Preferential Looking as a Measure of Visual Resolution in Infants and Toddlers: A Comparison of Psychophysical Methods

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LEWIS, TERRI L., and MAURER, DAPHNE. *Preferential Looking as a Measure of Visual Resolution in Infants and Toddlers: A Comparison of Psychophysical Methods.* CHILD DEVELOPMENT, 1986, 57, 1062–1075. We used preferential looking to estimate the monocular visual resolution of children 6–36 months old and compared results from 3 psychophysical methods: Taylor and Creelman's PEST staircase, our modification of the PEST procedure, and the method-of-constant stimuli. Estimates of visual resolution for 48 children tested with the original and modified PEST procedures and for 50 children tested with the method-of-constant stimuli and the modified PEST procedure showed excellent agreement across procedures, with the modified PEST procedure requiring the fewest trials and the least time. Results from the modified PEST procedure for 168 children with normal eye alignment and minimal refractive errors indicated that monocular visual resolution improves from 6.5 min at 6 months to 1.2 min at 36 months. Preferential looking combined with the shortened PEST procedure should be useful for testing the visual resolution of preverbal children with eye problems.

Recently there have been a number of attempts to estimate the visual resolution of individual infants and toddlers. One method, preferential looking, takes advantage of the fact that even newborns look longer at a patterned stimulus than at a plain grey one (cf. Fantz, Ordy, & Udelf, 1962). Typically, black-and-white stripes are paired with a plain grey stimulus matched in mean luminance to the stripes. The size of stripe is varied across trials, and the narrowest stripes that an infant prefers reliably over grey provide a measure of visual resolution. Using this technique, investigators have estimated the visual resolution of individual infants who range in age from 2 weeks to 6 or 12 months (cf. Allen, 1979; Atkinson & Braddick, 1981; Gwiazda, Brill, Mohindra, & Held, 1978; Sokol & Moskowitz, 1985). Preferential looking has also been used successfully to estimate the visual resolution of older children who were first trained to choose the stripes and then rewarded for correct responses (cf. Birch, Gwiazda, Bauer, Naegele, & Held, 1983; Mayer & Dobson, 1980, 1982).

The visual resolution of individual children with eye problems has also been assessed with preferential looking (Atkinson, Braddick, & Pimm-Smith, 1982; Jacobson, Mohindra, & Held, 1981, 1982; Lennerstrand, Andersson, & Axelsson, 1983; Manning et al., 1982; Mayer, Fulton, & Hansen, 1982, 1985; Mayer, Fulton, & Sossen, 1983; Mohindra, Jacobson, Zwaan, & Held, 1983; Mohn & van Hof-van Duin, 1983; Sokol, Hansen, Moskowitz, Greenfield, & Towle, 1983). Although most of these patients were tested monocularly, their results typically were compared with those from normal children tested binocularly. This comparison is inappropriate, since normal children tend to show poorer visual resolution when tested monocularly than when tested binocularly (Atkinson et al., 1982; Dobson, 1983; Mayer et al., 1982). Despite the fact that monocular norms are essential to evaluate adequately the results from patients, few investigators have measured the development of monocular visual resolution in normal infants and toddlers. Those that did have tested only a few children at each age or

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only a few ages (Atkinson & Braddick, 1981; Atkinson et al, 1982; Dobson, 1983; Mayer et al., 1982).

If preferential looking is to be useful in the clinic, it is important not only to establish monocular norms for the test but also to use a version of the test that is short and reliable and that can be completed by most children regardless of age. Mayer and Dobson (1982) used a lengthy psychophysical procedure, the method-of-constant stimuli,[1] and required each child to complete 20 trials for each of four stripe widths. Each test took 1.5–6 hours to complete, and perhaps for that reason only 10% of the 18-month-olds and only 27% of the 24-month-olds completed the procedure. There have been two approaches to shortening the test. One approach has been to use the method-of-constant stimuli with only 8–12 trials per stripe width (Birch et al., 1983; Goldblatt, Strauss, & Hess, 1980; Gwiazda et al., 1978). Unfortunately, using fewer trials greatly increases the possible error in the estimate of threshold (McKee, Klein, & Teller, 1985; Teller, 1985). The other approach has been to use a staircase procedure. For example, Gwiazda and her associates (Gwiazda, Brill, Mohindra, & Held, 1980; Gwiazda, Wolfe, Brill, Mohindra, & Held, 1980) used a "quick assessment" to test a large number of infants up to 12 months of age, but the validity of their staircase procedure has been questioned (Banks, Stephens, & Dannemiller, 1982; Nachmias, 1982; Teller, Mayer, Makous, & Allen, 1982). Others have used more traditional staircases but have tested only one age group (Atkinson et al., 1982; Manny & Klein, 1984) or very few normal children at each age (Manning et al., 1982; Mayer et al., 1982).

