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A THREE ALTERNATIVE TRACKING PARADIGM TO MEASURE VERNIER ACUITY OF OLDER INFANTS

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Abstract—Vernier acuity was measured in infants 1 to 14 months of age using a dynamic three alternative tracking paradigm. The location of the vernier offset would move randomly to one of three screen locations. An observer, unaware of the stimulus location, viewed the infant from behind a screen and guessed the position of the vernier offset. The magnitude of the vernier offset was controlled by a staircase and the results were analyzed using a broken line psychometric function. These thresholds were compared to thresholds obtained from the same infants during the same session with a two alternative forced choice preferential looking paradigm. Differences in the results of these two procedures and those reported previously in the literature are discussed in terms of the differences in the nature of the visual stimuli, one containing motion and one without motion.

Vernier acuity Development Preferential looking Three alternative forced choice Tracking

INTRODUCTION

The development of the visual system's spatial resolving abilities has been studied extensively over the past several decades (see Dobson and Teller, 1978; Salapatek and Banks, 1978 for review). Until recently however, these assessments of spatial resolution have been limited to measurements of grating acuity. While estimates of grating acuity have provided valuable information about the adult and the developing visual system, grating acuity does not represent the limit of the visual system's spatial discrimination abilities. In adults' vernier acuity, the detection of an offset or misalignment, is approximately an order of magnitude better than grating acuity (Westheimer, 1979; Westheimer, 1981). In addition, vernier acuity may be more sensitive to certain types of spatial deficits, i.e. strabismic amblyopia (Levi and Klein, 1982) and perhaps refractive error (Gwiazda *et al.*, 1984), than is grating acuity.

Two recent studies of vernier acuity in infants (Manny and Klein 1984; Shimojo *et al.*, 1984) and one study of children, age 4 to 9 years, (Gwiazda *et al.*, 1984) have found finer resolution for vernier targets than for gratings. However, the difference in these two spatial resolution measures was not as great as that shown by adults. While the developmental time course for vernier acuity is beginning to unfold, there is little information for children between 6 months and 4 years of age. Shimojo *et al.* (1984) tested infants up to 9 months of age, but due to limitations in the stimulus, they were not able to present offsets smaller than 2.5 min. Hence, as they comment, the vernier thresholds of their older infants may have been underestimated. Furthermore, the results of the two infant studies differed both in the time course of the development between 2 and 6 months of age (ages where the subjects overlapped in the two studies), and in the magnitude of the vernier thresholds. The purpose of this report is to describe a new technique developed to test the vernier acuity of older infants between 6 and 14 months of age, ages difficult to test by standard techniques, and to reconcile some of the differences in the data of the two previous infant studies of vernier acuity for infants under 6 months of age.

METHODS

Two alternative forced choice preferential looking

Vernier thresholds were measured using two different techniques, the standard two alternative forced choice preferential looking paradigm (Teller *et al.*, 1974; Teller 1979) and a new three alternative tracking procedure. The stimulus for the two alternative forced choice preferential looking procedure was identical to that used in our previous study (Manny and Klein, 1984) of vernier acuity except no white border surrounded the horizontal vernier grating (white lines on black surround). The infant's eyes were illuminated by a lamp placed above the display in an otherwise dark room. Before the introduction of the vernier offset on one half of the screen, the screen contained 5 unbroken horizontal lines. Movement artifacts which would have occurred as the vernier offset was introduced, were masked by displacing the entire display upwards except for a few short line segments which were displaced less, to create the vernier offset. The display remained motionless until a judgement about the infant's preference was made by the observer. To hold the

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viewing distance constant at 0.5 m while allowing an adequate range of vernier offsets to be presented for different aged children, the gain of the vertical amplifier was modified to vary the vertical screen dimension from 20.3° to 5.2° in 5 descrete, half-octave steps. The horizontal dimension was 25.5° and constant for all screen sizes.

