Volume 3 number 3 1984

Current Eye Research

The development of vernier acuity in infants

Ruth E. Manny and Stanley A. Klein

University of Houston, College of Optometry, Houston, TX 77004, USA

Received on 8 September 1983; accepted on 22 November 1983

ABSTRACT

Vernier and grating acuity were measured in infants up to 6 months of age using a two-alternative forced-choice preferential looking technique. Vernier resolution was measured using a horizontal vernier grating. The grating was presented on half of the screen while the other half contained horizontal lines which were continuous with the vernier grating. Movement artifacts were eliminated by making both halves of the display move as the offsets were introduced in half of the display field. Vernier acuity, like grating acuity, improved about 3 octaves over the first 6 months of life. Moreover, the vernier resolution of infants, as of adults, was better than grating resolution.

INTRODUCTION

One of the finest measures of spatial resolution, vernier acuity, requires the detection of an offset or misalignment (1). Since vernier thresholds in adults with normal vision are better than would be naively predicted on the basis of the optical or anatomical properties of the eye, vernier acuity has been termed hyperacuity to distinguish it from other measures of visual acuity (2). While the mechanism(s) responsible for vernier discriminations remain speculative, they are believed to represent cortical processing (3,4).

Over the past decade, numerous behavioral and electrophysiological techniques have been used to study the development of the visual system's capacity to discriminate or detect sine or square wave gratings (see (5) for a review). Grating acuity has been shown to improve over the first year of life and this improvement in resolution is believed to be the result of neural development rather than an improvement in image quality (5,6). However, nothing is known about the development of the finer spatial resolving abilities shown by adults for vernier targets. If the developmental time course is different for vernier and grating acuity these two measures of spatial resolution could be tapping different neural mechanisms. The purpose of this study was to describe the development of vernier acuity in human infants over the first six months of life.

In addition to adding to the understanding of spatial resolution and its development, the measurement of vernier acuity in human infants may have important clinical implications. Vernier acuity, like other measures of spatial resolution, is reduced in adults with strabismic and anisometropic amblyopia. Unlike anisometropic amblyopes, strabismic amblyopes show a greater reduction in vernier acuity than would be expected based on measures of grating acuity (7). Thus, vernier resolution may be a more sensitive index of losses in spatial resolution present in certain ocular disorders. A description of the normal development of vernier resolution in human infants is important for understanding the effects of abnormal visual experience on the development of this fine spatial capacity.

METHODS

Subjects

Infants 6 months of age and younger were recruited by flyers distributed in natural childbirth classes and placed around the university campus. Parents were paid $5.00 per session and their infants received a complimentary eye examination. Infants were excluded from the study if large refractive errors (greater than 2.00D myopia, 3.00D hyperopia or 2.00D astigmatism) were found by near retinoscopy (8) or if

TABLE 1: The total number of infants who began the vernier and grating acuity assessments along with the number of infants who did not complete testing (fussy/asleep) and those who completed testing but whose data sets were near chance using a binomial comparison (see Appendix) are shown for each age group. The screen size used to test each age group is also indicated.

Age (weeks)	Screen Size (min)	VERNIER Total attempted	VERNIER Fussy/ asleep	VERNIER Chance data	VERNIER Successful	GRATING Total attempted	GRATING Fussy/ asleep	GRATING Chance data	GRATING Successful
2	222	7	3	1	3	7	0	1	6
4	222	4	0	3	1	5	0	0	5
6	222 & 156	7	0	5	2	7	1	0	6
8	156	10	2	4	4	12	0	1	11
10	156	3	0	1	2	5	1	0	4
12	156 & 110	11	1	1	9	12	1	1	10
14	156 & 110	8	1	0	7	8	1	1	6
16	110	11	0	1	10	11	0	1	10
18	110 & 78	6	0	0	6	7	0	1	6
20	110 & 78	8	0	0	8	9	2	0	7
22	110 & 78	3	0	0	3	3	0	0	3
24	78 & 55	10	0	3	7	10	1	1	8

other ocular abnormalities were noted during the eye examination. Those infants born more than 3 weeks premature (by the parents' report) were also excluded from the study. Table 1 shows the total number of infants evaluated at each 2-week interval (total attempted) and the number of infants who successfully completed the testing (successful).

