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Article

Neonatal Contrast Sensitivity and Visual Acuity: Basic Psychophysics

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Purpose: This research was prospectively designed to determine whether a 0.083 cycles per degree (cy/deg) (20/7200) square-wave stimulus is a good choice for clinical measurement of newborn infants' contrast sensitivity and whether the contrast sensitivity function (CSF) of the newborn infant is band-pass. The results were retrospectively analyzed to determine whether the method of constant stimuli (MCS) and the descending method of limits (dLIM) yielded similar results.

Methods: In across-subjects experimental designs, a pilot experiment used MCS ($N = 47$ visual acuity; $N = 38$ contrast sensitivity at 0.083 cy/deg), and a main experiment used dLIM ($N = 22$ visual acuity; $N = 22$ contrast sensitivity at 0.083 cy/deg; $N = 21$ at 0.301 cy/deg) to measure visual function in healthy newborn infants. Three candidate CSFs estimated maximum neonatal contrast sensitivity. MCS and dLIM psychometric functions were compared while taking the stimulus presentation protocols into account.

Results: The band-pass CSF fit the data best, with a peak sensitivity near 0.31 at 0.22 cy/deg. However, the 0.083 cy/deg square-wave stimulus underestimated the best performance of newborn infants by less than 0.15 $\log_{10}$ units. MCS and dLIM data agreed well when the stimulus presentation contingencies were taken into account.

Conclusions: Newborn contrast sensitivity is well measured using a 0.083 cy/deg square-wave target, regardless of which CSF shape is correct. MCS and dLIM yield wholly comparable results, with no evidence to suggest effects of other factors such as infant inattention or examiner impatience.

Translational Relevance: These measurements open the way for clinical behavioral measurement of infant visual acuity and contrast sensitivity in the neonatal period.

Introduction

The main challenge in designing a test of contrast sensitivity is to choose the appropriate size or spatial frequency of the target. This is difficult because the normal patient's sine-wave contrast sensitivity function (CSF) has a single peak in the middle spatial frequency range. A stimulus that is too small or too large (with dominant Fourier components that are at too high or too low spatial frequency) will not reveal the patient's maximum contrast capability. In the case of infants and patients with disorders of the visual system, the challenge is to choose the stimulus size in the face of uncertainty about the patient's CSF.

We have been working to develop the Newborn Contrast Cards and the Newborn Acuity Cards. The Newborn Contrast Cards present a very low spatial frequency square-wave at variable contrast.[1] We chose a square-wave stimulus because it has a higher contrast than a sine-wave at the same spatial frequency,[2] by a factor of $\sqrt{2}$, and it is much easier to create printed square-wave stimuli than printed sine-waves. Furthermore, recent modeling efforts[3] have suggested that even if the CSF is band-pass, the difference between the measured square-wave contrast sensitivity and the best sensitivity of which the patient is capable will be small. The Newborn Acuity Cards present a square-wave grating at maximum contrast and variable spatial frequency.[4] Both card tests involve a centrally presented grating

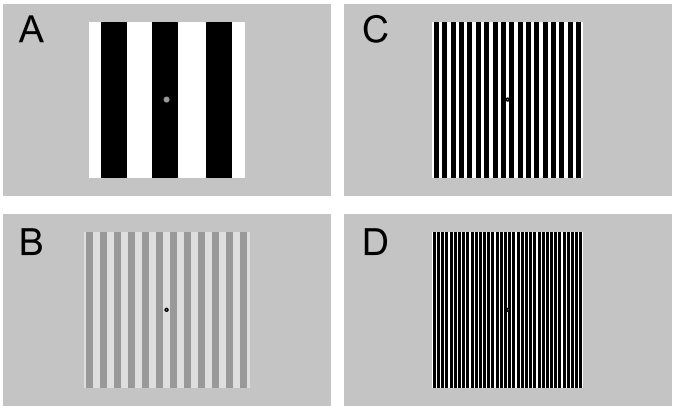

Figure 1. Examples of the Newborn Acuity Cards and Newborn Contrast Cards. (A) The "easy" contrast card (0.083 cy/deg, 0.86 contrast); (B) a typical contrast card (0.303 cy/deg, 0.50 contrast); (C, D) acuity cards (0.50 and 1 cy/deg, both at 0.86 contrast). The luminance mismatch between the grating and the surrounding gray in this figure is an artifact of reproduction. In the actual stimuli, the space-averaged luminance match was excellent.

(Fig. 1) and a fixation-refixation behavior. The examiner performs a "yes/no" judgment for each card, similar to the method of the Teller Acuity Cards,[5,6] and contrast sensitivity or visual acuity is based on those judgments. The present project is the next step toward the goal of establishing these cards for clinical use on newborn infants. We recognize that, before they can be adopted into clinical practice, research will be required to establish their repeatability across examiners and their validity in discriminating between healthy infants and those with visual or neurologic disorders.

We have recently reported that the Michelson contrast sensitivity of the newborn infant is about 2.0 (contrast threshold = 0.497, or −0.303 $\log_{10}$ Michelson contrast), when measured using a 30 × 30-degree square-wave stimulus at 0.10 cycles per degree (cy/deg).[1] Here, we investigate the appropriateness of that type of stimulus because studies of repeatability and validity cannot occur until the correct stimulus design and testing methods are chosen. We collected contrast sensitivity and visual acuity data on newborn infants using the method of constant stimuli (MCS) in a pilot study, and the descending method of limits (dLIM) in the main experiment. We extracted thresholds from individual infants' data sets using logistic regression. We then fitted the resulting data using three candidate shapes of the CSF to determine whether the underlying CSF is band-pass (single-peaked) or low-pass. We used those fits to estimate the maximum possible sensitivity of the newborn infant as well as the spatial frequency at which it occurs. In a secondary analysis, we used the results we obtained in a pilot study using the MCS to predict the results from the main experiment using the dLIM, according to the stimulus presentation schedule in each data set.

Methods

Subjects

Newborn infants in the postpartum unit of the Ohio State University Wexner Medical Center participated in this study with the informed permission of a parent. An infant was eligible for participation if the mother was over age 18 and able to give informed permission and if the infant and mother were both healthy (Table 1). The mother was given a $10 gift card for a local business to thank her for her infant's participation. The research was approved by the Ohio State University Institutional Review Board for protection of human subjects, and conformed to the tenets of the Declaration of Helsinki.

Stimuli

The stimuli were 30.5 × 61-cm cards, printed with a gray surrounding field, and a 24.8-cm square light-and-dark grating in the center of the face of the card (Figs. 1A, 1C, 1E). Each card had a peephole in the center of the grating through which the examiner could observe the infant's looking behavior. The stimuli were designed to be large enough that, when the infant viewed the center of the card at a distance of 38 cm, the left and right edges of the card were at an eccentricity of 38.75° of visual angle. This placed the edges of the cards and the examiner's hands outside the horizontal visual field extent of the newborn infant, which is about 30° of visual angle, when measured using a 99% contrast stimulus.[7] It is therefore unlikely that the infant's refixation behavior was guided by the edges of the card or the examiner's (low-contrast) hands rather than the position of the grating itself. We provide further information in support of this below.