Changing the gain of the vertical amplifier when the entire display was uniformly illuminated, resulted in a change in the space average luminance from 36 cd/m² on the largest screen size to 142 cd/m² on the smallest screen size. This four fold change in luminance might contribute to a change in vernier acuity as a function of age, since screen size was systematically decreased as the infant's age increased. However, Dobson *et al.* (1983) have shown that the grating acuity of infants is not significantly affected by changes in luminance within this range. It is also not clear what the most appropriate calibration is when the stimuli are bright lines on a dark background such as the ones used in this study. The width of the line was always 18.5% of the spacing and the line width varied from 27.5 to 6.9 min at the 0.5 m viewing distance. Westheimer (1985), and Klein and Levi (1985) have argued that linear luminance may be the more appropriate metric for thin lines. In addition, Westheimer and McKee (1977) found little change in vernier acuity of adults as long as the line luminance of the test target was greater than 0.003 cd/m when long viewing durations were used. Since the line luminance was inversely proportional to screen size and the line width was directly proportional to screen size, the line intensity (luminance times the line width) for our display was constant at 0.18 cd/m for all screen sizes.

The vernier offset for each test stimulus was chosen by using a maximum likelihood staircase (Manny and Klein, 1984; Pentland, 1980) to place the offset 1/3 octave above or below the current threshold estimate. The maximum likelihood staircase concentrated the trials around the observer's 72.5% correct. However, all thresholds were calculated off-line from the staircase data using a broken line psychometric function described in the data analysis section.

Three alternative tracking

The stimulus used for the three alternative tracking was displayed on the same equipment. The duty cycle, intensity, and number of lines composing the horizontal grating were identical to that used in the two alternative forced choice procedure. While the physical aspects of the stimuli were similar in the two threshold measures, the display and the observer's judgements were different. The tracking display was dynamic. The location of the vernier offset would move randomly to one of three screen locations, left, center or right. Once the offset reached the test location, it would jump back and forth over a 3.4° area synchronized with a tone similar to the technique used by Shimojo *et al.* (1984) in their two alternative forced choice paradigm.

Following a guess or a passage of 1.6 sec without guess, the offset had a 33% probability of remaining at that position or moving to one of the other two screen locations. The movement of the vernier offset between the three test locations was jerky, jumping 6 times for a change of one screen location, 8.35° total excursion, (i.e. left to center) or 12 times for a change of two screen locations, 16.7° total excursion, (left to right or right to left). The speed of movement was the same regardless of the distance travelled. However, since the distance travelled, varied from trial to trial (0°, 8.35° or 16.7°) the time required to reach the new position varied and might have been able to cue the observer as to the location of the vernier offset. Therefore, when the offset remained in the same location or moved only one position, it would oscillate back and forth at the new location for the *remainder* of the time which would be required to travel 2 stimulus locations, 2.4 sec, (i.e. 2.4 sec if it remained at the same location and 1.2 sec if it moved only one stimulus position). After the lapse of a total of 2.4 sec the auditory stimulus would begin, synchronized to the oscillations which cued the observer that a guess of stimulus position could be made. Thus, timing cues which could have aided the observer in determining the position of the stimulus were eliminated.

The observer, unaware of the stimulus location, viewed the infant from behind a screen and guessed the position of the vernier offset during the auditory synchronization which always began 2.4 sec after the end of the previous trial. The observer was not required to guess on each trial but was given feedback after each trial. The feedback was provided by the computer through a tone, the frequency of which was correlated to the location of the offset. The observer used the infant's tracking movements, eye position and feedback from the previous trial to make a judgement about the location of the vernier offset.

Expanding the resolution of the display

Evaluating the visual resolution of older infants has been a problem due to limited resolution of video displays coupled with the necessity to test at close distances, typically less than 1 m, to keep the childs attention. Shimojo *et al.* (1984) encountered this problem with their infants 6–9 months of age, the majority of whom obtained 80% correct at their smallest vernier offset, 2.5 min. Smaller offsets could be achieved by reducing the screen height or by increasing the viewing distance. Further reductions in screen size might make the display less compelling and reduce the child's attention. Increasing the viewing distance would make it more difficult for the observer to judge eye position on the three alternative procedure.