Several infants were tested at more than one age and some were tested twice in the same session. Thirty-four infants generated 62 different vernier sessions (15 tested at 1 age, 14 tested at 2 ages, 2 tested at 3 ages, 2 tested at 4 ages and 1 tested at 5 ages). In addition, five infants were tested twice during the same session. Thus, a total of 67 vernier thresholds were measured. Vernier resolution was also measured in 2 adults with normal binocular vision.

Stimulus

Vernier resolution was measured behaviorally using the two-alternative forced-choice preferential looking procedure described by Teller et al. (9) and Teller (10). The stimulus, a horizontal vernier grating, was generated with a microprocessor (Commodore VIC-20) and displayed on a 12-inch black and white monitor (Amdek 100). The vernier grating was presented on half of the screen while the other half contained horizontal lines which were continuous with the vernier grating. In order to present an adequate range of vernier offsets to infants of various ages while maintaining a viewing distance of 0.5m, the gain of the vertical amplifier of the monitor was modified so that the vertical dimension of the screen could be varied in five discrete steps. Screen sizes ranged from 20.3° (screen size 1) to 5.2° (screen size 5) in approximately half-octave steps. Changing the vertical dimension of the screen varied the spacing of the lines composing the vernier grating from 222 min for screen size 1 to 55min for screen size 5 at the 0.5m viewing distance. The width of each line was always 18.5% of the spacing. Thus, the fundamental spatial frequency of the vernier grating ranged from 0.27 c/deg to 1.1 c/deg at 0.5 meters. The horizontal dimension of the vernier grating (25.5°) remained constant for all screen sizes. In order to test the adults using the same apparatus and staircase, viewing distances were increased to 20 to 24 m. At these distances the fundamental spatial frequency of the vernier grating varied between 24.6 and 26.9 c/deg. The line intensity of the vernier target (measured by the luminance times the line width) was 19cd/cm and was unchanged for all screen sizes since the luminance was inversely proportional to screen size, whereas line width was directly proportional to screen size. The space average luminance of the vernier test varied by 0.53 log units from screen size 1 to screen size 5. The small change in luminance which occurred as the screen size was varied, did not affect the thresholds of the adult observer. Hence, it is unlikely that the infants' thresholds were influenced by this small luminance difference. In addition, a recent report by Dobson et al. (11) suggests that grating acuity is relatively independent of luminance for gratings in this luminance range.

The test phase of the vernier grating is shown in the inset of Fig. 2. The white border served to illuminate the infant's face. Before the vernier offset was presented, the screen contained unbroken horizontal lines. A movement artifact might have been possible if the infants were attracted to the motion rather than to the vernier offset. Movement artifacts were eliminated by displacing the entire display upwards except for a few short line segments which were displaced less to create the vernier offset. By this technique motion could not be used as a cue. The pattern then remained stationary until a judgment about the infant's preference was made. The judgment was typically made within 2 sec.

Procedure

Infants were held by a parent 0.5m from the screen. Based on the infant's age, the screen size was selected to place the eight stimuli (covering about a 3 octave range) more or less symmetrically about the anticipated threshold. The screen sizes used for each age group are shown in Table 1. All testing was done binocularly with the room lights off. The parent's view of the screen was blocked by wearing a pair of spectacles covered with frosted tape. Observers were required to judge the location of the stimulus (by viewing the infant's eye movements and other behavioral cues) and were given trial-by-trial auditory feedback (10). On each trial the observer made an estimate of her/his confidence in the judgment of the stimulus location. The low confidence judgments were weighted at half the value of the high confidence judgments during the offline estimates of threshold (see Appendix). Six trained observers were used to test the infants.