All the cards used in this study were manufactured by Precision Vision, Inc. (Woodstock, IL). Testing was under available light, and the average luminance of the cards during testing was 299 cd/m^2 (SD: 90). The stimulus values are listed in Appendix Tables A1 and A2. Contrasts were calibrated using a photometer (Pritchard SpectraScan PR-670; Photo Research, Syracuse, NY), and all data analyses were based on the calibrated contrast values. There were three sets of

Table 1. Participant Demographics

Infant Information	Number (Dispersion)
Number[a]	113
Number female	59
Median birth age at test	1 day (95% < 2 days)
Gestational age	39 weeks 2 days (SD: 8.4 days)
Mother Information	**Number (Dispersion)**
Age	29.8 years (SD: 4.8 years)
Postelementary education	7.5 years (SD: 2.6 years)
Race/ethnic group	
Number Caucasian	72
Number African-American	23
Number Asian	3
Number Hispanic	5
Number mixed or other groups	8

[a] The number of infants is less than the number of data sets because a few infants were tested in two or three conditions, within experiments. There were more infants than mothers because there were two sets of twins.

contrast cards and two sets of acuity cards. The contrast cards varied from 0.123 to 0.695 Michelson contrast, and within each stimulus set their contrasts were separated in contrast by approximately 0.15 $\log_{10}$-unit steps. There was also a high-contrast card at 0.86 contrast. There were two sets of acuity cards, which were similar to the contrast stimuli in size and general description. Their contrast was 0.86, the maximum that could be produced using printing technology, and their spatial frequencies varied from 0.33 to 2.84 cy/deg (1.024–2.079 logMAR or 20/211–20/2400 Snellen) in approximately 0.15 $\log_{10}$-unit (half-octave) steps, plus a low-frequency grating of 0.025 cy/deg. Stimuli were sanitized daily using hospital wipes.

Procedures

Testing occurred in the participants' hospital rooms in the postpartum unit of the Ohio State University Wexner Medical Center. During testing, a research nurse held the infant in her arms, standing or sitting with the light coming from behind so that the light fell onto the cards while keeping the infant's eyes in shadow as much as possible. Two other adults (coauthors AMB and FOO) were involved in testing: the "examiner," who presented the cards to the infant and judged whether the infant saw the grating, and the "assistant," who randomized the order of the cards, gave them to the examiner in such a way that the examiner could not learn their values, and recorded the examiner's judgments.

The examiner presented the cards one at a time, while observing the infant's looking behavior through the peephole in the center of each card.[1,4] At the beginning of a trial, the examiner placed the card along the infant's line of sight at a distance of 38 cm. If the infant continued to look at the central grating, that was the first indication that the infant may have seen the grating. The examiner then moved the card stepwise a few centimeters to the right or left, attempting to elicit a refixation of the displaced grating. The examiner continued to present the card, placing it and moving it as necessary, until the examiner could judge whether or not the infant saw the grating using a fixation-refixation criterion. While the method is similar to the familiar "fixation and following" method, the movements of the card were not large, and the eye movements rarely resembled smooth pursuit. Thus, examiners performed a "yes/no" psychophysical judgment, just as for the Teller Acuity Cards.[5,6] The average test time was 12.28 minutes (SD: 5.08).

Experiment I

To choose the range and spacing of the stimulus values for the main experiment, we performed a pilot study in which we measured contrast sensitivity and visual acuity using MCS.

Methods

For this pilot experiment, we used three trial sets of Newborn Contrast Cards (Appendix Table A1),

which had slightly different calibrated contrast values for each of the three stimulus sets. The first two corresponding sets of acuity cards had identical contrast and spatial frequency specifications, and the third set had slightly different spatial frequencies. Thirty-three infants were tested using only one stimulus type: 20 infants were tested using only the Newborn Acuity Cards, and 13 infants were tested using only the Newborn Contrast Cards. These tests always began with an "easy" card (in Table A1, these were card no. 9 or no. 10 for the contrast tests, card no. 16, no. 17, or no. 18 for the acuity tests). This easy card established that the infant could see "something," and it allowed the examiner to familiarize herself with that infant's looking behavior and state of alertness. Next, the examiner attempted to present four or five additional stimuli, in a predetermined random order, while being kept unaware of the values of the cards. If the examiner was uncertain whether an infant saw a particular card, she could set it aside to be presented a second time, while she remained unaware of its value. If the infant was not awake for the second presentation, that card was scored as "not presented." The test continued until the examiner had reached a decision on all the cards, producing a complete data set, or the infant fell asleep, producing an incomplete data set.

Twenty-seven additional infants were tested using mixed sets of contrast and acuity stimuli. In those experiments, the first card to be presented was always an easy contrast card, and the subsequent cards were intermixed sets of 8 to 10 total cards (Newborn Contrast Cards plus Newborn Acuity Cards), which were presented in a predetermined random order. The examiner was kept unaware of the contrast value or spatial frequency of the grating on each card and whether the card was a contrast or an acuity card. We eventually abandoned this procedure because some infants fell asleep before completing the full set of stimuli. As described under Data Analysis, we included all the complete and incomplete data sets (except for one) in our nonparametric statistical analyses.

A total of 60 infants participated in this pilot experiment, and there was a total of 39 contrast sensitivity tests and 47 visual acuity tests.

Data Analysis

We used logistic regression software (Mathematica version 11.1.0; Wolfram, Champaign, IL) and the Mathemataica LogitModelFit command to estimate, for each infant, the contrast or spatial frequency value that elicited 50% "yes" responses. The psychometric functions fitted by Mathematica to the $\log_{10}$-transformed data were constrained to pass through zero ("no") at a visual acuity value of 30 cy/deg or a contrast value of 1%.

Out of a total of 47 infants tested for visual acuity, logistic regression converged on a threshold estimate within the tested range for all but three infants. The data of 37 infants were complete and strictly monotonic, and the resulting threshold estimates were within the stimulus range. For those infants, we could also estimate threshold by linear interpolation between the $\log_{10}$ values of the last-seen and the first not-seen stimulus values. The difference between the logistic and the interpolated thresholds was always less than 0.0005 $\log_{10}$ units. The data sets of seven additional infants were successfully fit by logistic regression even though they were incomplete or nonmonotonic. The acuity of one infant was too high to be measured because she saw all of the stimuli that were presented and was assigned an out-of-range value for the purpose of nonparametric statistical analysis. The logistic functions fitted to the data of two additional nonmonotonic infants had such shallow slopes that their thresholds fell outside the range of tested data.

Out of 39 infants tested with the Newborn Contrast Cards, seven infants' thresholds were not within the tested range, according to logistic regression analysis. Six of these infants saw all the stimuli they were presented, so logistic regression produced thresholds outside the tested range. The data of 10 infants were nonmonotonic, but all but one of these data sets were fit successfully. The data set that was not fit contained only a single observation and was discarded.

