contrast sensitivity is plotted against flicker rate.

Figure 3 implies that overall temporal contrast sensitivity increases with age and that the shape of the threshold function changes with age. To examine the statistical reliability of these trends, we conducted two repeated measures ANOVAs on the individual subject data. The first included all three age groups as a between-subjects factor and temporal frequency (three rates) as a within-subjects factor. The main effects of age ($F = 29.69$, $P < 0.0001$), temporal frequency ($F = 20.70$, $P < 0.0001$) and the age × temporal frequency interaction were significant ($F = 15.05$, $P < 0.0001$). The second ANOVA included only the two infant age groups as a between-subjects factor with temporal frequency (three rates) as the within-subjects factor. The main effects of age ($F = 6.30$, $P < 0.031$) and temporal frequency ($F = 15.50$, $P < 0.0001$) were significant; the age × temporal frequency interaction approached significance ($F = 2.97$, $P < 0.075$). *Post hoc* comparison of means (Tukey's Studentized Range) demonstrated a significant difference ($P < 0.05$) between the 1.5- and 3-month-old infants at 20 Hz only.

The temporal CSF seems to become more bandpass with age. This apparent shape change is further illustrated in Fig. 4 which plots the ratio of adult/infant contrast sensitivity as a function of temporal frequency.

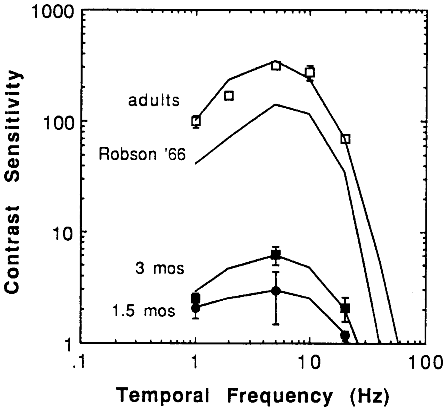

FIGURE 3. Average temporal CSFs for 1.5- and 3-month-olds and adults. Error bars represent standard errors of the mean. The solid lines are best fits of the equation $ae^{-f/s1} - be^{-f/s2}$. Also shown are adult data for very similar conditions from Robson (1966).

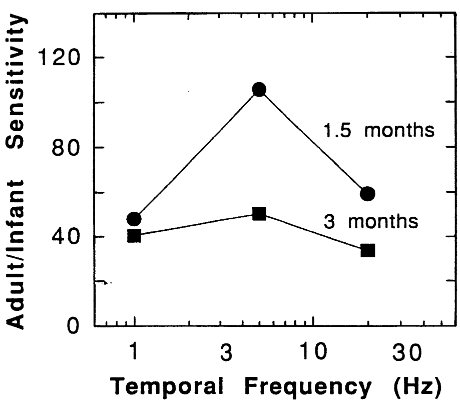

FIGURE 4. Ratios of adult to infant temporal contrast sensitivity. The ratios of average temporal contrast sensitivity are plotted against temporal frequency for adults compared to 1.5-month-olds and adults compared to 3-month-olds.

The ratio is nearly constant for 3-month-olds, implying that the shape of the temporal CSF for this age group is nearly adultlike. The 1.5-month-olds show the highest ratio at 5 Hz, implying a flatter function than the adult function.

We fit the group average CSFs with a function of the form $ae^{-f/s1} - be^{-f/s2}$. These best-fitting functions are the solid lines in Fig. 3. Extrapolation of the functions to the high frequency cut-off (contrast sensitivity equals 1.0) yields estimated CFFs of 60, 24, and 20 Hz for the adults, 3-month-olds and 1.5-month-olds, respectively.

DISCUSSION

Previous electrophysiological (Heck & Zetterström, 1958; Horsten & Winkelman, 1964) and behavioral (Regal, 1981) studies found that the highest resolvable temporal frequency—the CFF—was nearly adultlike by 2 months of age. Our data and that of Teller, Lindsey, Mar, Succop and Mahal (1992) suggest that other dimensions of temporal processing are far from mature at 1.5–3 months. In particular, contrast sensitivity for temporal frequencies below CFF are significantly different from adults'. Furthermore, Swanson and Birch (1990) reported that such immaturities persist until at least 8 months. The CFF and temporal CSF measurements, consequently, appear to be at odds with one another.

Some of the inconsistency may stem from the use of different response measures—ERG and FPL—that index different levels of processing. Specifically, it is plausible that temporal information available to the retinal sites responsible for the ERG is lost further upstream in immature central visual pathways. This argument, however, does not account for the apparent inconsistency between behavioral CFF estimates and the temporal contrast sensitivity measurements of the present study, Teller *et al.* (1992), and Swanson and Birch (1990). Although CFF and contrast sensitivity index different aspects of temporal processing, we would expect our extrapolated CFF estimates to agree with Regal's direct measurements. In fact, they are significantly lower (see Fig. 3). Differences in stimulus conditions between these two studies suggest a partial reconciliation of this discrepancy. Regal conducted his study at 34 cd/m^2, a value more than three times higher than our average luminance. Regal also used squarewave flicker whereas we used sinusoidal flicker. Hence, the fundamental contrast of Regal's stimulus was 27% higher than ours for the same waveform contrast. We examined the possibility that these differences in luminance and flicker waveform accounted for the apparent discrepancy in CFF estimates. Specifically, we estimated how the temporal CSFs reported here would have differed had the luminance been raised to Regal's level and the waveform changed to a squarewave. The shift due to the luminance difference was the square-root of the luminance ratios of the two studies, 1.79 (Kelly, 1971; Banks, Geisler & Bennett, 1987). The shift due to the waveform difference was 27%. These shifted functions are shown in Fig. 5. Once the curves are shifted vertically, the estimated CFFs increase to 29, 33 and 68 for 1.5-month-olds, 3-month-olds, and adults respectively. The infant values change more than the adult values because the high-frequency limb of the infant temporal CSFs is shallower. The open squares in Fig. 5 represent the mean CFFs reported by Regal (1981). From left to right, they are: 2-month-olds (3.4 cd/m^2); 1-month-olds (34 cd/m^2); and 3-month-olds (3.4 cd/m^2). With the shifts, estimated CFFs more closely approach those reported by Regal (1981).