The vernier stimuli were presented using a staircase procedure. In the staircase procedure, a rapid maximum likelihood search program similar to that described by Pentland (12), Watson and Pelli (13) and Klein (14) was used to obtain an estimate of the threshold after each trial. The stimulus size for the next trial was then placed (with equal probability) one stimulus level (approximately 1/3 octave) either above or below the estimated threshold. Thus, the maximum likelihood staircase placed the stimuli on the steep portion of the psychometric function. Threshold estimates were based on the results of 25 to 35 trials. Figure 1 illustrates a typical data set obtained from the staircase. The filled symbols show the observer's percent correct as a function of the vernier offset in minutes of arc. The open symbols represent the percent correct when the low confidence trials are evaulated differently (Δ high confidence only; O low

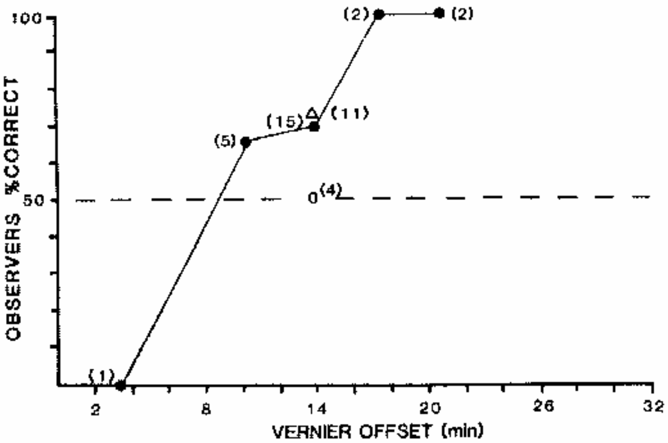

Figure 1. An example of a typical data set obtained by the maximum likelihood staircase is shown as the observer's percent correct as a function of the vernier offset in minutes. The filled symbols illustrate the observer's percent correct when the low confidence trials are weighted at half the value of the high confidence trials. The open symbols represent other manipulation of the low confidence trials (Δ high confidence trials only; O low confidence trials only). The number of trials used to determine the percent correct is shown in parentheses near each data point.

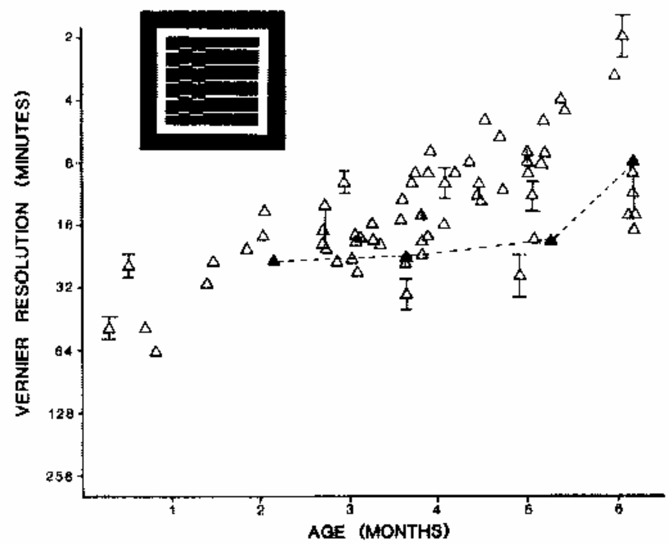

Figure 2. Vernier resolution in minutes of arc as a function of age in months. Due to the changes in screen size with age, the abscissa represents both age and luminance. The filled symbols connected by the dashed line are the results of one infant tested longitudinally. This infant is the same infant represented in Fig. 3 connected with the dashed line. The five pairs of data points connected with vertical lines represent two measures of threshold repeated on the same infant in one session. Representative error bars depicting ±1 standard error are shown. The half-filled symbol is the threshold obtained from the data set shown in Figure 1.

confidence only). The number of trials per point is shown in parentheses. Thresholds were then calculated off-line using a modified probit analysis. Details of the off-line data analyses are described in the Appendix.

RESULTS

Figure 2 shows the individual vernier thresholds obtained for all runs which were successfully completed. Vernier acuity in minutes of arc is plotted as a function of age in months. The age of premature infants was adjusted and thresholds were plotted according to conceptional age (5). For clarity, the error bars depicting ±1 standard error as obtained from the maximum likelihood fit (see Appendix) are shown for only a representative sample of threshold estimates. For infants less than 24 weeks of age, the variability (standard deviation) of infants of a given age was 0.5 octaves. This variability agrees with the data shown in Figure 2 with 37 of 59 infants (63%) falling within a 1-octave band. One of the infants tested longitudinally is shown by the filled symbols. Those infants tested twice in the same session are shown by the five pairs of thresholds connected with a vertical line. These data are similar to those reported for grating acuity (see (5) for review), showing an improvement in vernier acuity as a function of age.