The purpose of the present set of experiments was to compare estimates of monocular visual resolution obtained from preferential looking combined with three psychophysical procedures: Taylor and Creelman's (1967) probabilistic estimation by sequential testing (PEST) staircase, our modification of the PEST procedure, and the method-of-constant stimuli. We then used the modified PEST procedure to obtain norms for children 6–36 months old. The original PEST procedure has been used to estimate auditory thresholds in both adults (Taylor & Creelman, 1967) and infants (Bull, Schneider, & Trehub, 1981). Our modified version shortens the number of trials by omitting Taylor and Creelman's doubling rule and testing each stripe width only once. The method-of-constant stimuli is the standard psychophysical procedure that is described in note 1.

In the first experiment, we tested 48 children, 1–3 years old, and for each child we compared monocular visual resolutions estimated from Taylor and Creelman's PEST staircase and from our modification of the PEST procedure. In the second experiment, we tested 50 children, 1–3 years old, and compared monocular visual resolutions estimated from the method-of-constant stimuli and from the modified PEST procedure. In the third experiment, we evaluated the reliability of the modified PEST procedure and obtained norms for monocular visual resolution from 168 children, 6–36 months old, with no eye disorders.

Experiment 1

Method

Subjects

There were three groups of children: 16 12-month-olds (M age = 12.6 months, range 12.3–13.0 months), 16 24-month-olds (M age = 24.7 months, range 23.9–26.0 months), and 16 36-month-olds (M age = 36.8 months, range 35.7–37.8 months). (All ages refer to the child's age at the first testing session.) An additional 27 children were excluded from the final sample because they refused to wear an eye patch (N = 8) or to play the game (N = 6), because the parent would not return to complete the tests (N = 11), or because of procedural errors (N = 2). We completed two tests of one eye for 16/32 (i.e., 16 out of 32) (50%) 12-month-olds, 16/24 (67%) 24-month-olds, and 16/19 (84%) 36-month-olds (see Procedure section). We completed at least one test of one eye for 23/32 (72%) 12-month-olds, 17/24 (71%) 24-month-olds, and 16/19 (84%) 36-month-olds.

Parents were approached on the maternity wards of local hospitals, and the names of volunteers were kept on file until the child reached the appropriate age. All children had been born at term (gestational age at least 38 weeks and birth weight at least 2,500 grams).

[1] In the method-of-constant stimuli, the investigator selects a fixed number of values of the stimulus that are thought to bracket the subject's threshold and then presents them in a random order until a minimum number of trials per value has occurred. The percent correct is then plotted as a function of the stimulus value and the threshold is estimated from the resulting psychometric function.

Some had participated in unrelated studies during the first 3 months of life. Parents were paid bus fare or parking expenses.

Apparatus

The grey display panel was 57 cm wide × 69 cm high (59° wide × 69° high when viewed from 50 cm) and contained two 9-cm (10°) portholes through which the stimuli were displayed. The portholes were displaced 14 cm (16°) to the left and right of a central 5-mm (0.6°) peephole, through which an observer watched the child. Above and below the peephole were two 3-mm (0.3°) lights that could be flashed to attract the child's attention at the beginning of each trial. The stimuli were illuminated by an ellipsoidal spotlight (Altman 3.5Q) located behind the child. The spotlight was shuttered and feathered at the angle required to produce even illumination of the stimuli. A curtain could be pulled directly over the child's head to prevent the parent who held the child from seeing the stimuli. Blinders beside the peephole prevented the observer from seeing the stimuli.

A heterogeneous collection of 160 colored slides (toys, storybook characters, geometric patterns, etc.) served as reinforcers. The reinforcers could be projected onto rear-projection screens, 90 cm wide × 62 cm high (84° × 64°), located on either side of the display panel. Behind the display panel were two Kodak Ektagraphic projectors, each fitted with a 3-inch f/3.5 Ektanar lens. Shutters in front of each lens could be raised or lowered to turn on or off the reinforcers. Also behind the display panel were various controls for the shutters, projectors, and lights.

