The Contrast Sensitivity of the Newborn Human Infant

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Purpose. To measure the binocular contrast sensitivity (CS) of newborn infants using a fixation-and-following card procedure.

Methods. The CS of 119 healthy newborn infants was measured using stimuli printed on cards under the descending method of limits (93 infants) and randomized/masked designs (26 infants). One experienced and one novice adult observer tested the infants using vertical square-wave gratings (0.06 and 0.10 cyc/deg; 20/10,000 and 20/6000 nominal Snellen equivalent); the experienced observer also tested using horizontal gratings (0.10 cyc/deg) and using the Method of Constant Stimuli while being kept unaware of the stimulus values.

Results. The CS of the newborn infant was 2.0 (contrast threshold = 0.497; 95% confidence interval: 0.475–0.524) for vertically oriented gratings and 1.74 (threshold = 0.575; 95% confidence interval: 0.523–0.633) for horizontally oriented gratings ($P < 0.0006$). The standard deviation of infant CS was comparable to that obtained by others on adults using the Pelli-Robson chart. The two observers showed similar practice effects. Randomization of stimulus order and masking of the adult observer had no effect on CS.

Conclusions. The CS of individual newborn human infants can be measured using a fixation-and-following card procedure.

Keywords: newborn, neonatal, contrast sensitivity, fixation-and-following, card procedure

The visual capabilities of a newborn infant can be evaluated clinically using qualitative fixation-and-following of a toy, a penlight, or the examiner's face,[1] but are not well understood quantitatively. Here, we report the first quantitative, behavioral data on the contrast sensitivity (CS) of normal full-term infants in the first days of life. Our method combined the spontaneous fixation and following behavior of newborn infants with a card procedure (CP) similar to that of the Teller Acuity Cards and a low-spatial-frequency square-wave grating of variable contrast. By careful selection of stimulus parameters, our method provided a rapid estimate of the overall CS of newborn infants.

CS Measurement

A subject's CS is the reciprocal of the Michelson contrast of the lowest-contrast stimulus that he or she can detect at some criterion level of performance. For a sine-wave or a square-wave grating, the Michelson contrast is $(max–min)/(max+min)$, where max is the maximum luminance and min is the minimum luminance of a period of the grating. If the stimulus is a stationary sine-wave grating, the adult CS function (CSF) is bandpass (Fig. 1A, blue data and curve), and multiple threshold measurements, at multiple spatial frequencies, are necessary to determine the maximum CS of which the subject is capable (e.g., Refs. 2–4). If the stimulus is a stationary square wave, the adult CSF is constant at low spatial frequencies, but still has a small peak at middle spatial frequencies (Fig. 1A, red curve and data[3]). Furthermore, the mathematics of square waves yields a CSF that is 4/Pi higher (approximately 0.1 $\log_{10}$ units) higher.[4] If the stimulus moves or flickers, the adult CSF is rigorously low-pass[2,5] (Fig. 1B). All the curves in Figure 1 were collected using gratings of constant area and therefore a variable number of cycles.

Infant CS

Some investigators have reported low-pass sine-wave CS functions for infants aged 1 to 3 months,[6,7] even when measured with steady stimuli that did not flicker or move, but others report band-pass steady sine-wave CSFs for infants of all ages.[8,9] Therefore, we do not know which adult CSF, the bandpass or the low-pass CSF (the blue or the green curve in Fig. 1), is the best general model of newborn infant CS. We chose 0.1 and 0.06 cyc/deg square-wave stimuli, which we hoped would be on a constant part of the infant CSF, no matter which adult CSF applied in the case of sine-waves. These spatial frequencies are well below the newborn visual acuity, which was 1.01 cyc/deg, averaged across eight studies.[10–18] Furthermore, the square wave should give us the 4/Pi advantage over sine-wave stimuli, which might prove critical if neonatal CS were very low.

We used a fixation-and-following CP.[19,20] In experiments I and II, we explored the impact of our initial choice of 0.1 cyc/deg and vertical orientation, using the descending method of limits. To determine whether the psychophysical method is important to the results, we performed experiment III using

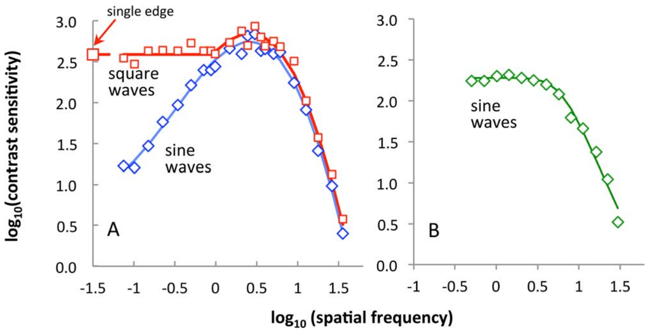

Figure 1. Adult CSFs. (**A**) steady square waves (*small red squares*), single edge (large red square), and steady sine waves (*blue diamonds*, after Ref. 3). (**B**) flickering sine wave (after Ref. 2).