To compare the development of vernier acuity with the development of grating acuity, square wave grating acuity was also measured in these infants using the same apparatus and staircase procedure. In an attempt to equate the two test conditions as much as possible, the same apparatus and staircase procedure were used to measure both thresholds. Both vernier and grating resolution were attempted on each infant during a single session but the order of testing

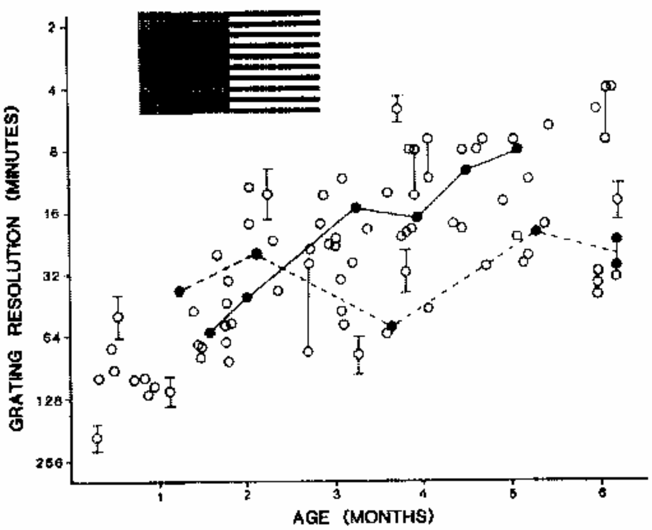

Figure 3. Grating resolution in minutes of arc as a function of age in months. Due to the changes in screen size with age, the abscissa represents both age and luminance. The filled symbols connected with the solid or dashed lines show two infants who were tested longitudinally. The six pairs of data points connected with vertical lines represent two measures of threshold repeated on the same infant in one session. Representative error bars depicting ±1 standard error are shown.

was varied among the infants. In addition, the same observer was used for both the grating and vernier acuity testing on a single infant and the same screen size was used for both resolution measures. However, the duty cycle varied between the two displays; a 50% duty cycle was selected for the square wave grating to conform with previous measures of grating acuity (5). The duty cycle of the vernier display was 18.5%. Due to the difference in the duty cycles of the two tasks, it was not possible to equate the space average luminance of the two resolution tasks and also to equate the luminance of the bright bars of the vernier target and the square wave grating. Hence, the luminance of the bright bar of the grating was equated to the luminance of the vernier bar. An additional difference between the two measures was that the infants were reinforced with a cartoon figure and music following a correct response by the observer during the estimates of grating threshold (15), although no attempt was made to operantly train the infants. No figure or music was used during the vernier measurements. The consequences of these differences between the vernier and grating measures are addressed in greater detail in the Discussion.

Figure 3 shows the individual grating thresholds obtained for thirty-nine infants (16 tested at 1 age, 12 tested at 2 ages, 3 tested at 3 ages, 5 tested at 4 ages, 1 tested at 5 ages, 1 tested at 6 ages). Thresholds obtained from six infants tested twice in the same session are connected by a vertical line. Two of the infants tested longitudinally are shown by the filled symbols. While both infants showed no abnormalities upon ocular examination, the infant shown by the dashed line was atypical in that little change in resolution was noted over the ages tested. The age of premature infants was adjusted as in Figure 2. The error bars depicting ±1 standard error as obtained from the maximum likelihood fit are shown for a representative sample. The variability (standard deviation) among infants less than 24 weeks of age was around 0.8 octaves. Although the grating acuity is poorer (1 to 2 octaves) than that typically reported for preferential looking acuity in this age group using similar contrast and space average luminance values, the data show improvement in resolution (approximately 3 octaves) over the first six months of life similar to that previously reported by others (5,15,16,17). These poorer acuities may be the result of the stimulus configuration and/or staircase procedure. The stimulus configuration was selected to be similar to that used for the measurement of vernier acuity and, hence, the field size was smaller than that typically used by other investigators. In addition, the two paired stimuli were presented adjacent to one another in a discrimination paradigm which required the observers to detect small eye movements from midline. Furthermore, the maximum likelihood staircase tended to place the trials close to the infant's threshold. While this procedure has the