All but two of the 60 infants who participated (97%) showed evidence of not seeing at least one stimulus. This suggests that the grating itself controlled infant behavior, because if the examiner's hands or the edge of the card were controlling infant fixation-refixation behavior, "yes" responses would occur often even for very hard-to-see gratings.

In preliminary analyses, we performed two parametric analyses of variance under the general linear model, with threshold as the dependent measure, omitting the out-of-range data sets. These analyses were designed to reveal effects of card set or examiner, if they existed, as well as any effect of the mixed versus separate experimental designs, such as might occur if the experimenter were hurrying to complete two stimulus sets before the infant fell asleep. We note that AMB has been testing for 34 years, whereas FOO

Table 2. Median Results

Data Distributions[a]	Method	Median	Interquartile Range
Acuity (cy/deg)	MCS	1.203	0.784–1.415
	dLIM	0.783	0.783–0.783
Contrast threshold, 0.083 cy/deg	MCS	0.330	0.241–0.356
	dLIM	0.458	0.339–0.474
Contrast threshold, 0.303 cy/deg	dLIM	0.330	0.235–0.451
Sampling Distributions	**Method**	**Median**	**95% Confidence Interval[b]**
Acuity ($\log_{10}$ cy/deg)	MCS[c]	0.080	−0.07 to 0.092
	dLIM pred[c]	−0.106	−0.106 to 0.044
	dLIM[d]	−0.106	−0.257 to 0.044
$\log_{10}$ contrast sensitivity, 0.083 cy/deg	MCS	0.481	0.449–0.573
	dLIM pred	0.338	0.246–0.464
	dLIM	0.339	0.339–0.339
$\log_{10}$ contrast sensitivity, 0.303 cy/deg	dLIM	0.481	0.346–0.63

[a] Medians and interquartile ranges of individual data.
[b] Confidence intervals around the medians (compare to 1.96 standard errors of the mean).
[c] Data obtained from resampling 50% subsets of individual data.
[d] Data obtained from resampling simulated data sets. See text for details.

had only approximately 1 month's experience before this project started. None of these three factors were significant for either contrast sensitivity or visual acuity (examiner, contrast: $P = 0.503$; visual acuity: $P = 0.090$; card set, contrast: $P = 0.130$; visual acuity: $P = 0.421$; experimental design, Contrast: $P = 0.739$; visual acuity: $P = 0.234$). Therefore, for the rest of our analyses, we pooled the data across the mixed and separate experimental designs, without regard to examiner or which contrast card stimulus set was used.

We performed our main data analyses using nonparametric statistics, which can handle out-of-range data. This was important here because if we had selected only "good" data for analysis, we could easily bias the estimated central tendencies and underestimate the dispersion of the data. This strategy allowed us to include the data on every infant tested but one. Our measure of central tendency was the median, and the dispersion was the interquartile range of the thresholds (compare to ±0.67 standard deviations). Confidence intervals around the medians were estimated as the 95% intervals of 10,000 resamplings of 50% subsets of the thresholds (compare to ±2 standard errors of the mean).

Results

Every infant tested in this pilot study demonstrated that he/she could see at least the easy card in the

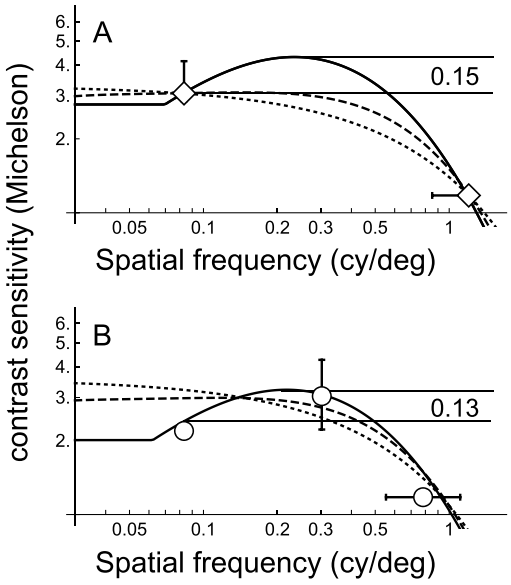

Figure 2. Results of experiment I (A) and experiment II (B). The *data points* are the medians and the *error bars* are the 95% confidence intervals of the medians. *Continuous curves*: the standard model of the adult CSF applied to square-waves.[9,10] *Dashed curves*: the same model, only with the Minkowski pooling exponent set to 1 instead of 4. *Dotted curves*: a generic low-pass CSF, with $\log_{10}$(CS) being a linear function of the linear spatial frequency. The difference between the maximum of the CSF and the measured contrast sensitivity at 0.083 cy/deg was no more than 0.15 $\log_{10}$ units (a factor of 1.41), regardless of which model is correct. The fit of the standard (band-pass) model is much better than either low-pass model (see Discussion for details).

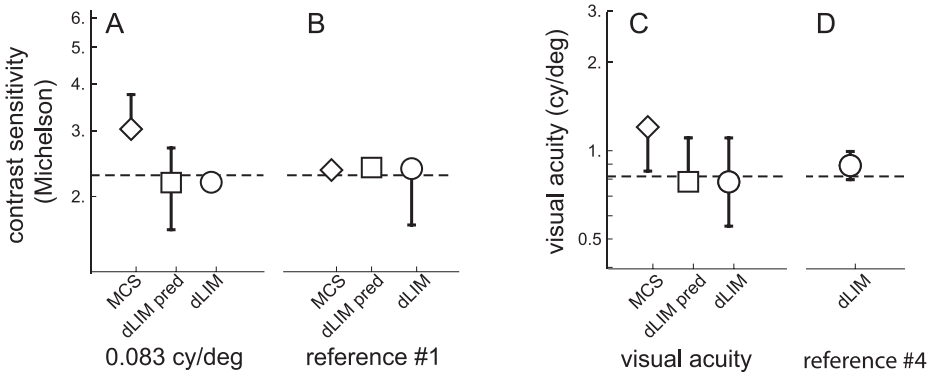

Figure 3. Threshold comparisons. The *data points* are the medians of individual subjects' thresholds (medians in panels A and C are also shown in Fig. 2). *Error bars* (when visible) are 95% sampling confidence intervals of the thresholds. *Diamonds*: MCS data. *Circles*: dLIM data. *Squares*: Predicted dLIM data (see Discussion). (A) Contrast sensitivities at 0.083 cy/deg from experiments I and II. (B) contrast sensitivities from Brown et al.[1] (C) Visual acuities from experiments I and II. (D) Visual acuities from Brown and Yamamoto.[4] *Horizontal dashed lines*: averages of all predicted or measured dLIM contrast sensitivity (A, B) and predicted or measured dLIM visual acuity (C, D).

stimulus set. The median linear Michelson contrast threshold was 0.330 (median contrast sensitivity: 3.030), which is below the 0.47 contrast threshold we reported previously.[1] We discuss this discrepancy below. The median linear visual acuity was 1.204 cy/deg (logMAR: 1.396; Snellen equivalent: 20/498), which is within the rather wide range of newborn visual acuities reported by others.[8] The results are presented in the MCS rows in Table 2, as CSFs in Figure 2A, and as thresholds (diamonds) in Figures 3A, 3C.