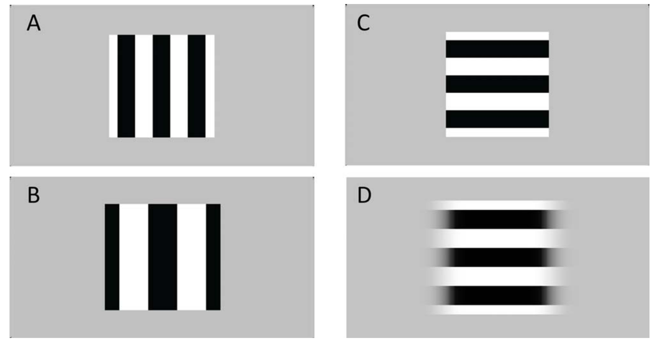

Figure 2. Stimuli, at 0.96 contrast. (**A**, **B**) vertical stimuli (experiment I); (**C**, **D**) horizontal stimuli (experiment II). The grating in (**C**) is identical to the grating in (**A**) except for 90° rotation.

randomized stimuli presented under the method of constant stimuli.

Experiment I: Pilot Data

Experiment I was designed to establish whether newborn infant CS can be measured using the fixation-and-following CP method and to determine whether there was an obvious difference in newborn infant CS measured using two low spatial frequencies of grating.

Methods

Stimuli. Each W 57 × H 30.5 cm stimulus card had a vertical grating centered on its face and a 4-mm peephole within the center of the middle dark bar of the grating (Figs. 2A, 2B).[11] Two gratings were used (Figs. 2A, 2B): a three-period grating of 3.33 cm vertical stripes (0.10 cyc/deg at 38 cm testing distance 20/6000 nominal Snellen equivalent), and a two-period grating of 5.55 cm vertical stripes (0.06 cyc/deg, 20/10,000 Snellen). Calibrated contrasts were 0.96, 0.71, 0.50, 0.35, and 0.25, and the reflectance of the gray surrounding region of each card was 0.50 ± 0.02. Fourier analysis of the horizontal modulation of 0.96-contrast vertically oriented gratings (Figs. 3A, 3B, 3E) revealed prominent energy bands with maxima of 0.96*4/Pi, at spatial frequencies of 0.06 and 0.10 cyc/deg, and full bandwidths at half height of 0.63 and 0.54 octaves ($\log_2$ units), respectively. The next-highest-contrast harmonics had contrasts of 0.32 and 0.42, respectively.

Subjects. The subjects were healthy, awake newborn infants, all under 72 hours old, of healthy mothers (by their own and nurses' report) in the postpartum unit of The Ohio State University–Wexner Medical Center (Fig. 4).

Observers. The two adult observers were coauthors on this report. AMB had over 30 years' experience in testing infants using forced-choice preferential looking (FPL) and CP; JGC was a second-year optometry student with no prior experience.

Procedure. This research protocol adhered to the tenets of the Declaration of Helsinki, and was approved by the Institutional Review Board of The Ohio State University. After a research nurse obtained informed consent from a parent, the testing team waited until the parents notified the nurse that their infant was awake. Testing took place under available light in the infant's hospital room. The median reflected light from the card was 29 cd/m^2 (range, 6–204 cd/m^2), and varied somewhat as the position of the card varied during testing. This light level is well above the 1.0 cd/m^2 required for maximum photopic visual acuity in infants.[21] The nurse held the infant so that he/she could view the cards with both eyes.

AMB and JGC alternated their roles: the "observer," performed the test and the "experimenter" handled the logistics. The experimenter arranged the cards in order, starting with either one or two 0.96 contrast "easy" cards, and handed the cards to the observer, one at a time, proceeding from higher to lower contrasts, while not allowing the observer to see the faces of the cards. The observer did not know whether there were one or two "easy" cards, so she knew the order of the cards, but not their exact values.

The observer placed each card along the infant's line of sight, at a distance of 38 cm, while watching the infant's eyes through the peephole. If the infant "locked onto" the stimulus, the observer displaced the card quickly to the right or left, by approximately 15 cm (at approximately 22°/s relative to the infant's retina), attempting to induce the infant to follow the stimulus with his/her eye or head movements, waiting several seconds for a response, if necessary. If the infant did not move his/her eyes to follow, the infant would then be looking at the blank gray part of the card, and the grating would be to the right or left of fixation. The observer judged the stimulus to be "seen" if the infant locked onto the card with his/her gaze and followed the stimulus as the observer moved it, and "not seen" otherwise. This procedure was followed as many times as necessary for the observer to conclude either that the stimulus was seen or that it was not seen. Whenever there was still doubt about whether the infant saw the card, the observer could request the 0.96 contrast card to verify that the infant was still alert, or the lowest-contrast (0.25 contrast) or blank card to evaluate the infant's behavior when the stimulus was probably not visible. The observer rarely asked for any of these cards. This procedure continued until the observer completed the measurement or the infant fell asleep.

A measurement was considered complete when the observer found at least one card that was seen and at least one card that was not seen. Whenever possible, the observer verified the test by presenting a previously seen card a second time. The infant's contrast threshold was the lowest value of contrast that the observer judged that the infant could see. If the infant was still awake at the end of testing, the experimenter and observer exchanged roles, and a second measurement was made. Infants were tested either at 0.10 cyc/deg (observer AMB: 20 infants; observer JGC: 13 infants; of these, nine infants were tested by both observers) or at 0.06 cyc/deg (observer AMB: 26 infants; observer JGC: 13 infants; 11 were tested by both observers).