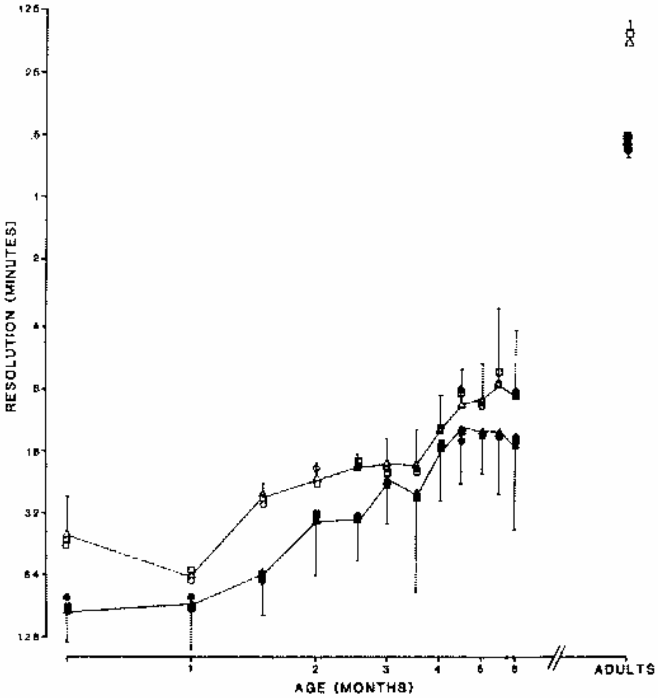

Figure 4. The geometric means of the grating acuity (filled symbols) and vernier acuity (open symbols) in minutes of arc as a function of age (and luminance). The different symbols show the thresholds determined when different slopes were used in the probit analysis (O = 0.1; Δ = 0.3; □ = 0.6). The error bars show one standard deviation for the thresholds determined using a slope of 0.3. No error bar is shown for the vernier threshold at one month of age since it represents the threshold of a single infant. The vernier error bars at 1½ and 2½ months are each based on two infants who by coincidence happened to have similar thresholds producing abnormally small error bars.

advantage of placing trials where the psychometric function is the steepest, the infant's attention may wane when most stimuli are presented near threshold. Any or all of these factors could be contributing to the poor grating acuities reported here.

In order to display the changes with age in both vernier and grating resolution, the thresholds in each age group were averaged on an octave scale. The mean thresholds for grating resolution (filled symbols) and vernier resolution (open symbols) in minutes of arc are plotted as a function of age in months on log-log coordinates in Fig. 4. The threshold obtained by a probit fit for several slopes of the psychometric function with the upper asymptote fixed at 0.9 are shown by the different symbols (O = 0.1 octaves; Δ = 0.3 octaves; □ = 0.6 octaves). Slope, as used here, is the number of octaves per standard deviation of the cumulative normal psychometric function. Error bars are shown for the 0.3 octave slope and represent one standard deviation. The standard deviations obtained for the other slopes were similar. The vernier threshold at one month represents a single threshold for one infant and, hence, no error bar is shown. It is interesting that large changes in the slope of the psychometric function have very little effect on either the grating or the vernier thresholds. This may be attributed to the use of a staircase procedure which concentrates the data near threshold. The differences in grating and vernier thresholds seen individually in Figs. 2 and 3 are also apparent in the grouped data shown in Fig. 4. These results show that: 1) both vernier and grating resolution improve approximately 3 octaves over the first six months of life; 2) the variability of the vernier estimates is less than that of the grating thresholds; and 3) vernier acuity in infants, as in adults, is better than grating acuity.