Experiment II

In the main experiment, we measured the visual acuity or contrast sensitivity using dLIM. We chose this method for three reasons. First, it is the method that will most likely be used by clinicians.[6,11] Second, it allows for a better completion rate than MCS, because under MCS a great amount of time is spent trying to coax a response from an infant using stimuli that are below that infant's threshold, with the result that infants often fell asleep before testing was completed. Finally, dLIM psychometric functions are necessarily monotonic, so individual thresholds can be extracted easily by both logistic regression and linear interpolation.

Methods

The infants were recruited and consented as in experiment I (Table 1). We used three card types: visual acuity cards, contrast cards at 0.083 cy/deg that were similar to stimulus set 3 used in experiment I, and a set of higher spatial frequency cards at 0.303 cy/deg (e.g., Fig. 1B; calibrated values listed in Appendix Table A2). A total of 53 infants were tested. Forty-three infants were tested once, nine infants stayed awake long enough to be tested with two card types, and one infant stayed awake for all three tests.

Before testing an infant using dLIM, the assistant chose one of the three stimulus sets from a predetermined schedule and placed the cards in descending order, starting with easier stimuli (lower spatial frequency or higher contrast) and proceeding to harder stimuli (Table 3). Then she cut the deck so that the start card was unknown to the examiner (bold numbers Table 3 and Appendix Table A2). This procedure is similar to the random start card method often used in research with the Teller Acuity Cards.[5,6] The nine possible orderings of three stimulus types (0.083 cy/deg, 0.303 cy/deg, and visual acuity) and three possible start cards were repeated twice, in different prerandomized orders; additional infants were tested for each data set, with the examiner choosing a start card at random, resulting in 22 visual acuity tests and 22 tests at 0.083 cy/deg and 21 tests 0.303 cy/deg. The roles of assistant and examiner were decided by a randomized schedule.

As in experiment I, the examiner presented the cards one at a time while remaining unaware of the values of the cards. In a few cases, the start card was judged to be "not seen," at which point the examiner requested a different easy card, generally taken from the bottom of the cut deck, then the descending procedure continued as usual. When a not-seen card was reached, the examiner could terminate the test. However, if the infant was still awake, the examiner could verify her judgment of the last-seen and the

Table 3. Order of Card Presentation in Experiment 2[a]

Newborn Contrast Cards: Nominal (Michelson) Stimulus Contrasts[b] at 0.083 cy/deg in Order of Test								
Card Number	Start Card	2	3	4	5	6	7	8
Order 1	**0.86**	**0.86**	**0.71**	0.50	0.35	0.25	0.175	0.125
Order 2	**0.86**	**0.71**	0.50	0.35	0.25	0.175	0.125	**0.86**
Order 3	**0.71**	0.50	0.35	0.25	0.175	0.125	**0.86**	**0.86**
Newborn Contrast Cards: Nominal (Michelson) Stimulus Contrasts at 0.303 cy/deg in Order of Test								
Card Number	Start Card	2	3	4	5	6	7	8
Order 1	**0.86**	**0.86**	**0.71**	0.49	0.35	0.25	0.175	0.125
Order 2	**0.86**	**0.71**	0.49	0.35	0.25	0.175	0.125	**0.86**
Order 3	**0.71**	0.49	0.35	0.25	0.175	0.125	**0.86**	**0.86**
Newborn Acuity Cards: Spatial Frequencies (cy/deg) at 0.86 Michelson Contrast in Order of Test								
Card Number	Start Card	2	3	4	5	6	7	8
Order 1	**0.10**	**0.33**	**0.50**	0.71	1.00	1.43	2.00	2.84
Order 2	**0.33**	**0.50**	0.71	1.00	1.43	2.00	2.84	**0.10**
Order 3	**0.50**	0.71	1.00	1.43	2.00	2.84	**0.10**	**0.33**

[a] Each type of stimulus card was presented in one of three orders, defined by the start card (bold numbers on the left). Zero, one, or two unused start cards were placed at the end (bold numbers on the right), so the cut deck always consisted of eight cards.

[b] The calibrated values are listed in Appendix Table A2.

first-not-seen cards. Occasionally, the examiner would change her judgment based on these last trials.

Results

Every infant was judged to see at least one stimulus. There were four incomplete data sets on infants who fell asleep after seeing one to three stimuli but before failing to see any stimulus. Logistic regression fit out-of-range thresholds to these data sets. It was possible to include all the data, both in range and out of range, because we used nonparametric statistics. All complete data sets were successfully fitted by both logistic regression analysis in Mathematica of the $\log_{10}$-transformed data and by interpolation to the geometric average of the last-seen and the first-not-seen stimulus values. The maximum difference between the 50% point on the logistic functions and interpolated values was less than 0.008 $\log_{10}$ units.

The median contrast threshold was 0.458 linear Michelson contrast at 0.083 cy/deg and 0.330 linear Michelson contrast at 0.303 cy/deg. The median visual acuity was 0.783 cy/deg (1.558 logMAR, 20/766 Snellen). These results are presented, along with their interquartile ranges, in Table 2. The $\log_{10}$ medians and 95% sampling intervals are shown as a CSF in Figure 2B and are the circles in Figures 3A and 3C. The contrast sensitivity at 0.083 and the visual acuity in experiment II were both less sensitive than the results of experiment I (Mann-Whitney U tests: $P = 0.004$ for contrast and $P = 0.001$ for acuity). We discuss this in depth in the Discussion.

For comparison to the present results, we reanalyzed the original data from two previous experiments,[1,4] applying our 50% seeing criterion for threshold. The contrast sensitivity results of experiment II were similar to the reanalyzed dLIM contrast sensitivity data from Brown et al.[1] (compare the circles in Figs. 3A, 3B). The visual acuity results of experiment II were similar to the reanalyzed dLIM results of Brown and Yamamoto[4] (compare the circles in Figs. 3C, 3D).