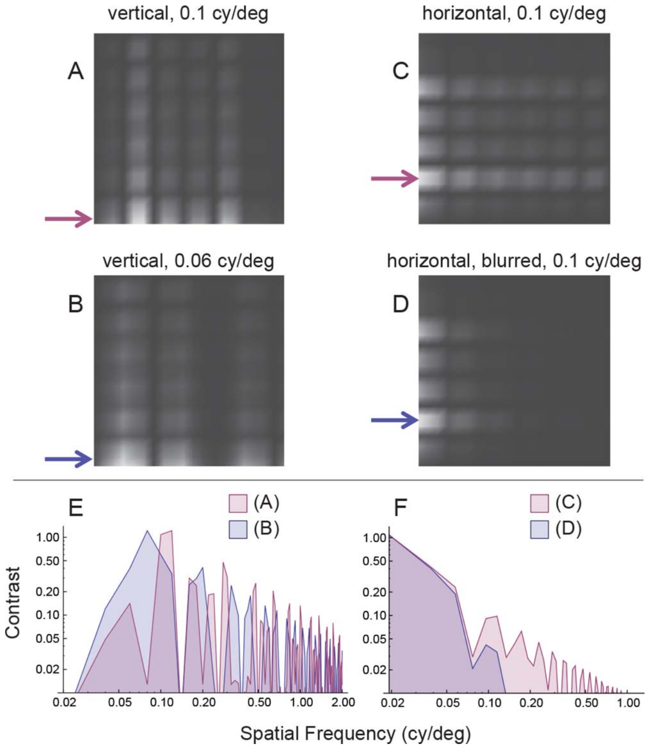

FIGURE 3. Fourier spectra of 0.96 contrast gratings. (**A–D**) the first 20 Fourier components, in two dimensions, keyed to the corresponding stimuli shown in Figures 1A through 1D. (**E**) Fourier spectra of the modulation in the horizontal direction (*arrows* in [**A**, **B**]) in the vertical gratings in experiment I. (**F**) Fourier spectra of the modulation in the horizontal direction of the main Fourier components (*arrows* in [**C**, **D**]) in the horizontal gratings in experiment II.

Results of Experiment I

Fifty-one infants (33 females) were tested once, and 20 of those infants were tested twice (39%). The sex imbalance was due to male infants being asleep after their circumcisions. Every infant was judged to see at least the 0.96 contrast grating of the stimulus set. Overall, 90% of all tests were complete, with 92% first-test completions and 85% second-test completions.

The ability of an infant to see a card was judged mostly from infant fixation and following eye movements, with head movements being visible only occasionally. It was easy to determine whether the infant was awake or not, and the eye movements were easy to judge. When it was used, the blank card never elicited a fixation or following response. Subjective observation suggested that most eye movements were saccadic re-fixations of the displaced grating, but smooth eye movements also occurred on some trials.

Contrast Threshold

The $\log_{10}$ contrast threshold data were examined using the Mixed Model (SPSS), with fixed factors for "observer," "spatial frequency," and "infant number" in order of test, with "test number" (test 1 versus test 2) as a repeated measure. Infant number was statistically significant ($F_{1,58.52} = 6.730$, $P = 0.012$), but neither the main effects for observer, spatial frequency, or test number, nor any of their interactions, was statistically significant.

The geometric average binocular contrast threshold of all the complete tests was 0.568 at 0.10 cyc/deg (95% confidence interval [CI]: 0.503–0.642; CS = 1.75), and 0.600 at 0.06 cyc/deg (95% CI: 0.545–0.663; CS = 1.78). There was no appreciable difference in infant threshold for the 0.06 cyc/deg and 0.10 cyc/deg gratings ($F_{1,50.70} = 0.497$, $P = 0.484$ on the ANOVA), and the observers showed nonsignificant differences in opposite directions (Fig. 5A). As in the adult literature, infant square-wave threshold does not depend on spatial frequency at very low spatial frequencies.

In general, the two observers' data sets were similar. For 16 of the 17 infants tested twice to completion, the two observers differed by 0.00 $\log_{10}$ units (nine infants) or 0.15 $\log_{10}$ units (seven infants) (zero or one card-step). The infant number effect is shown by the regression lines in Figures 5B and 5C, where each CS result appears in the order of test, within observers, regardless of whether it was from a first or second test. The similarity of thresholds across observers for the infants who were tested twice and the similar improvement of the observers as they tested more infants are in agreement with the ANOVA, which showed no statistically significant difference between observers in their overall level of performance or in their trend to improve over time. Thus, these results do not suggest any statistically or clinically significant difference between observers based on their prior experience testing infants.

EXPERIMENT II: GRATING ORIENTATION

To explore the impact of our choice of vertical gratings in experiment I, we collected within-subjects data using vertical and horizontal gratings in experiment II.

Methods

There were three 0.10 cyc/deg grating stimuli in experiment II, one vertical and two horizontal. The same vertical 0.10 cyc/deg grating from experiment I (Fig. 2A) was used on all infants and a "sharp-edged" horizontal grating identical to the vertical grating, only rotated through 90° (Fig. 2C), was used on the first 12 infants. The Michelson contrast across the vertical contours at the ends of the sharp-edged stimuli was half of the overall grating contrast. A "blurred" horizontal stimulus was used on the remaining 25 infants. It had the vertical edges of the grating tapered to zero (Fig. 2D) to minimize the high-spatial-frequency edge information contained in those vertical contours.