The shape of the temporal CSF appears to change with age in two ways: (1) The low frequency rolloff is steeper in the average 3 month and adult data than in the 1.5-month data. (2) The high frequency rolloff is steeper in adults than in 1.5- or 3-month-olds.

We consider the low frequency rolloff first. Although the change in the steepness of the rolloff is evident in Fig. 4, averaging data across individuals can distort the shape of the underlying functions (Movshon & Kiorpes,

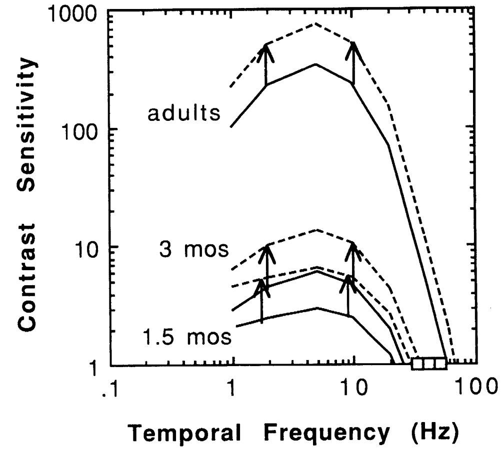

FIGURE 5. Expected contrast sensitivity for the conditions of Regal (1981). The average temporal CSFs from Fig. 3 are plotted as solid lines. The broken lines are functions shifted by the amounts expected for the luminance and waveform differences between our study and Regal's. The open squares represent the mean CFFs reported by Regal (1981). From left to right, they are: 2-month-olds (3.4 cd/m^2); 1-month-olds (34 cd/m^2); and 3-month-olds (3.4 cd/m^2).

1988). Inspection of the individual data reveals that all six of the 3-month functions exhibited a contrast sensitivity increase of 40% or more from 1 to 5 Hz, while only two of the six 1.5 month functions did. Thus, the steepness of the low frequency rolloff across that range of frequencies seems in fact to increase from 1.5 to 3 months. It remains possible that a more prominent low frequency rolloff would be observed in the younger infants at yet lower temporal frequencies. The cause of the developmental change is uncertain. It could reflect changes in the temporal tuning properties of the young visual system or in the spatial tuning properties of different temporal mechanisms. Swanson and Birch (1990) provide some evidence, albeit at different ages, in support of the second hypothesis. They showed that the effect of spatial frequency on the shape of the temporal CSF changes with age. Four-month functions are bandpass at 0.35 c/deg and lowpass at 1.0 c/deg. On the other hand, 6- and 8-month functions, are bandpass at 1.0 c/deg (and presumably bandpass at 0.35 c/deg, although they did not measure this point). Thus, as in adults, bandpass temporal functions are more common at low than at high spatial frequencies. However, the spatial frequency range over which bandpass functions are observed includes progressively higher spatial frequencies with increasing age. The age-related changes in the shapes of the temporal CSFs, therefore, might reflect changes in spatial tuning of the underlying spatiotemporal filters rather than changes in temporal tuning *per se*. A similar line of reasoning could explain the age changes we observed in the low frequency rolloff. We presented both groups of infants a fixed spatial frequency of 0.1 c/deg. This frequency is lower relative to the peak of the spatial CSF at 3 months than at 1.5 months (Atkinson, Braddick & Moar, 1977; Banks & Salapatek, 1978).

The high-frequency limb of the temporal CSF appears steeper in adults than in 1.5- and 3-month-olds [see Fig. 3 and Teller *et al.* (1992)]. The age-related change could be an artifact of averaging individual functions with peaks at different temporal frequencies (Movshon & Kiorpes, 1988). One suspects that it is not, because the individual infant functions (see Figs 1 and 2) are in every case shallower than the adult functions from 5 to 20 Hz. The cause of the apparent development change in the slope of the high frequency limb is unknown. As pointed out above, a consequence of the slope change is that estimates of CFF are very susceptible to experimental conditions and scoring criteria. It is also interesting to note that the development of the temporal CSF is quite unlike the development of spatial CSF: infants' temporal contrast sensitivity is most adultlike at high temporal frequencies whereas their spatial contrast sensitivity is most adultlike at low spatial frequencies (Atkinson *et al.*, 1977; Banks & Salapatek, 1978; Norcia, Tyler, Hamer & Wesemann, 1989; Norcia, Tyler & Hamer, 1990). Further examination of age-related changes in spatiotemporal mechanisms (Pirchio, Spinelli, Fiorentini & Maffei, 1978; Banks, Stephens & Hartmann, 1985; Wilson, 1988; Swanson & Birch, 1990) should provide an explanation of these differing developmental trends, and as a result, aid our understanding of how infants process visual information over space and time.

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