Discussion

This project had two main goals. The first was to determine whether the 0.083 cy/deg grating was suitable for measuring newborn infant contrast sensitivity. That is, will the contrast sensitivity of an infant, when measured using this grating, be close to the best contrast sensitivity of which that infant is capable? The second was to determine whether the newborn infant's CSF was band-pass (with a sensitivity peak at a spatial frequency below the acuity

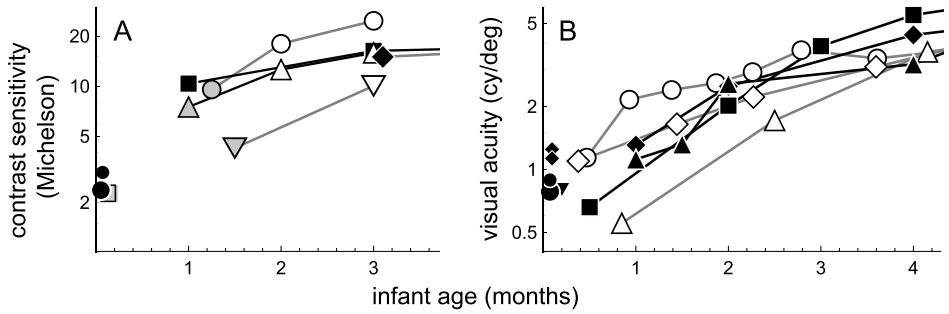

Figure 4. The present dLIM data (larger *black disks*: contrast data at 0.301 cy/deg, acuity data at 0.86 contrast) compared to data from the literature on infants age 4 months or younger (*lines* extending to the right indicate other data on infants over age 4 months). *Black symbols*, card data; *white* or *gray symbols*, forced-choice preferential looking (FPL) data. Data that were scored as the last-seen stimulus (e.g., see McDonald et al.[5]) are shown as one half "step" (typically, 0.075 $\log_{10}$ units) above their reported values so that all the data in both panels are defined at 75% correct (FPL) or 50% seeing ("yes/no"). For clarity, superimposed *data points* have been displaced by 2 days along the age axis. (A) Contrast sensitivity. *Gray symbols*, the maximum of the CSF is a lower bound on contrast sensitivity because the CSF was low-pass over the range of spatial frequencies tested. Data from Adams et al.[20] (*black squares*); Adams and Courage[21] (*black diamond*); Brown et al.[1] (*smaller black circle*); Slater and Sykes[22] (*gray square*); Atkinson et al.[19] (*white* and *gray circles*); Banks and Salapatek[15] (*white* and *gray upright triangles*); and Banks et al.[23] (*gray inverted triangles*). (B) Visual acuity. Data from Allen[24] (*white circles*[11,25]); Van Hof-Van Duin and Mohn[26] (*white diamonds*); Gwiazda et al.[27] (*white triangles*); McDonald et al.[5] (*black diamonds*); Mayer et al.[6] (*black triangles*), (*black squares*); Dobson[8] (*small black diamonds*); Ipata et al.[28] (*small black inverted triangle*), present data (*black circle*); Brown and Yamamoto[4] (*smaller black circle*).

limit) or low-pass (with sensitivity monotonically improving as spatial frequency is reduced).

To answer these questions, we fitted three alternative CSFs to the results of experiments I and II. The first (continuous curves in Fig. 2) was the shape of the adult CSF for square-waves, as predicted when the standard "modelfest" model of adult contrast sensitivity[9] was applied to square-wave stimuli (see Ref. 10 for review). Notice that this predicted CSF is truncated on the low spatial frequency end at about 0.19 $\log_{10}$ units below the maximum value, as is commonly found empirically in adult CSFs for square-wave stimuli (e.g., see reviews in Refs. 2 and 12). The second "modified modelfest" function (dashed curves in Fig. 2) was from the same model as the continuous curve, except that the contributions of the spatial frequency-tuned channels were combined using a Minkowski exponent of 1 instead of the more typical value of 4. In the third "generic low-pass" model (dotted curves in Fig. 2), the logarithm of contrast sensitivity is a linear function of linear spatial frequency.[13] We fitted these three models to the logistic contrast sensitivity and acuity data by displacing them relative to logarithmic spatial frequency and contrast axes. For experiment I, the curves all passed through the two median values, and the fits were uniquely determined. For experiment II, we used the nonparametric least median squares criterion[14] for the fits to the logistic threshold data. The standard model fit the results of experiment II best. We evaluated this fit statistically by calculating the residual difference between each model results (for the three threshold data points) and the measured thresholds of 10,000 combinations of the thresholds of three randomly chosen infants, one from each threshold group. In 7523 of the 10,000 cases, the modelfest data fit best; in 2477 cases the low-pass model fit best; and the generic model never fit best. This result rejects the hypothesis that all three models were equally good fits at $P < 10^{-6}$ on a binomial probability test.

The peak of the band-pass CSF was 0.232 contrast threshold (4.31 contrast sensitivity) at 0.234 cy/deg for the MCS results of experiment I and 0.311 contrast (3.15 contrast sensitivity) at 0.218 cy/deg for the dLIM data of experiment II. The largest difference between the peak CSF sensitivity and the CSF value at 0.083 cy/deg was for the band-pass model, where the difference was 0.148 $\log_{10}$ units (a factor of 1.41) in experiment I and 0.128 $\log_{10}$ units (a factor of 1.34) in experiment II. This result is quantitatively similar to the results of a similar analysis (see review in Ref. 10). In short, the choice of 0.083 cy/deg as a spatial frequency does not substantially underestimate infant contrast sensitivity.

Comparison to Previous Results

To place these results into the context of the published literature, Figure 4 shows the contrast sensitivity and visual acuity of infants from birth

through age 4 months, measured psychophysically using grating stimuli that do not drift or flicker. Where necessary, the results from those studies were adjusted to reflect the 50% seeing criterion of the results we report here. The contrast sensitivity data (Fig. 4A) are the maximum measured values near the peak of the CSFs. There is controversy about the shape of the CSF at age 1 month,[15–18] with some authors reporting low-pass CSFs in one-month-old infants and band-pass CSFs in older infants.[15,19] Therefore, some data in Figure 4A are lower-bound estimates because the maxima of the CSFs may have been below the spatial frequency ranges tested (gray symbols). See Movshon and Kiorpes[17] for a discussion on this point. Here, we show that even when tested using square-waves, the spatial CSF is band-pass at birth. The overall contrast sensitivity results on newborn infants are generally what one would expect by extrapolating from the data on older infants.

The band-pass shape of the CSF from the present experiments may be compared to the results of two other studies of the contrast response in newborn infants. Atkinson et al.[29] measured newborn contrast responses using visually evoked potentials (VEPs) and showed low-pass CSFs using 10-Hz flickering stimuli. However, their results are not incompatible with ours because flickering stimuli yield low-pass CSFs with both psychophysical[30] and VEP[31] methods in subjects of all ages. In a psychophysical experiment, Slater and Sykes[22] measured contrast threshold at 0.43 cy/deg (gray square, Fig. 4) and also a point of subjective equality (PSE) between visible square-wave gratings at 0.1 cy/deg and 0.43 cy/deg. Their PSE occurred when the 0.1 cy/deg grating was 0.21 $\log_{10}$ units lower in contrast, suggesting a low-pass underlying CSF. Figure 2 predicts that the contrast sensitivity at those two spatial frequencies should be essentially equal (difference < 0.032 $\log_{10}$ units). We are unsure why their results differ from ours, but we suspect this is related to their lower luminance levels (44 vs. 299 cd/m^2), which would probably have moved the peak of the underlying CSF to lower spatial frequencies,[30,32] producing the appearance of a low-pass function under their conditions.