Stimuli

The stimuli were photographically reproduced black-and-white, square-wave gratings (Intergraphics Precision Photographic Services, Kirkland, WA). On each trial the child was shown a "grey" stimulus through one 10° porthole and one of 15 "test" stimuli through the other 10° porthole. The grey stimulus was a subthreshold grating of stripes that were .375 min wide when viewed from 50 cm. The 15 test stripes varied in width from 132 min to .75 min in approximately .5-octave steps.[2]

The brightness and hue of each of the test stripes were matched to those of the grey stimulus by placing various chromatic and achromatic papers behind them. (Although the stimuli were putatively achromatic, some had a bluish or yellowish tinge that could be neutralized by placing chromatic papers behind them of a complementary hue and of an appropriate saturation.) We achieved the best match by observing the stimuli through blurring lenses under the lighting conditions that were to be used in the experiment. Each stimulus (and its backing) was dry mounted on a piece of Gator board (Masuka International, Woodbridge, ON), and the front surface was laminated with glossy, clear laminate for protection. The contrast of the stripes was 89%, and the space-average luminance of the stimuli was 103 cd/m^2 (Tektronix photometer, Model J16, fitted with luminance probe J6523 for measurements of contrast and with J6503 for measurements of space-average luminance).

Procedure

General procedure.—The procedure combined a modification of the operant preferential looking procedure reported by Mayer and Dobson (1980, 1982) with a staircase procedure (see below). After one of the child's eyes was patched, he or she was seated, either alone or on a parent's lap so that the unpatched eye was 50 cm from the display panel. (For half the children in each group we covered the left eye, and for the other half, the right eye.)

At the beginning of each trial the room was dark except for a dim night-light behind the display panel. An experimenter placed the stimuli in the portholes, and the observer flashed the central lights to attract the child's attention. The observer then turned on the overhead spotlight to illuminate the stimuli and judged the location of the stripes based on the child's behavior. The experimenter kept track of the child's responses and gave feedback as to whether the observer's judgment had been correct. When it was, the observer turned on a slide adjacent to the stripes. When a judgment was incorrect, the observer turned off the overhead spotlight without presenting a reinforcer. Note that these changes in illumination might have affected the absolute value of the estimated threshold but should not affect comparisons across tests.

Training phase.—The procedure began with a training phase, which was designed to teach the child to choose the stripes over the grey stimulus. On each trial, the child was shown wide (66 min) stripes paired with grey. The stripes were presented alternately on the left and on the right, and the observer was

[2] An octave is a halving or a doubling of a value.

aware of their location. When the child chose the stripes by looking, pointing, or any other reliable response, the observer presented a slide adjacent to the stripes. This phase continued until the observer was confident that the child had learned the task or for a maximum of 20 trials.

Criterion phase.—The purpose of the criterion phase was to determine objectively whether the child had learned the task. The stimuli were identical to those used during the training phase: the 66-min stripes paired with grey. During the criterion phase and the subsequent acuity phase, the curtain was drawn in front of the eyes of the parent holding the child, and the observer was not told the location of the stripes.

During both the criterion and acuity phases, the stripes were presented on the left or on the right in a pseudo-random order designed to reduce the adoption of a side bias (Fellows, 1967). One restriction was that stripes were never presented more than three times in a row on the same side. After such a sequence, the observer could figure out the location of the stripes on the next trial. To overcome this problem, we treated this next trial as an extra "training" trial: The child was shown wide stripes (66 min), the observer was informed of their location, and she rewarded the child for choosing them. Training trials were not counted in the staircase but were included in the tabulation of the total number of trials required to complete the test.

The criterion phase continued until the observer met a criterion of four correct judgments in a row, providing that, during these four trials, the stripes had not appeared in an alternating left-right sequence. (Alternating response strategies are commonly used by young children.) In this case the criterion phase continued until the pattern was broken and the observer had judged correctly on the last four trials in the series. If the child's responses were, or became, unreliable during the criterion phase, the observer had the option of returning to the training phase and then repeating the criterion phase. Note that the probability of responding correctly on four trials in a row simply by chance is greater than 5%. This is not a concern if the child passes the smaller stripe width presented next during the acuity phase (see below). Should the child fail that stripe width, the staircase would require the retesting of the 66-min stripes to determine whether, in fact, they were above threshold.