Each stimulus set contained both vertical and horizontal stimuli. In the first stimulus set, vertical stimuli as in experiment I were paired with sharp-edged horizontal stimuli. Cards were presented in descending order of contrast, but within each contrast level, the vertical and horizontal stimuli appeared in random order. For example: 0.96V, 0.96H, 0.71H, 0.71V, 0.50V, 0.50H, 0.35H, 0.35V, 0.25H, and 0.25V. Thus, the observer did not know, for any given card, whether its orientation was vertical or horizontal, but she did know that the stimuli in the stack progressed from easier-to-see to harder-to-see. This experimental design prevented infant fatigue from differently affecting the thresholds measured using the vertical versus the horizontal stimulus. Testing started with the 0.96 contrast vertical and horizontal cards, and continued until the observer judged that three cards in succession were not seen, and therefore there were both "seen" and "not seen" stimuli of each orientation. The observer was always coauthor AMB.

Results of Experiment II

Infant behavior elicited by the horizontal gratings was difficult to judge at first, but the judgments became easier for successively tested infants. The final results measured using the sharp-edged stimuli (Fig. 6B, dark gray triangles) were

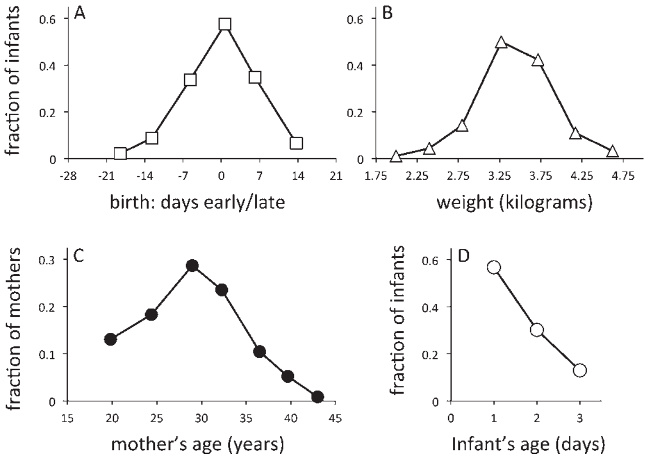

FIGURE 4. Mothers' ages and ages and weights of the infants, across all three experiments.

similar to the overall results measured using the blurred stimuli (light gray triangles). The lack of an obvious edge blur effect is not surprising, because it is unlikely, in retrospect, that infants saw the edge information, even in a sharp-edged grating at 0.96 contrast. Fourier analysis of 0.96 contrast versions of the two horizontal gratings (Figs. 3C, 3D, 3F) revealed that the low-spatial-frequency modulation in the horizontal direction (arrows) for the two horizontal stimuli was closely similar. The higher-order horizontal harmonic components associated with the sharp or blurred edges were all below 0.098 in contrast (Fig. 3F), and the linear contrast difference between the sharp-edged and blurred gratings was less than 0.06 at every spatial frequency. In view of the results of experiment I, it is unlikely that infants were able to see those relatively low-contrast higher-order harmonics.

A multivariate analysis of variance (GLM, SPSS) revealed that the results for horizontal ($F_{1,31} = 7.079$, $P = 0.012$) but not vertical gratings ($F_{1,31} = 3.382$, $P = 0.075$) depended on the infants in order of test. Thus, only partial transfer of training occurred between tests performed using the vertical gratings in experiment I and horizontal gratings in experiment II.

To guide interpretation of these results, we fitted all the horizontal-stimulus data with a single elbow-shaped function:

$$\log_{10}(\mathrm{T}) = \mathrm{Max}[(a^{*}s + b), (c)], \qquad (1)$$

(Fig. 6B), where T is threshold, s is the number of the subject in order of test, and ***a***, ***b***, and ***c*** are constants, using a least-squares criterion. We also fitted the ratios between the horizontal and vertical data (Figs. 5B, 6C) with Equation 1. After the inflection points (where $\boldsymbol{a}^{*}\mathrm{s} + \boldsymbol{b} = \boldsymbol{c}$), there was no correlation between subject number and either the contrast thresholds ($r = -0.141$, $P = 0.493$) or the ratios ($r = 0.351$, $P = 0.068$).

We use the fitted functions to examine infant contrast thresholds that were free of observer practice effects. Over the constant part of the function, the geometric average contrast threshold for horizontal gratings was 0.575 (95% CI: 0.523–0.633; CS = 1.74); the median, including the two infants who did not fixate or follow any horizontal grating, was 0.543 (Fig. 6B). The geometric average threshold for vertical gratings was 0.499 (95% CI: 0.457–0.546; CS = 2.00) for those same infants. After the ratio data (Fig. 6C, gray level coding as in 6B) had reached their asymptote, the geometric average ratio between the horizontal and vertical grating contrast thresholds was 1.19 (95% CI: 1.09–1.30). The difference in performance for vertical and horizontal stimuli was statistically significant ($t_{28} = 3.94$, $P < 0.0006$, paired *t*-test). Over this same range, the results with vertical and