The visual acuity values from the present experiment (the big black circle in Fig. 4B) are quite compatible with the known development of visual acuity in older infants.

The precision of the present results can also be compared with data from the literature. For contrast sensitivity, the literature reports 95% sampling confidence intervals (about 4 standard errors of the mean) for 1-month-old infants measured at 0.3 cy/deg to be 1.52 $\log_{10}$ units (MCS)[15] and 0.474 (dLIM).[20] For comparison, our full 95% sampling confidence interval at 0.3 cy/deg was 0.568 $\log_{10}$ units (dLIM) (Table 2). The visual acuity literature reports 95% sampling confidence intervals of 0.48—0.65 $\log_{10}$ units (newborn)[8,28] and 0.304 $\log_{10}$ units (1-month-old infants),[6] both measured using dLIM, whereas our 95% sampling confidence intervals were 0.328 $\log_{10}$ units (MCS) and 0.602 $\log_{10}$ units (dLIM) (Table 2). On the individual level, we calculated the range embraced by the 84th percentile and the 16th percentile of our individual threshold data as our best approximation to the ± 1 SD in parametric statistics. For contrast sensitivity, the literature shows a $\pm$SD range of 1.861 $\log_{10}$ units measured using MCS[15] and 1.06 $\log_{10}$ units using dLIM,[21] both at 0.3 cy/deg and both on 1-month-old infants, compared to a 16th to 84th percentile range of 0.433 $\log_{10}$ units for contrast at 0.3 cy/deg for the present data on newborns. For visual acuity, the literature showed $\pm$SD range of 0.32 to 0.44 $\log_{10}$ units on newborns[8,28] and 0.259 $\log_{10}$ units for 1-month-old infants,[6] both measured using dLIM. This may be compared to 16th- to 84th-percentile ranges of 0.416 $\log_{10}$ units (MCS) and 0.433 $\log_{10}$ units (dLIM) for the present data sets. Thus, the precision of the present results, both in how precisely we know the means of our data and in the range of data values obtained, is wholly comparable to the results obtained by other investigators on newborn and one-month-old infants.

Psychophysical Methods

In comparing the results obtained using MCS in experiment I and dLIM in experiment II, we found a consistent, statistically significant difference between the two methods, with MCS producing better performance than dLIM (Figs. 3A, 3C: compare the diamonds to the circles). Here, we account quantitatively for this discrepancy.

Consider an ordered set of stimuli **a**, **b**, **c**, **d**, **e**, with **a** being easiest to see and **e** being the hardest to see. Let $P_{mcs}(\mathbf{a})$, $P_{mcs}(\mathbf{b})$, . . . $P_{mcs}(\mathbf{e})$ be the probability that each stimulus is "presented" under MCS, and let $P_{dlim}(\mathbf{a})$ . . . $P_{dlim}(\mathbf{e})$ be the probably that it is presented under dLIM. Let S(**a**), S(**b**) . . . S(**e**) be the independent probability that each stimulus will be "seen" if it is presented (under either method). Data D(**n**) associated with a typical stimulus **n** will be

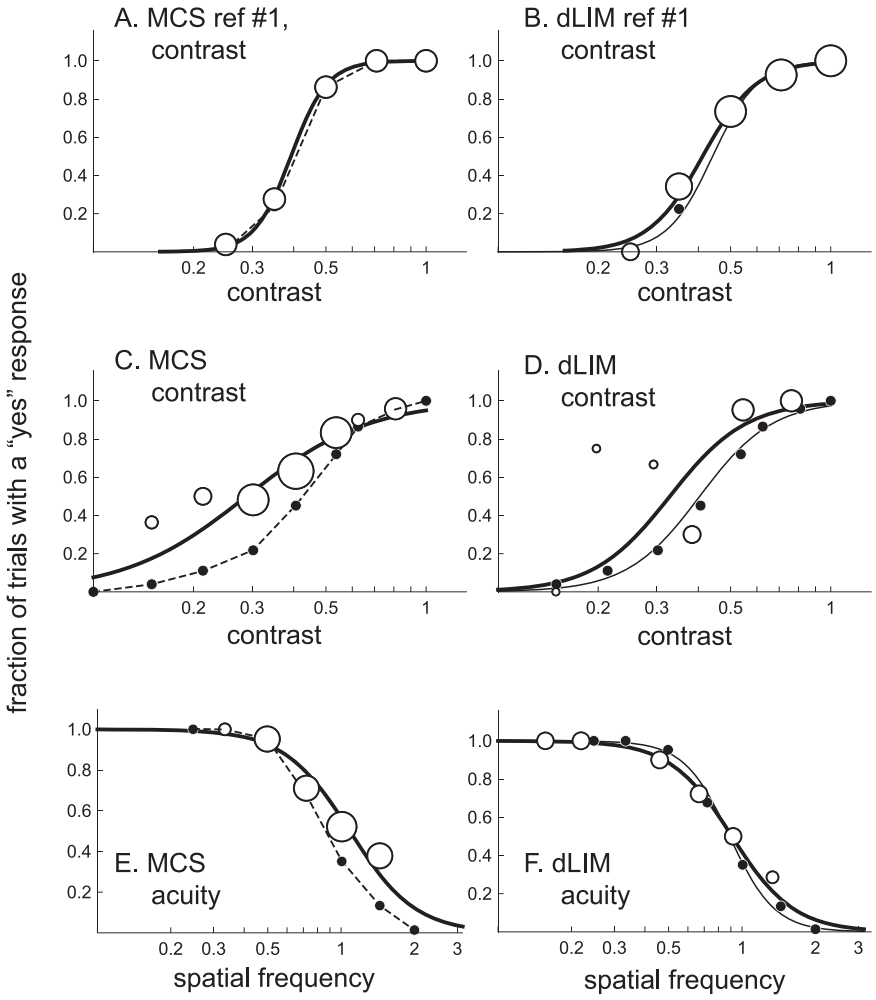

Figure 5. Group psychometric functions. Data collected using dLIM (*right panels*) are compared to data collected using MCS (*left panels*). *White circles* indicate pooled data on all infants (including incomplete data sets), with the area of each *data point* proportional to the number of observations. *Bold smooth curves* are weighted logistic functions fitted to the *white data points. Black dots* indicate predicted dLIM performance from simulations based on MCS data. *Dashed lines* in *left panels* are the analytic predictions from Eq. 5, *fine smooth curves* fitted to the simulations. (A, B) Results from Brown et al.[1]; (C–F) results of the present experiment.