An alternative procedure is to create small vernier offsets using the centroid method of Westheimer and

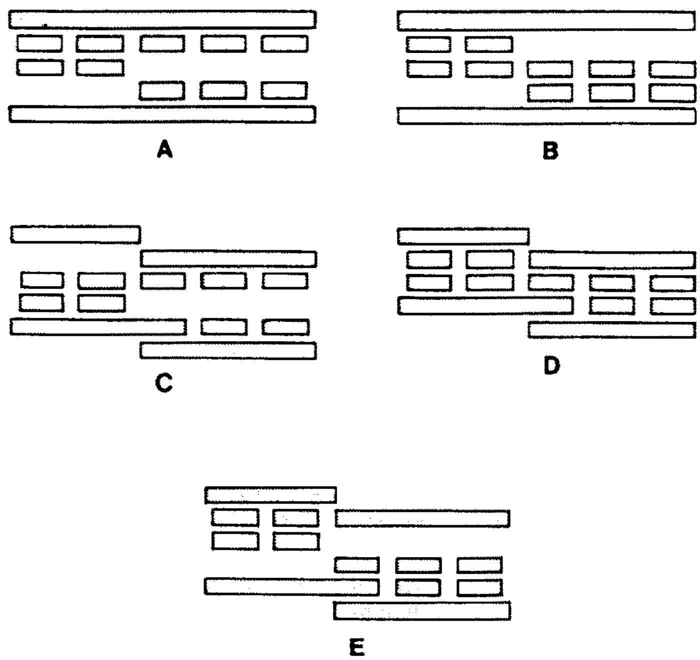

Fig. 1. Schematic representation of several of the smaller vernier offsets assuming the line position is based on the centroid of the luminance distribution. The breaks in the middle two line segments served to mask potential luminance cues. The vertical scale is greatly expanded for clarity. (a) Offset of 1/4 of a pixel representing 0.43 min when viewed at 0.5 m on the smallest screen size, 5.2°. (b) Offset representing 1/2 pixel (0.86 min). (c) offset representing 3/4 pixel (1.29 min). (d) Offset representing 1 pixel (1.72 min). (e) Offset representing 3/2 pixel (2.15 min).

McKee (1977). They used a ribbon of light consisting of 10 closely spaced lines which subtended 2.7′ at their test distance. Two of these ribbons were abutted and used as a vernier target. The vernier offset was produced by two methods. In the first method the entire ribbon was displaced to create the vernier offset. The vernier offset was created in the second method by displacing one of the central ten thin lines which made up the test ribbon. The threshold found using method 1 was 4.23 sec of arc. When method 2 was used, the center of gravity threshold (centroid) was 4.33″. Their results suggest that the vernier judgement is based on the centroid of the luminance distribution.

As show schematicaly in Fig. 1, the centroid method of Westheimer and McKee (1977) was used to expand the resolution of the test display for the three alternative tracking paradigm. An offset of

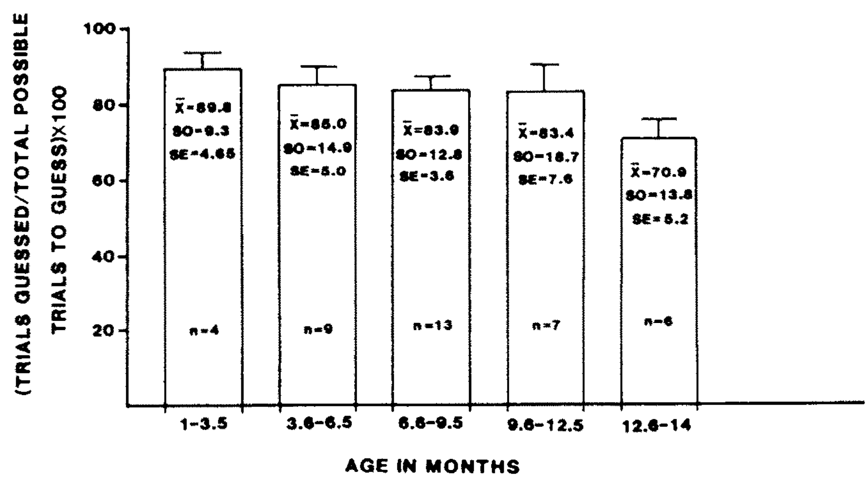

Fig. 2. The percentage of trials on which the observer quessed out of the total number of trials possible to guess is averaged for the infants in the various age groups. The error bar represents +1 SEM. The number of infants in each age group is specified by n.

0.43 min (one fourth the size of a pixel) was created by displacing only one of the four elements comprising the test ribbon by 1 pixel [Fig. 1(a)]. Similarly, offsets of 0.86, 1.29 and 2.15 min were created by displacing additional elements. Under the test conditions, the horizontal gap shown in Fig. 2 was not visible on the monitor viewed at 1 m by an adult with normal vision due to the blur of the video monitor. The full range of possible offsets was 1/4, 1/2, 3/4, 1, 3/2, 2, 3, 4, 6, 8 and 12 pixels, corresponding to approximately half octave steps.