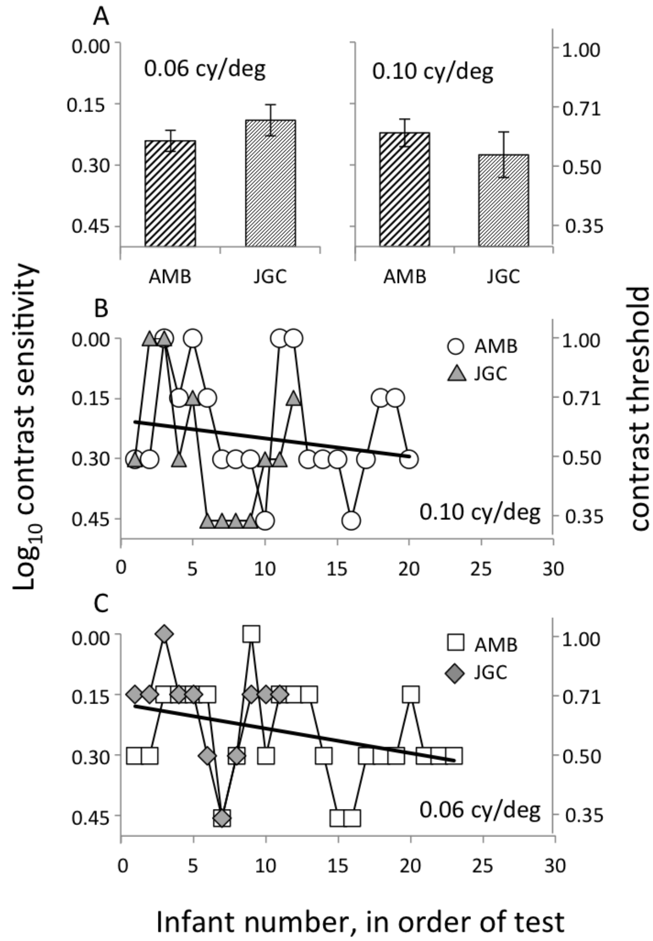

FIGURE 5. Results of experiment I. (**A**) average newborn CS and threshold ± SEM for two observers and two spatial frequencies. (**B**, **C**) Contrast sensitivities and thresholds improved for both testers as they gained experience (linear regression lines).

horizontal stimuli were highly correlated across infants ($r = 0.633$, $P = 0.0003$), indicating that much of the variability in the overall level of performance with the vertical and horizontal gratings was statistically due to infant-to-infant variability rather than in card-to-card variability in infant performance.

Discussion of Experiment II

The difference between the thresholds measured with vertical and horizontal gratings was initially large, and even after the observer gained experience with the horizontal gratings, there remained a modest but highly statistically significant difference in threshold. As it was moved laterally, the vertical grating was a classic "first-order" motion stimulus because the grating boundary and the black and white stripes that defined the grating moved in tandem. In contrast, the horizontal grating was a "second-order" stimulus because the boundary moved as the card was moved, while the black and white stripes remained (approximately) fixed in visual space. It would not be surprising if the first- and second-order stimuli elicited a different mix of eye movement types in infants,[22] as they do in adults.[23] The practice effect at the beginning of experiment II may have occurred as the observer learned to judge the new range of behavior elicited by the horizontal gratings. The neurophysiology behind the various types of slow and saccadic eye movements may differ in infants and adults.[24–26] Therefore, future work will be required to determine whether perfor-