To compare the vernier and grating resolution of infants to that of adults tested under similar conditions and to check for possible stimulus artifacts in the system, two adults with normal binocular vision and with no experience on these tasks were tested (see METHODS for additional details). Thresholds were determined using 100 trials for each staircase. The data were analysed in the same manner as those for the infants. Grating resolution averaged for the two adults was 0.54 minutes, while vernier resolution was 0.16 minutes. This grating resolution is not unexpected for normal observers detecting high contrast square wave gratings (15). The average vernier resolution, 9.6 seconds, is within the range reported for normal unpracticed observers using a variety of stimulus configurations

(18,19, 20).

DISCUSSION

The average spatial resolution of adults with normal vision is better for vernier stimuli than for square wave gratings and this superior resolution for vernier targets is also found for infants under 6 months of age. The results shown in Figure 4 also suggest that the difference between the vernier and grating resolution found in adults may be greater than that found in infants. However, several methodological differences between the measurements of vernier and grating acuity suggest using caution with this interpretation of the results. For example, a white border was used to illuminate the infant's face during the measurements of vernier acuity but was not needed during the grating acuity measurements due to the brighter display. The presence of the border may have distracted the infant during the assessment of vernier acuity.

Another factor which could have contributed to the difference between the vernier and grating acuities found in adults compared to that found for the infants was the use of a reinforcer during estimates of grating acuity. While observers received trial-by-trial auditory feedback during both grating and vernier resolution measures, infants were visually reinforced when the observer was correct only during the estimates of grating threshold. Although no attempt was made to condition the infant to the reinforcer, the reinforcer could have improved the infants' performance on the grating task, reducing the difference between the grating and vernier thesholds for the infants compared to that of the adults (21).

The duty cycles of the two tasks also differed. An equal duty cycle (50%) was used for the square wave grating acuity while an 18.5% cycle was used to assess vernier acuity. These different duty cycles resulted in a different space average luminance for the vernier and grating displays, since the luminance of the bright bar of the grating was equated to the vernier bar. It is possible that the lower space average luminance of the vernier display resulted in poorer thresholds relative to those measured with the grating display.

It is interesting, however, that despite these methodological differences between the two acuity measures, the vernier resolution of infants was better than grating resolution. This superior resolution for vernier targets is also seen in adults. To our knowledge, this is the first published report of the development of vernier acuity in infants (23,24). The measurement of vernier acuity free of movement artifacts using a small microprocessor-based display holds promise for the clinical assessment of spatial vision. Vernier acutiy may provide a better indication of foveal function than does grating acuity and it appears to accurately reflect deficits in spatial vision in adults (7). Thus, vernier acuity may provide a sensitive indicator of the maturation of the developing visual system.

ACKNOWLEDGEMENTS

Supported by a Research Initiation Grant from the University of Houston, 1982 and a grant from the National Eye Institute R01EY01728. Presented in part at the American Academy of Optometry, December 14, 1982. We thank Dennis M. Levi, Davida Teller, Ben Stephens, and Marty Banks for their helpful discussions and advice with earlier drafts of this manuscript and Joy Gruber, Les Harrell, David Miller, Bruce Ousley and Bob Zipper for their help in data collection. We also extend our thanks to the Houston Organization for Parent Education for help in recruiting infants.

Corresponding author: Ruth E. Manny, University of Houston-University Park, College of Optometry, Houston, Texas 77004.

REFERENCES

1. Westheimer, G. (1981) Progress in Sensory Physiology 1. Visual hyperacuity. (Ed. D. Ottoson). Pp. 1-30, Springer-Verlag, Berlin-Heidelberg-New York.