According to the results of Westheimer and McKee (1977) an adult with normal acuity (presumably 20/15 Snellen) uses the centroid of a 2.7′ ribbon. If the infants visual system behaves similar to that of adults, an infant with a Snellen equivalent acuity of 20/60 would use a centroid created by a 10.8′ ribbon (4 × 2.7′). The grating acuity of a one year old infant has been reported to be between 20/122 [Mayer and Dobson (1982), Fig. 4]; and 20/40 [Gwiazda *et al.* (1978), Fig. 1] Snellen equivalent. Children 2 years of age have been reported to have a Snellen equivalent grating acuity of 20/44 [Mayer and Dobson (1982), Fig. 4]. To the extent that the infant's visual system behaves like the adult in making vernier judgements based on the centroid, our testing conditions (the test line subtends 6.88, and the oldest infant tested was under 14 months of age) should be within the region where the centroid is operating.

It is interesting to note that if the infant's resolution were better than that reported above, and the infants were able to make vernier judgements based on the local features of the stimulus, the vernier thresholds in this study would have been underestimated. This underestimation is due to the fact that the $1\frac{1}{2}$ pixel offset was the only offset that played a role in estimating the infant's thresholds. (The 1/4 and 3/4 pixel offset was never presented and the 1/2 pixel offset was only presented to one infant.) As shown in Fig. 1(e) the local features of the $1\frac{1}{2}$ pixel offset are only 1 pixel, and hence, if local features were used the vernier thresholds reported here are conservative.

The vernier offset was created by turning off a line on one scan and turning on a line in the succeeding scan. If the timing of the onset and offset were not matched a potential luminance artifact could have been present. This potential cue to the offset's position was masked by placing numerous breaks along the line. These breaks are schematically illustrated in Fig. 1.

Presentation of stimuli

Stimuli were presented in blocks of trials. The magnitude of the vernier offset remained constant for each block of trials. Typically the maximum number of trials per block on which the observer could guess was set at 9. [Some of the first babies were tested with 8 trials per block (5 infants) and one infant was tested with 10 trials per block]. The observer was not required to guess on every trial and rarely guessed on the first trial of each block, using the feedback of the stimulus position to provide a calibration of the baby's eye position. If the observer failed to guess on any of the first 9 (8 or 10) trials, more stimuli were presented during that block until the observer guessed the maximum number of trials specified for the block or until a maximum of 15 (13 or 16) trials was presented.

Eight blocks of trials were attempted on all infants. However, for 10 infants the number of blocks was cut short (after 5 to 7 blocks) when the baby became inattentive or fussy. The data analysis indicated that 9 of these 10 data sets were significantly different from chance and hence, these 9 data sets were included in the results.

With 8 blocks of trials and 9 trials per block the maximum number of trials on which the observer could guess was 72. The average number of trials *guessed* by the observer was 56.5. Figure 2 shows the percentage of trials on which the observer guessed out of the total number of trials possible to guess for babies in various age groups. The average number of trials *presented* to the infants was 100.1 ± 13.9 (SD). Since each trial required a maximum of 4 sec, 100 trials could be presented in 6.67 min. However, with the short breaks between blocks of trials, testing was typically completed in 15 min.

The magnitude of the vernier offset varied between blocks according to the following rules. The number of observer correct responses was reduced by half the number of responses which represented an error of 2 positions (i.e. stimulus on the right, observer guessed left or vice versa). The percent correct was adjusted in this manner in order to make full use of all the available information. The observers erred by two locations less than they erred by one location. This adjusted percent correct was only used to select the next stimulus level; it was not used in the final data analysis. If the adjusted percent correct was less than 11% the offset increased by 1 octave, if it was between 11% and 33% the magnitude of the offset increased by about 0.5 octaves. The vernier offset decreased by 1 octave if the adjusted percent correct was greater than 70% and decreased about 0.5 octaves if it was between 40 and 70%. When the adjusted percent correct was between 33 and 40% the offset remained at the same level. The initial offset was selected to be above the infant's threshold based on the results of previous measures of vernier acuity in infants. If it is assumed that the number of one position errors made by the observer is equal to the number of two position errors when the actual stimulus is located on the right or left of the display, then the trials are concentrated at the observer's 45% correct level. This is confirmed by the fact that the observer was correct on 46.5% of the trials guessed. Thresholds were always estimated off-line using the procedure described below.