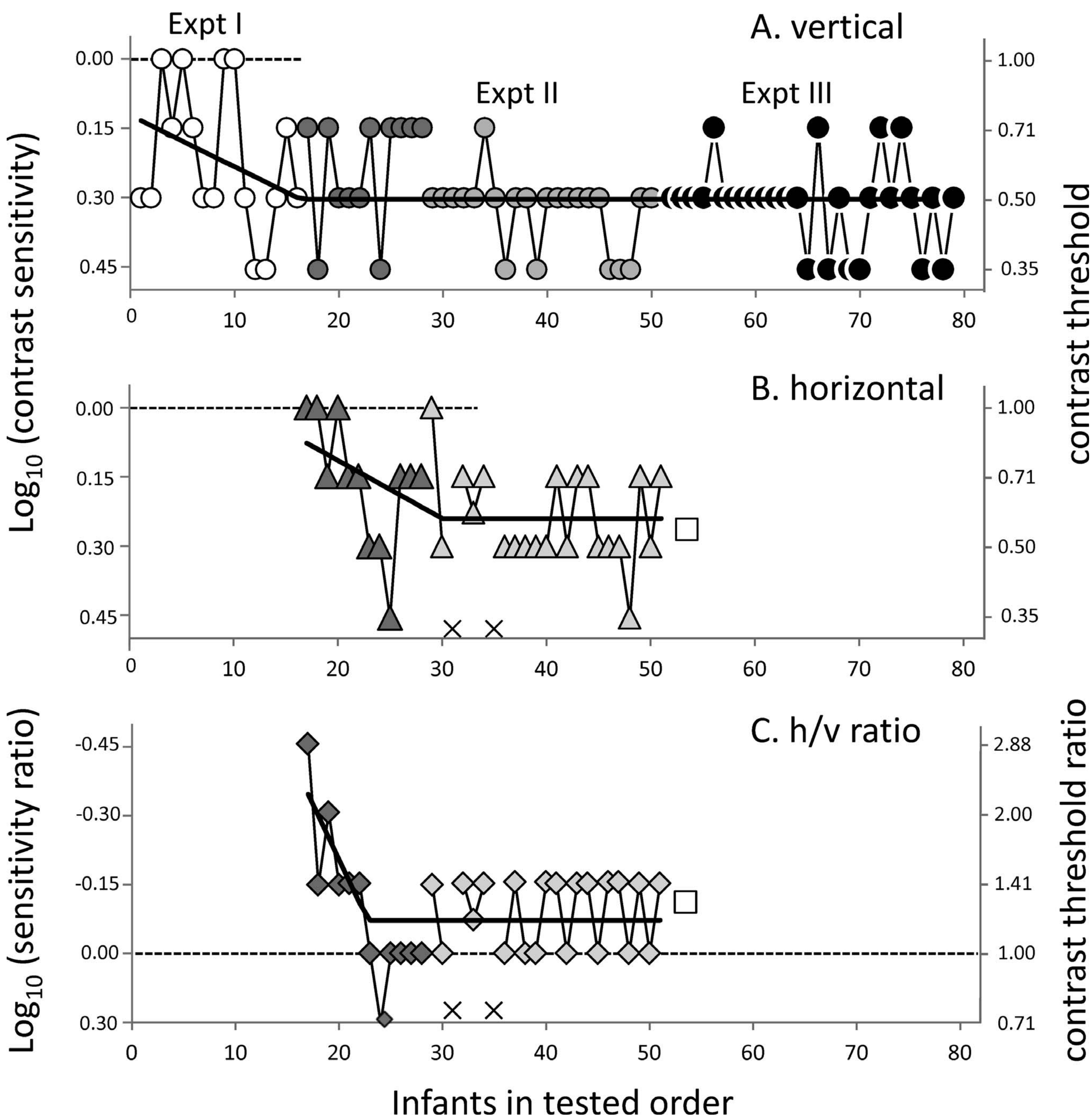

FIGURE 6. Tests with 0.1 cyc/deg stimuli, as a function of test order. Observer AMB. Elbow functions fitted by least-squares criterion. **A**, vertical gratings. White disks: experiment I, first tests only; gray disks: experiment II, vertical stimuli tested in conjunction with the sharp-edged (*dark gray*) and blurred-edged (*light gray*) horizontal gratings; black disks: experiment III, random/masked experimental design. (**B**) Experiment II, horizontal gratings; (**C**) The ratio between the data from **B** and **A**. Gray-level coding in **B** and **C** as in **A**. Xs: missing data on two infants who failed to see any horizontal grating. Squares: median of the data over the constant parts of the functions, including the missing data.

mance by newborn infants with different vision disorders is differently impaired when measured using vertical versus horizontal gratings.

Experiment III, Random/Masked Presentation

The use of stimulus cards presented in descending order of visibility is common in clinical infant testing using the CP.[19,20] This has the advantage that the observer always determines immediately whether the infant can see anything, and the observer becomes familiar with the infant's "looking style" at the beginning of the test. However, it has three important disadvantages. First, the progress of the test is confounded with the infant's state of arousal. An infant who is awake and alert at the beginning may become less so as the test progresses, sometimes even falling asleep partway through testing. The experienced observer will use the 0.96 contrast stimulus to verify that the infant is still awake and participating, but even so, newborn infants falling asleep is a chronic problem. Second, because the stimuli become harder and harder for the infant to see over the course of the test, the observer must exert greater and greater patience to elicit and

Investigative Ophthalmology & Visual Science

recognize looking behavior as the test progresses. Thus, the observer's patience is confounded with the visibility of the stimuli. Third, and most important for testing in research, there is the worry that the tester knowing the values of the cards influences the tester's judgments. Put bluntly, infant thresholds could be entirely wishful thinking.

To examine these issues, we performed experiment III using only the 0.10 cyc/deg vertical grating, with the stimuli in random order, and with the observer kept unaware of the contrasts of the cards. The first card was always at 0.96 contrast, allowing the observer to determine immediately whether the infant could see at all, and to determine how the infant reacted to a clearly visible card. After that, stimuli at contrasts 0.71,0.50, 0.35, and 0.25 were presented, in a strictly random order determined in advance by a random numbers table. An assistant prepared the stimulus sets, provided the cards to the observer while concealing the stimulus contrast values, and tabulated the results. The observer (AMB) could always ask for the 0.96 contrast card (to verify that the infant was awake and to reacquaint herself with the infant's looking style), or a blank gray card with no grating on it (to observe the infant's behavior when there was no grating to see). Sometimes the observer asked to repeat one of the "provisionally not seen" or "provisionally seen" cards to verify previous judgments.

Results of Experiment III

The geometric average contrast threshold ($N = 27$, 10 females) was 0.493 (95% CI: 0.457–0.533; CS = 2.03). This result (Fig. 6A, black disks) was close to the results obtained for the vertical grating in experiment II (gray disks) ($t_{61} = 0.04$, $P = 0.968$). These data provide no evidence that either the confounding of test difficulty and test duration with infants' flagging attention and the observer's reservoir of patience, or the observer's knowledge of the stimulus values, had any effect on the tests reported here. Furthermore, there was no learning curve visible in this data set. The observer used the blank card on approximately half the tests, moving it in the same way as a "real" stimulus. The infant never fixated or followed it.