2. Westheimer, G. (1979) The spatial sense of the eye. Proctor Lecture. Invest. Ophthalmol. Vis. Sci., 18, 893-912.
3. Barlow, H.B. (1979) Reconstructing the visual image in space and time. Nature, 279, 189-191.
4. Westheimer, G. (1982) The spatial grain of the perifoveal visual field. Vision Res., 22, 157-162.
5. Dobson, V. and Teller, D.Y. (1978) Visual acuity in human infants: A review and comparison of behavioral and electrophysiological studies. Vision Res., 18, 1469-1483.
6. Williams, R.A. and Boothe, R.G. (1983) Effects of defocus on monkey (Macaca nemestrina) contrast sensitivity: Behavioral measurements and predictions. Am. J. Optom. Physiol. Opt., (in press).
7. Levi, D.M. and Klein, S. (1982) Differences in vernier discrimination for gratings between strabismic and anisometropic amblyopes. Invest. Ophthalmol. Vis. Sci., 23, 398-407.
8. Mohindra, I. (1977) A non-cycloplegic refraction technique for infants and young children. J. Am. Optom. Assoc., 48, 518-523.
9. Teller, D.Y., Morse, R., Borton, R., and Regal, D. (1974) Visual acuity for vertical and diagonal gratings in human infants. Vision Res., 14, 1433-1439.
10. Teller, D.Y. (1979) The forced-choice preferential looking procedure: A psychophysical technique for use with human infants. Infant Behavior Develop., 2, 135-153.
11. Dobson V., Salem D. and Carson J.B. (1983) Visual acuity in infants: The effect of variations in stimulus luminance within the photopic range. Invest. Opthalmol. Vis. Sci., 24, 519-522.
12. Pentland, A. (1980) Maximum likelihood estimations: The best PEST. Percept. Psychophys., 28, 377-379.
13. Watson, A.B. and Pelli, D.C. (1983) QUEST: A Bayesian adaptive psychometric method. Percept. Psychophys., 33, 113-120.
14. Klein, S.A. (1981) Rapid determination of the psychometric function. Abstract, American Academy of Optometry. Am. J. Optom. Physiol. Opt., 58, 1038.
15. Mayer, D.L. and Dobson, V. (1982) Visual acuity development in infants and young children as assessed by operant preferential looking. Vision Res., 22, 1141-1151.
16. Allen, J.L. (1979) The development of visual acuity in human infants during the early postnatal weeks. Doctoral Dissertation, University of Washington.
17. Gwiazda, J., Brill, S., Mohindra, I., and Held, R. (1980) Preferential looking acuity in infants from two to fifty-eight weeks of age. Am. J. Optom. Physiol. Opt., 57, 428-432.
18. Findlay, J.M. (1973) Feature detectors and vernier acuity. Nature, 241, 135-137.
19. Beck, J. and Schwartz, T. (1979) Vernier acuity with dot test objects. Vision Res., 19, 313-319.
20. McKee, S.P. and Westheimer, G. (1978) Improvement in vernier acuity with practice. Percept. Psychophys., 24, 258-262.
21. Several factors suggest that the reinforcement of correct responses during measures of grating acuity should have little effect on the grating thresholds for children less than 6 months of age (22,14). However, nothing is known about the effect of an external reinforcer on vernier thresholds. It is conceivable that a reinforcer could have improved the vernier acuities measured in these young infants and that if a reinforcer had been used, the difference between the grating and vernier thresholds would have been similar to that found for the adults tested in this study.
22. Stephens, B.R. (1982) The effect of reinforcement of acuity performance in young infants. Unpublished orals paper. University of Texas at Austin.
23. Manny, R.E. and Klein, S.A. (1983) The development of vernier acuity in human infants. Invest. Ophthalmol. Vis. Sci. (Suppl) 24, 93.
24. Shimojo, S., Birch, E.E. and Held, R. (1983) Development of vernier acuity in infants assessed by preferential looking. Invest. Ophthalmol. Vis. Sci. (Suppl) 24, 93.
25. Finney D.J. (1971) Probit Analysis. The University Press. Cambridge.
26. McKee, S.P., Teller, D.Y., and Klein, S. (1983) Statistical properties of forced-choice psychometric functions. Implications of probit analysis. Percept. Psychophys., (in review).
27. To illustrate the effect of slope on the standard error of the threshold estimate, suppose (as is typical in the present experiments): a) the underlying psychometric function has an upper asymptote of 90% correct; b) the slope is such that the psychometric function goes from 60% to 80% in about 0.5 octaves; and c) twenty trials occur at the steep portion (70% correct) of the psychometric funtion. Binomial statistics imply the standard error of the probability correct is given by $\sigma = \sqrt{p(1-p)/N} = \sqrt{0.7\times0.3/20} = 10\%$. When translated back to the stimulus domain, the SE (68% confidence interval) becomes 0.5/2 octaves. That is, there is a 68% chance that the true threshold lies within 0.25 octaves of the estimated threshold. This threshold confidence interval is inversely proportional to the slope.