Data analysis

Broken line psychometric function. Thresholds were calculated off-line from the data generated by the two different testing procedures. Traditionally, probit analysis has been used to estimate thresholds from psychophysical data (Finney, 1971). However, if the upper asymptoter is low, probit analysis may underestimate the threshold since the low upper asymptote would be misinterpreted as a flat slope. The data obtained by the two testing techniques used in this study had low upper asymptotes. Several factors produced these low asymptotes. The tracking procedure presented numerous trials in a short period time, and as seen in Fig. 2, the observer guessed on the average on about 86.6% of the trials. This rapid presentation and frequent guessing could result in lower upper asymptotes. The methods used to place the trials during both testing procedures, placed most of the trials near threshold and hence, reduced attention. We believe the upper asymptote is a reflection of the baby's attention.

Since probit analysis often interprets a low upper asymptote as a flat slope, we have estimated thresholds using a new technique, the broken line psychometric function. The broken line function fits the data with three line segments; (1) a fixed lower asymptote corresponding to chance (50% for the two alternative and 33% for the three alternative procedure), (2) the upper asymptote is the optimum fit of the data for the larger offsets given by the probability correct of the data spanning the upper asymptote, (3) the data in the middle region between the lower and upper asymptotes is fit by having the psychometric function pass directly through the data points, subject to the constraint that the psychometric function should never have a negative slope. Three classes of psychometric functions were used in which either zero, one, or two data points were in the middle region. The likelihood function was calculated for each possible location of the middle region. The likelihood function for each trial is given by P, the probability value of the psychometric function for a correct response, or given by $1\text{-}P$ for an incorrect response. The total likelihood function is given by the product of all the individual likelihoods. The log likelihood of the medium width (one datum in middle region) and broad (two data in middle region) psychometric functions were adjusted downward by 0.5 and 1.0 respectively to compensate for the reduced number of degrees of freedom. The breakpoints (X) which produced the maximum likelihood (L) were chosen as the best fitting psychometric function. The threshold value and error bars were determined by fitting a parabola $[L = A\text{-}1/2(X - T)^2/\sigma^2]$ to the data point with maximum likelihood plus the two neighboring points. The threshold is given by T and the standard error by σ.*

*The data analysis program containing several options for analyzing the psychometric function is available upon request for Commodore computers.

Two alternative forced choice vs three alternative tracking

The broken line psychometric function defines threshold to be halfway between the upper and lower asymptote. Since the lower asymptote varies between the two procedures, 33% for the three alternative tracking technique and 50% for the two alternative forced choice procedure, a fixed observer's percent correct actually represents different detectability for the two procedures. One way to equate these two procedures is to determine the d' using Elliot's tables (Hacker and Ratcliff, 1979). One assumption is made in our use of Elliot's tables to determine the equivalant d' for each procedure. The assumption is that the data determined by each of the two test procedures represent the true psychometric function and the low upper asymptote is a reflection of the infant's variable attention even when the stimuli are visible. Therefore, the inattention does not alter the detectability and hence the true d' is halfway between the lower asymptote and 100% correct. When these assumptions are made, the d' for the tracking paradigm is 1.11 and the d' for the two alternative forced choice procedure is 0.95.

Subjects

Infants were recruited by letters distributed through a local diaper service and were offered a complimentary eye examination in exchange for participation in the study. Written informed consent was obtained from all parents. The majority of infants received the complimentary eye examination and none were omitted from the data analysis since no large refractive errors (greater than 2.00D myopia, 3.00D hyperopia or 2.00D astigmatism) or other vision anomalies were detected during the eye examination. Infants were held in their parent's lap or over their parent's shoulder at the 0.5 meter viewing distance. The room lights were turned off. The parents were instructed to keep their baby in the same position to maintain the proper viewing distance. When a change in position was needed, the distance was remeasured. The observer also monitored fixation distance when observing the infant through the peephole.