General Discussion

To summarize the results across experiments I to III, we fitted Equation 1 to the pooled results measured using vertical 0.10 cyc/deg gratings (Fig. 6A). The resulting curve shows that the practice effect was over at the end of experiment I, and the data from experiments II and III were on the constant part of the function. In experiments II and III, the geometric average contrast threshold was 0.497 (95% CI: 0.475–0.524; CS = 2.01) (Figs. 6A, 7A). The standard deviation in $\log_{10}$ units of the vertical CS data from experiments II and III was 0.097, which was similar to 0.08,[27,28] the standard deviation of CS for young adults, and 0.09[27] to 0.12,[28] the standard deviation of CS for older adults, measured by others using the Pelli-Robson chart. The similarity of the infant SD values to those of adults suggests that the variability in infant performance was due to variation across infants in their visual capabilities, with little variance added by variation across sessions in the acumen of the adult observer.

Experiment II determined that infant CS depends on stimulus orientation, but the difference was small (Fig. 7B) once the practice effect for the new, horizontal gratings had passed. The results with vertical and horizontal gratings were highly correlated across infants. In experiment III, randomizing the stimuli and keeping the stimulus value concealed from the observer had no effect on the measured value of contrast threshold. This result validates the clinical use of the descending method of limits when used by an observer with recent training.

The Fixation-and-Following CP

The fixation-and-following CP method was generally easy to use. It was easy to determine whether an infant was awake enough to test, and almost all tests on awake infants were complete. By definition, in every complete test, the infant "saw" at least the 0.96 contrast card, and "did not see" at least one lower contrast card. Whenever the observer requested the blank card, the infant never fixated or followed it. The lack of fixation and following of the low-contrast and blank cards shows that only the intended stimulus (not the card as a whole or the peephole in the center) elicited the infant's looking behavior.

The fixation-and-following method may be compared to three behavioral methods that others have used to measure newborn infant visual acuity. These were Optokinetic Nystagmus,[10,12] FPL,[10,14,16] and two versions of CP: dichotomous cards like the Teller Acuity Cards[13,15,17] and the fixation-and-following cards like what we use here.[11,13] Also, newborn visual acuity and CS have been measured using the visually evoked potential,[29] which produced data remarkably similar to the present results. Of these methods, only CP is fast enough and convenient enough to measure thresholds clinically during the brief awake period of the newborn infant, and the fixation-and-following version of the CP is best suited to the neonate's behavioral repertory. The Teller Acuity Cards and similar dichotomous tests were designed for older infants, who scan the environment widely and actively. When these methods are used on newborns, the person holding the infant must turn the infant to "show" him/her each possible stimulus location. Thus, dichotomous CP requires two trained adults, the observer and the holder, to test a newborn infant. In contrast, in the fixation-and-following CP used here, the stimulus is placed wherever the infant is spontaneously looking, so the infant can be held by any nurse, and only one specially trained adult (the observer) is required.

Observer Practice Effects

The use of cards to measure infant visual performance is well established, but it is well-known that observers need training and experience with CP for their results to be quantitatively reliable. The instruction manual[30] for the Teller Acuity Cards recommends that novices test approximately 15 infants (five infants at each of three ages), and demonstrate competence by random/masked testing, before their data are used. Similarly, the contrast thresholds reported here stabilized after 15 infants (vertical gratings, experiment I) or seven infants (horizontal gratings, experiment II), and observer AMB's results using random/masked presentation were similar to those obtained using the descending method of limits. Furthermore, experiment I data from AMB and JGC were similar in spite of AMB being a veteran infant tester and JGC being a novice. Thus, the present method does not appear to be very different from standard CP in terms of observer training requirements, and the data do not suggest that many years of prior testing experience are required for reliable thresholds to be measured.

The Visual CS of the Newborn Infant

The present results can be compared with neonatal visual acuity data and adult CSF data to obtain a more complete picture of the newborn infant's visual capabilities. CS measured with vertical stimuli (experiments II, III) was combined with the average newborn visual acuity value of 1.01 cyc/deg, which did not vary systematically across