An attempt to calculate the 95% confidence interval runs into a problem because the 2σ error of the probability correct is 20% which leads to a confidence interval of 70% ± 20%. This wide interval extends from the lower asymptote to the upper asymptote and implies that with 20 trials it is not possible to place 95% confidence intervals on the threshold estimate (26). One must be content with the less stringent confidence

intervals which are used in the present paper.

APPENDIX

Data Analysis

Prior to the off-line calculation of the thresholds, the data were tested to determine if the results were significantly different from chance. Beginning with the results for the largest vernier offset, the data were compared to a binomial distribution. If there was a 90% probability that the data differed from chance, the data set was included in the analysis. If, however, the results at the largest vernier offset were not different from chance, the results of the next level were added to the previous level and tested again. This continued until either the data differed significantly from chance or until 75% of the data set was included in the test. The data was excluded from further analysis if it did not differ significantly from chance before 75% of the data set was tested. Table 1 (in the text) shows the number of data sets eliminated from further analysis by this binomial comparison, in the column labeled chance data.

Thresholds were then obtained off-line from the raw data by a modified probit analysis (25). Those trials on which the observer was less certain (low confidence) were arbitrarily weighted at half the value of the high confidence trials when the thresholds were calculated. (For example, in Figure 1 [filled symbol] the results at 13.8 minutes would be calculated as 9 out of 13 trials correct since there were 11 high confidence judgements with 8 correct and 4 low confidence judgements with 2 correct.) In standard probit analysis both the threshold and slope are varied in a search for the maximum likelihood. However, several factors make it inappropriate to vary the slope on each run: 1) More trials are needed to establish a reliable slope estimate than are needed to establish a reliable threshold estimate. Thirty trials are insufficient to accurately determine the slope. 2) The upper asymptote is below unity for the infants tested. Since a low upper asymptote can be interpreted as a shallow slope, it is incorrect to find the optimal slope without also locating the optimal upper asymptote.

Therefore, probit analyses were made for each run with the slope and upper asymptote fixed at a wide variety of levels. Upper asymptotes were varied from 75% to 100% in steps of 5% and slopes were varied from 0.1 to 0.6 octave in steps of 0.1. For each run the threshold value which maximized the likelihood was determined and both the maximum likelihood and the chi-square value of each fit were tabulated. The optimal values of slope and upper asymptote implied by the likelihood maxima were not significantly different from the optimal values predicted by the chi-square minima; hence, only the chi-square values are discussed. When the grand total of chi-square for all runs of infants two through 26 weeks of age were totalled, the minimum chi-square occurred at an upper asymptote of 80% and a slope of 0.20 octave. These values imply the midpoint of the psychometric function is around a probability of 65% and the psychometric function extends from 55% to 75% in about 0.4 octaves. This low upper asymptote may have been the result of the maximum likelihood staircase which tended to place trials close to the infant's threshold. While this procedure has the advantage of placing trials where the psychometric function is the steepest, the upper asymptote is poorly defined and the infant's attention may wane when most stimuli are presented near threshold. Since we define threshold to be the midpoint of the psychometric function, a low upper asymptote would lead to a better acuity estimate. In an attempt to be conservative on the threshold estimates, all the results reported were calculated with an upper asymptote of 90% (rather than 80%), corresponding to a threshold of 70% correct.

To determine the effect of slope on the threshold estimate, the thresholds were calculated for each 2-week age group for upper asymptotes of 90% and slopes of 0.1, 0.3, and 0.6 octaves. The results (shown in Figure 4) indicated that the thresholds were minimally affected by the slope. However, the slope has an important effect on the standard error of the threshold estimates (26,27).

In order to determine whether the slope and upper asymptote showed a significant dependence on the age of the infant, the infants were divided into three groups: 2 to 9 weeks, 10 to 17 weeks and 18 to 26 weeks. No age dependence was found for the upper asymptote. However, the data did seem to show a decreasing slope with age, 0.2, 0.3, and 0.5 octaves for the vernier data and 0.3, 0.3 and 0.4 for the grating data. These slopes were used to fit the data shown in Figures 2 and 3.