Binocular vernier acuity was measured in 43 infants 1–14 months of age using either the two alternative forced choice procedure or the three alternative tracking paradigm. Measurements were attempted on 5 other infants but thresholds were not obtained due to equipment problems (2), siblings in the room which distracted the infant (1), both data sets at chance (1), or one data set at chance and the other measure not attempted due to poor attention (1). Twenty-three infants were cooperative enough to gather thresholds by both procedures during a single session with about half the infants tested using the two alternative forced choice procedure first and the remaining infants were tested first with the tracking procedure. Of the twenty infants with only one threshold measure, 16 were obtained with the tracking procedure and 4 with the two alternative forced choice preferential looking technique. Failures to obtain the second threshold were due to: data sets completed but data not significantly different from chance (15); the second measure was not attempted due to poor attention or participation in another experiment (2); testing was aborted early due to lack of attention with insufficient trials to estimate threshold (3).

RESULTS

The results are shown in Fig. 3 where vernier acuity in minutes of arc is plotted as a function of the baby's age in months (adjusted for prematurity by the parents report). The open symbols represent thresholds measured using the two alternative forced choice procedure and the filled symbols show the thresholds derived by the three alternative tracking paradigm. The different symbols represent the infants gender (circles-male, triangle-female). The vertical dashed line connects thresholds measured on the same infant during a single session. The error bars depict ± 1 SE. The typical standard error across all infants was about 1/3 octave. This value is small given the low number of trials and implies that the infant's psychometric function has a standard deviation of less than 2/3 octaves (McKee *et al.*, 1985). One of the most striking features of the data is the superior thresholds derived from the tracking paradigm compared to the thresholds obtained using the two alternative forced choice procedure measured in the same infant. Of the 23 pairs of data, 19 showed a better acuity using the tracking procedure (82.6%). The average threshold difference in octaves across all infants was 0.73. This is opposite to what was seen in adults, with all of the adults tested showing slightly better resolution for the static two alternative forced choice presentation compared to the moving three alternative tracking display. The average threshold difference for the adults was -0.51 octaves. Adults reported that the movement of the target made the tracking task more difficult.

The other interesting feature of the results is their compatibility with the two previous studies of vernier acuity in infants. The geometric mean (solid line) ± 1 SD (shaded region) in Fig. 3 shows the results we have reported previously using the two alternative forced choice paradigm (Manny and Klein, 1984). For infants under 6 months of age, the thresholds from the present two alternative forced choice procedure replicate those we have reported earlier. The results of Shimojo *et al.* (1984) have been replotted as the dashed and dotted line in Fig. 3. (The