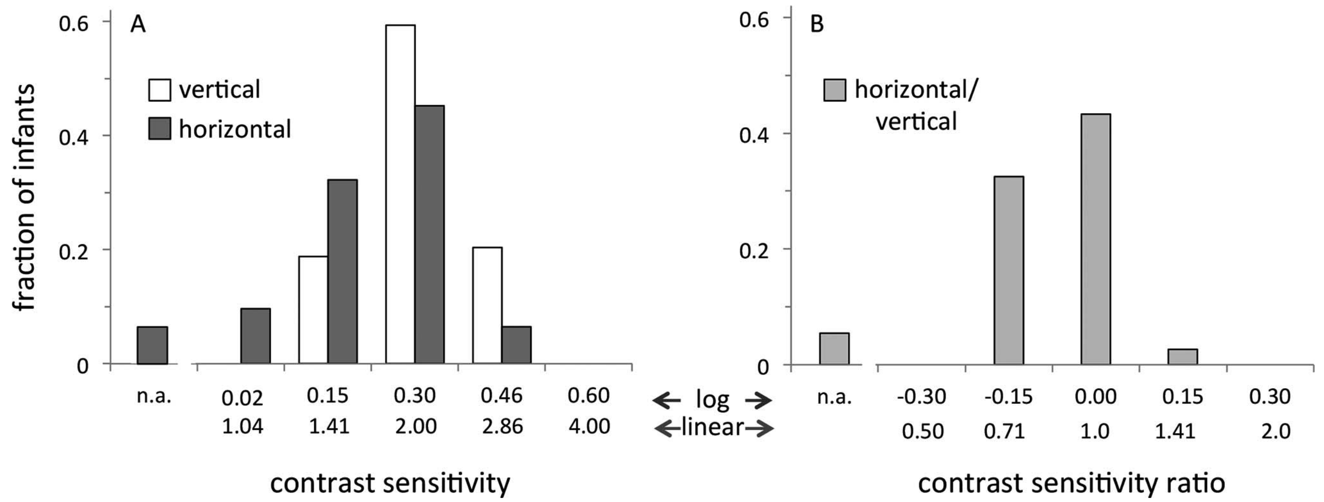

FIGURE 7. Data from experiments II and III, measured using 0.10 cyc/deg. (**A**) CS values. NA: infants saw the 0.96 contrast vertical grating, but fell asleep before seeing any other gratings. The standard deviation of the data measured with vertical gratings was 0.097, which is comparable to that of adults measured with the Pelli-Robson chart.[20,21] (**B**) Distribution of CS ratios across infants from experiment II. NA, no ratio available because no horizontal gratings were seen.

psychophysical methods.[10–18] The three adult CSF data sets[2,3] from Figures 1A and 1B were scaled vertically, parallel to the CS axis, then horizontally parallel to the spatial frequency axis, to fit the infant data by a least-squares criterion. The linear scale factors for the red curve were 208 (vertical) and 8.63 (horizontal); for the blue curve they were 144 (vertical) and 8.70 (horizontal); for the green curve they were 95 (vertical) and 6.11 (horizontal). Notice that as each adult CSF is shifted vertically downward, the predicted infant acuity naturally shifts to a lower value because of the shape of the CSF; the additional horizontal shift was required in addition to the vertical shift to fit the infant acuity data.

In Figure 8A, the adult square-wave data[2] (red curve, repeated from Fig. 1A) would be the appropriate model of infant square-wave data if infants, like adults, could see the higher-order square-wave harmonics (Fig. 2E) at their square-wave grating detection threshold. The adult sine-wave data[3] (blue curve, from Fig. 1A) would be the appropriate model if infants could not see the harmonics (Fig. 2E) at the detection threshold. The blue curve predicts that the 0.06 cyc/deg stimulus should be barely visible at 100% contrast, thus

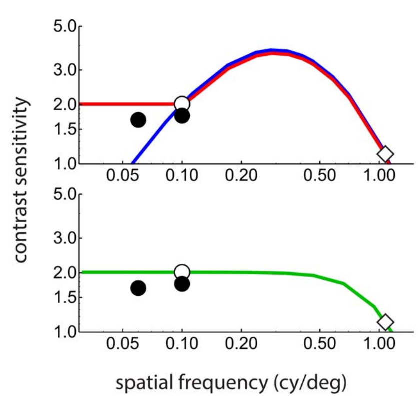

FIGURE 8. Adult CSFs fitted to infant data. Disks, infant CS data, vertical gratings (black disks, experiment I; white disks, experiments II, III; standard error bars smaller than the symbols). Diamonds, mean newborn visual acuity from the literature. Curves, fits of adult data from Figure 1. (**A**) Adult square-wave and sine-wave CSFs, steady presentation.[3] (**B**) Adult sine-wave CSF curve, flickered presentation.[2]

providing an explicit alternative to the null hypothesis that infant CS values at 0.06 and 0.10 cyc/deg in experiment I were equal. The blue curve is clearly rejected by the 0.06 cyc/deg data ($t_{36} = 8.81$, $P < 10^{-5}$), so statistically and practically, the CS at those two spatial frequencies are equal. The solid green curve in Figure 8B is the low-pass CSF from Robson's data for flickering stimuli (Fig. 1B), and it would be an appropriate model if infants were responding to the motion of the fixation-and-following stimuli.

The models in Figure 8 suggest different estimates of the maximum CS of the newborn infant: the red curve suggests a maximum value of approximately 3.64, located near the optimum spatial frequency of 0.29 cyc/deg (Fig. 8A), whereas the green curve suggests a maximum CS of approximately 2.01, reached asymptotically at very low spatial frequencies (Fig. 8B). Without measuring CS near 0.29 cyc/deg, we cannot choose between these two estimates.

All three curves in Figure 8 support the view that neonatal CS is much lower, relative to the adult value, than neonatal visual acuity is. However, the larger vertical shift does not necessarily mean that the vertical CS scale factor is more important than the smaller horizontal spatial frequency scale factor. The low visual acuity of infants has been linked conceptually to the known immature morphology of newborn infant foveal cones,[21,31–33] which may make the fovea less sensitive[21,33] and require the infant to rely on the extrafoveal retina.[21,34] The overall lower CS of infants has been linked to sensory noise in the ascending visual pathway,[34–36] and to the morphological immaturity of the fovea.[33] Future work will be required to determine what critical immaturities might be in common between reduced CS and visual acuity, what critical immaturities are different, and which factor varies more reliably with health and disease.

CONCLUSIONS

These are the first behavioral measurements of newborn infant CS, and they show that the fixation-and-following version of the CP can be used successfully to measure binocular contrast threshold on newborn infants. Neonatal contrast threshold is 0.50 for 0.10 cyc/deg vertical square-wave gratings, and 0.58 for 0.10 cyc/deg horizontal square-wave gratings, a small but highly significant difference. The standard deviation of infant performance for vertical gratings was similar to that of adults using the Pelli-Robson chart. Because all 119 awake infants tested in this study showed that they could see at least one stimulus, the fixation-and-following CP is promising for future clinical use.

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