$$D(\mathbf{n}) = P(\mathbf{n}) \times S(\mathbf{n}). \quad (1)$$

Under MCS, $P_{mcs}(\mathbf{n})$ will always be 1, because every stimulus in the stimulus set was presented as long as the infant was awake, thus

$$D_{mcs}(\mathbf{n}) = S(\mathbf{n}). \quad (2)$$

Under dLIM, stimulus **n** will be presented only if every higher-valued stimulus value in the series is presented and seen. Taking stimulus **d** as an example, the data under dLIM [$D_{dlim}(\mathbf{d})$] can be predicted from the data under MCS [e.g., $D_{mcs}(\mathbf{d})$]:

$$P_{dlim}(\mathbf{d}) = D_{mcs}(\mathbf{a}) \times D_{mcs}(\mathbf{b}) \times D_{mcs}(\mathbf{c}). \quad (3)$$

Substituting $P_{lim}(\mathbf{d})$ from Eq. 3 into Eq. 1,

$$D_{dlim}(\mathbf{d}) = D_{mcs}(\mathbf{a}) \times D_{mcs}(\mathbf{b}) \times D_{mcs}(\mathbf{c}) \times S(\mathbf{d}). \quad (4)$$

Substituting from Eq. 2,

$$D_{dlim}(\mathbf{d}) = D_{mcs}(\mathbf{a}) \times D_{mcs}(\mathbf{b}) \times D_{mcs}(\mathbf{c}) \times D_{mcs}(\mathbf{d}) \quad (5)$$

(see Pelli et al.,[33] Eq. 6, for a similar approach). Thus, the probability that typical stimulus **n** will be seen if it is presented will be lower under dLIM than it is under MCS.

To test this prediction, we pooled all the complete and incomplete MCS and dLIM data sets into their respective group psychometric functions (bold logistic curves, Figs. 5C–F), where the abscissa was the

stimulus value of contrast or spatial frequency and the ordinate was the total "yes" responses across all infants divided by the number of infants who were presented that stimulus. We also applied the same analysis to the data from Brown et al.[1] (Figs. 5A, 5B).

We predicted the dLIM psychometric functions from the MCS data using Eq. 5 (dashed lines in Figs. 5A, 5C, 5E). We confirmed the analysis by simulating 1000 dLIM experiments, each on 20 simulated infants. Each simulated infant started at 100% contrast or 0.01 cy/deg and contributed a "yes" or "no" response for each stimulus value in a descending sequence. The response for each stimulus was "yes" with probability equal to the observed fraction "yes" responses for the corresponding MCS contrast or acuity stimulus, interpolating along the logistic MCS curve if necessary. Each simulated dLIM data set remained "no" after the first "no" response was reached. The fraction "yes" in the simulation analysis agreed well with the analytic prediction from Eq. 5 (the black dots are the simulated data and are close to the dashed lines in Figs. 5A, 5C, 5E). We applied this analysis to the results of experiments I and II, as well as the MCS and dLIM data from Brown et al.[1] The results were encouraging: the small black dots and the smooth curve drawn through them fall close to all the dLIM data (white circles in Figs. 5B, 5D, 5F).

To compare the simulated dLIM results to the dLIM data quantitatively, we fitted a logistic function to the psychometric data from each simulated infant to produce a simulated 50% "yes" threshold. Next, we collated these individual threshold results into simulated 20-infant experiments. The final results of the simulation were the medians and the 95% sampling intervals of the median results of 1000 simulated experiments. The predicted thresholds from the simulations (listed as the "sampling distributions" for the "dLIM pred" results in Table 2 and shown as squares in Fig. 3) agreed well with the empirical thresholds (circles in Fig. 3).

The predicted difference between dLIM and MCS is generally greater when there are many stimuli separated by steps that are small when compared to the steepness of the psychometric function (as in Figs. 5C, 5E). This is because there are many steps of probabilities between 0 and 1 to be multiplied together in Eq. 5. By comparison, there is little difference between MCS results and dLIM predictions or data when the step size is larger compared to the steepness of the psychometric function (as in Figs. 5A, 5B). This suggests that clinical measurement using dLIM will be closer to the MCS results if larger step sizes are used, for example steps of 0.301 $\log_{10}$ units in contrast or one octave of spatial frequency.

More generally, predicted dLIM performance in the present experiments was both qualitatively (fine lines in Figs. 5B, 5D, 5F) and quantitatively (compare the squares to the circles in Fig. 3) similar to the empirical dLIM results. Therefore, we see very little reason to invoke explanations of the difference between MCS and dLIM based on the effort of the examiner, the alertness of the infant, or the incomplete blinding of the examiner to the values of the stimuli being presented in dLIM. This should be good news to those who use dLIM in a clinical setting.

Conclusions

The visual acuity of the newborn infant is 0.783 to 1.204 cy/deg, depending on psychometric method, which is similar to the overall results obtained by others using a range of methods.[8]

The CSF of the newborn infant is band-pass, with a peak located near 0.23 cy/deg. The peak contrast threshold of the newborn infant is about 0.232 to 0.311 contrast, depending on the psychophysical method.

A good square-wave spatial frequency for testing the contrast sensitivity of newborn infants is 0.083 cy/deg because it underestimates an infant's maximum contrast sensitivity by no more than 0.15 $\log_{10}$ units (a linear factor of 1.41), no matter what shape of CSF is assumed.

MCS yields better performance than dLIM, but the results of the two methods predict similar performance once the contingent presentation of stimuli under dLIM is taken into account. The agreement between dLIM and MCS is better when fewer stimuli, separated by wider step sizes, are used. dLIM can be used clinically on newborn infants with confidence.