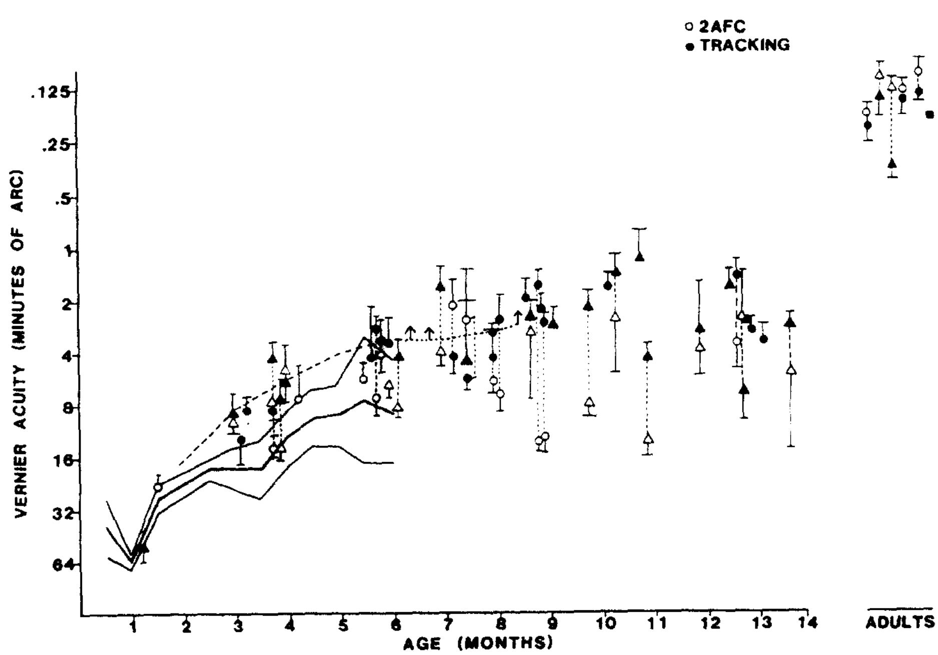

Fig. 3. Vernier acuity in minutes of arc as a function of age in months. The open symbols represent thresholds measured by the two alternative forced choice paradigm. Thresholds derived from the three alternative tracking procedure are shown by the solid symbols. Data points connected by a dashed vertical line were measured on the same infant during a single session. The gender of the infants is indicated by the symbol shape (○ male, △ female). The dashed and dotted line represent the mean vernier thresholds replotted from Shimojo *et al.* (1984). The shaded region (replotted from Manny and Klein, 1984) shows the geometric mean vernier acuity ± 1 SD. The error bars represent ± 1 SE. The solid square is the mean adult threshold measured with the tracking procedure.

upperward arrows associated with the dotted portion of the line illustrate that Shimojo *et al.* were near the limit of resolution of their display.) Thresholds obtained by the three alternative tracking procedure (solid symbols) are in reasonable agreement with the data reported by Shimojo *et al.*, and suggest that although the older infants were above chance on their smallest available offset that vernier thresholds were probably not significantly underestimated.

DISCUSSION

The results shown in Fig. 3 indicate that vernier acuity improves as a function of age for infants up to at least 11 months of age. The apparent discontinuity seen at about 11 months of age is probably a reflection of the difficulty in testing this age group, even with the three alternative paradigm. This is supported by the data shown in Fig. 2, where the percentage of trials on which the observer guessed was lower than that of the other age groups, presumably due to the infants attending to things other than the stimulus display. We are currently experimenting with the tracking paradigm to improve testability for these older infants and toddlers. Procedures under investigation include: (1) incorporating an *adaptative* staircase to more efficiently control stimulus presentation, (2) incorporating more stimuli which are highly visible, (3) centering the trials at a more visible level, and (4) presenting novel video and auditory stimuli in between the blocks of trials to hold the infants attention during the trials.

Despite these current difficulties in testing older infants a three alternative paradigm offers several advantages over a two alternative forced choice procedure (Shelton and Scarrow, 1984). Our methodology is especially good for testing infants. Each trial required a maximum of 4 sec. With short breaks between blocks of trails, approximately 60 trials were accumulated in about 15 min. The large number of trials over a short period of time is an attractive feature for any infant testing procedure where the subject's attention is critical but limited. In a three alternative procedure the chance performance is at 33% rather than 50% and thus 3 alternatives expands the range of the psychometric function thereby improving the confidence interval. The expanded range of the three alternative procedure also allows thresholds to be estimated with a lower upper asymptote (presumably reflecting poor attention and the observer's more difficult task requiring numerous rapid judgments) than is possible for a two alternative procedure.

Although these features make the three alternative procedure attractive for infant testing by reducing error bars they do not account for the superior vernier thresholds obtained with the three alternative procedure as compared to the two alternative forced choice technique. One possible explanation for the superior thresholds obtained with the tracking paradigm is that the assumption which attributes a low upper asymptote to attention and the rapid presentation of stimuli during the tracking paradigm is in error. If the assumption is in error, then the poorer thresholds obtained with the two alternative procedure compared to those measured with the tracking technique, may simply be the result of a higher d' on the two alternative forced choice procedure. Since the tracking data obtained in this study agree with those found by Shimojo *et al.* (1984) using 75% correct on a two alternative procedure ($d' = 0.95$) this alternative appears unlikely.

Another possibility that may account for the different thresholds found by the two test procedures is the differences in the test stimuli. One of the main differences between the two procedures is that the stimulus in the three alternative procedure contained motion while motion was carefully excluded from the stimulus used in the two alternative forced choice procedure. Hence, the higher thresholds obtained with the tracking paradigm could reflect both vernier acuity and relative motion. This interpretation is consistent with the difference obtained between the 2 previous studies of vernier acuity, one which used motion (Shimojo *et al.*, 1984) and one which did not (Manny and Klein, 1984). Another possible interpretation is that the motion coupled with the sound provided a more compelling stimulus for the infants, holding their attention better as the stimulus approached threshold but did not influence the threshold directly since the motion was not visible unless the vernier offset could be detected. Until more is known about the infant's sensitivity to motion, both alternatives seem likely.

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