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References

1. Brown AM, Lindsey DT, Cammenga JG, Giannone PJ, Stenger MR. The contrast sensitivity of the newborn human infant newborn contrast sensitivity. *Invest Ophthalmol Vis Sci*. 2015;56:625–632.
2. Campbell F, Robson J. Application of Fourier analysis to the visibility of gratings. *J Physiol*. 1968;197:551–566.
3. Hopkins GR, Douherty BE, Brown AM. The Ohio Contrast Cards: visual performance in a pediatric low-vision site. *Optom Vis Sci*. 2017;94:946.
4. Brown AM, Yamamoto M. Visual acuity in newborn and preterm infants measured with grating acuity cards. *Am J Ophthalmol*. 1986;102:245–253.
5. McDonald M, Dobson V, Sebris SL, Daich L, Varner D, Teller DY. The acuity card procedure: a rapid test of infant acuity. *Invest Ophthalmol Vis Sci*. 1985;26:1158–1162.
6. Mayer DL, Beiser AS, Warner AF, Pratt EM, Raye KN, Lang JM. Monocular acuity norms for the Teller Acuity Cards between ages one month and four years. *Invest Ophthalmol Vis Sci*. 1995;36:671–685.
7. Lewis TL, Maurer D. The development of the temporal and nasal visual fields during infancy. *Vision Res*. 1992;32:903–911.
8. Dobson V, Schwartz TL, Sandstrom DJ, Michel L. Binocular visual acuity of neonates: the acuity card procedure. *Dev Med Child Neurol*. 1987;29:199–206.
9. Watson AB, Ahumada AJ. A standard model for foveal detection of spatial contrast. *J Vis*. 2005;5:6–6.
10. Hopkins GR, Dougherty BE, Brown AM. The Ohio Contrast Cards: visual performance in a pediatric low-vision site. *Optom Vis Sci*. 2017;94:946–956.
11. Mayer DL, Dobson V. Grating acuity cards: validity and reliability in studies of human visual development. In: Dobbing J, ed. *Developing Brain Behaviour: The Role of Lipids in Infant Formula*. San Diego, CA: Academic; 1997:253.
12. Campbell FW, Howell ER, Johnstone JR. A comparison of threshold and suprathreshold appearance of gratings with components in the low and high spatial frequency range. *J Physiol*. 1978;284:193–201.
13. Campbell FW, Green DG. Optical and retinal factors affecting visual resolution. *J Physiol*. 1965;181:576–593.
14. Rousseeuw PJ. Least median squares regression. *J Am Statist Assoc*. 1984;79:871–880.
15. Banks M, Salapatek P. Acuity and contrast sensitivity in 1-, 2-, and 3-month-old human infants. *Invest Ophthalmol Vis Sci*. 1978;17:361–365.
16. Atkinson J, Braddick O, Moar K. Development of contrast sensitivity over the first 3 months of life in the human infant. *Vision Res*. 1977;17:1037–1044.
17. Movshon JA, Kiorpes L. Analysis of the development of spatial contrast sensitivity in monkey and human infants. *J Opt Soc Am*. 1988;5:2166–2172.
18. Peterzell DH, Teller DY. Individual differences in contrast sensitivity functions: the lowest spatial frequency channels. *Vision Res*. 1996;36:3077–3085.
19. Atkinson J, Braddick O, Moar K. Contrast sensitivity of the human infant for moving and static patterns. *Vision Res*. 1977;17:1045–1047.
20. Adams RJ, Courage ML. Using a single test to measure human contrast sensitivity from early childhood to maturity. *Vision Res*. 2002;42:1205–1210.
21. Adams RJ, Courage ML. Monocular contrast sensitivity in 3-to 36-month-old human infants. *Optom Vis Sci*. 1996;73:546–551.
22. Slater A, Sykes M. Newborn infants' visual responses to square wave gratings. *Child Dev*. 1977;545–554.
23. Banks MS, Stephens BR, Hartmann EE. The development of basic mechanisms of pattern vision: spatial frequency channels. *J Exp Child Psychol*. 1985;40:501–527.
24. Allen JL. *Visual Acuity Development in Human Infants up to 6 Months of Age*. Seattle, WA: University of Washington, 1979. Unpublished doctoral dissertation.
25. Teller DY. The development of visual acuity in human and monkey infants. *Trends Neurosci*. 1981;4:21–24.
26. Van Hof-Van Duin J, Mohn G. The development of visual acuity in normal fullterm and preterm infants. *Vision Res*. 1986;26:909–916.
27. Gwiazda J, Brill S, Mohindra I, Held R. Preferential looking acuity in infants from two to fifty-eight weeks of age. *Optom Vis Sci*. 1980;57:428–432.
28. Ipata A, Cioni G, Boldrini A, Bottai P, Van Hof-van Duin J. Visual acuity of low-and high-risk

neonates and acuity development during the first year. *Behav Brain Res*. 1992;49:107–114.
29. Atkinson J, Braddick OJ, French J. Contrast sensitivity of the human neonate measured by the visual evoked potential. *Invest Ophthalmol Vis Sci*. 1979;18:210–213.
30. Kelly D. Adaptation effects on spatio-temporal sine-wave thresholds. *Vision Res*. 1972;12:89–I N81.
31. Norcia AM, Tyler CW, Hamer RD. Development of contrast sensitivity in the human infant. *Vision Res*. 1990;30:1475–1486.
32. Van Nes F, Koenderink J, Nas H, Bouman M. Spatiotemporal modulation transfer in the human eye. *J Opt Soc Am*. 1967;57:1082–1088.
33. Pelli DG, Robson JG, Wilkins AJ. The design of a new letter chart for measuring contrast sensitivity. *Clin Vis Sci*. 1988;2:187–199.

Table A1. Stimuli Used in Experiment I

Contrast Sensitivity							Visual Acuity								
	Set 1		Set 2		Set 3			Sets 1, 2				Set 3			
Stim[a]	Contrast[b]	*N*[c]	Contrast	*N*	Contrast	*N*	Stim	cy/deg[d]	logMAR	Snellen[e]	*N*	cy/deg	logMAR	Snellen	*N*[c]
1					0.123	5	11	2.84	1.024	211	2				
2	0.153	1					12	2	1.176	300	25	1.84	1.213	326	16
3					0.174	5	13	1.44	1.319	417	23	1.33	1.352	450	14
4	0.213	4	0.232	4			14	1.01	1.473	594	30	0.92	1.514	652	16
5	0.298	10	0.313	3	0.261	19	15	0.72	1.620	833	21	0.67	1.653	900	17
6					0.362	20	16	0.5	1.778	1200	29	0.46	1.815	1305	13
7	0.425	9	0.411	8			17	0.33	1.959	1818	11				
8			0.528	8	0.504	20	18	0.25	2.079	2400	7				
9	0.604	2	0.649	8	0.695	11									
10	0.86	1	0.812	1											

[a] Stim, stimulus number. For analysis, contrast sensitivity data and visual acuity data are pooled across stimuli within rows. All contrast cards in experiment 1 were at 0.083 cy/deg.
[b] Contrast is in Michelson units.
[c] Number of subjects tested with the card set listed at the head of each group.
[d] Cycles per degree of visual angle, at a test distance of 38 cm.
[e] Snellen denominator; the Snellen numerator was always 20.

Table A2. Stimuli Used in Experiment II

Contrast Sensitivity				Visual Acuity				
Nominal Contrast[a]	Calibrated Contrast	*N*[c]	*N*[d]	Nominal cy/deg	Calibrated cy/deg	logMAR	Snellen[e]	*N*[f]
0.125	0.149	3	4	1.89	1.84	1.213	326	3
0.175	0.198	4	8	1.33	1.33	1.352	450	7
0.25	0.293	6	11	0.95	0.92	1.514	652	14
0.35	0.383	20	18	0.67	0.67	1.653	900	18
0.50	0.545	21	19	0.48	0.46	1.815	1305	20
0.71[b]	**0.762**	**21**	**21**	**0.22**	**0.22**	**2.137**	**2741**	**21**
0.86	**0.866**	**16**	**16**	**0.17**	**0.16**	**2.283**	**3838**	**14**
0.86	**0.866**	**7**	**6**	**0.11**	**0.12**	**2.400**	**5025**	**9**

[a] Contrast is in Michelson units.
[b] Bold numbers are the "easy" stimuli used in the dLIM protocol.
[c] Number of infants tested at 0.083 cy/deg.
[d] Number of infants tested at 0.301 cy/deg.
[e] Snellen denominator; the Snellen numerator was always 20.
[f] Number of infants tested with the visual acuity gratings.