Acuity phase.—The acuity phase began after the child met the criterion for training. During this phase we used either Taylor and Creelman's (1967) staircase procedure (PEST) or our modified version of that procedure (modified PEST). In general, PEST searches for the value of the stimulus that yields a particular probability of a correct response. An initial value is selected (preferably one that is likely to be above threshold), and the results indicate whether that value is too high or too low. A step is then made in the appropriate direction, and testing begins again at the new value. The size of the first step is arbitrary, but subsequent step sizes are determined by the history of the run: the step size is cut in half on every reversal of direction, and it is doubled after a given number of steps in the same direction. The test is complete when the rules call for a step of some predetermined minimum size (see Taylor & Creelman, 1967, for a detailed discussion). Our modified PEST rules differed from PEST in that we eliminated the doubling rule and did not repeat tests of a particular stripe width. For both PEST and modified PEST, we chose a deviation limit (W) of 1.0, a p value of .75, an initial stripe width of 15.5 min, an initial step size of 2 octaves, and a final step size of .25 octave.

We began the test by showing the child 15.5-min stripes paired with grey. For this and all subsequent stripe widths, the procedure was identical to that of the criterion phase except that the number of trials per stripe width was determined by PEST rules rather than by a fixed criterion of four correct judgments in a row. We concluded that a stripe width was above threshold when the number correct after x trials was at least $px + W$, or $.75x + 1$. We concluded that a stripe width was below threshold when the number correct after x trials was $px - W$ or less *and* when the child passed three subsequent "catch" trials. For catch trials we paired wide stripes (at least 2 octaves wider than the test stripes) with grey.[3] If the observer judged the location of the stripes incorrectly on any of the three catch trials, we concluded that the child was no longer playing the game. At this point, we usually gave the child a rest or additional practice with wide stripes. Then the test width was repeated until a definite decision could be reached.

[3] If, during the three catch trials, the stripes appeared all on one side or on alternating sides, we added more catch trials until the pattern of presentation was broken.

The width of the test stripe was decreased after a pass and increased after a fail. The initial change in stripe width was always 2 octaves. Each time the direction was changed (increase to decrease or vice versa), the step size was halved. The final step size was .25 octave (i.e., when the rules called for a change of .25 octave, the test was over), and the size yielded by that .25-octave change was the estimate of the child's visual resolution. This is the estimate of the stripe width that the child would have passed 75% of the time.

For tests with PEST rules the fourth and subsequent steps in a particular direction resulted in a doubling of the step size, as did in some cases the third step in a particular direction (see Taylor & Creelman, 1967). Also, under some circumstances a stripe width had to be tested more than once. For example, if the child passed the 15.5-min stripes, the next width tested would be 2 octaves narrower (the width closest to 3.9 min). If the child failed that width, we would increase the width by one octave to the width closest to 7.8 min. If the child failed again, we would increase the width by another octave and retest the 15.5-min stripes.

For tests with our modified PEST rules, we deleted the doubling rule and shortened the procedure by testing a stripe width only once. In the example given above, after the child failed with the width closest to 7.8 min, we increased the width by only .5 octave, since a 1-octave increase would result in retesting the 15.5-min stripes. Since our new step size of .5 octave was closer to the final step size of .25 octave, the procedure would be shorter with the modified PEST rules than with the original PEST rules. In all other respects, both sets of rules were identical.

We tested one eye of each child twice, once with PEST rules and once with modified PEST rules. Half the children at each age were tested first with PEST rules, and the other half, first with modified PEST rules. Whenever possible, we completed both tests on the same day and eliminated the training phase from the second test. The training phase was eliminated from the second test for five 12-month-olds, eight 24-month-olds, and 16 36-month-olds. In some of these cases, the children had responded so reliably on the first test that we also eliminated the criterion phase from the second test. This was so for four 24-month-olds and for 15 36-month-olds, all of whom completed both tests in 1 day. Eliminating the training and/or criterion phases from the second test did not bias the results because these phases were eliminated equally often for tests using PEST rules and for tests using modified PEST rules.

If either test was incomplete on the first day, we scheduled additional appointments during which we attempted to redo that test, always from the beginning. Children were included in the final sample only if they completed both tests within 2 months of their first appointment.

Results

Table 1 shows, for each age, the mean number of trials and the mean amount of time required to complete a test, both for tests using PEST rules and for tests using the modified PEST rules. Wilcoxon tests of matched pairs that compared these values showed no significant difference between tests in the number of trials to complete the training phase—12-month-olds, $T(16) = 66.5$; 24-month-olds, $T(16) = 53$; 36-month-olds,

TABLE 1

Mean Number of Trials and Mean Amount of Time Required to Complete Tests Using PEST Rules and Tests Using the Modified PEST Rules

	No. of Trials							
	Training Phase		Criterion Phase		Acuity Phase		Time (Min)	
Age (Months)[a]	PEST	Modified PEST	PEST	Modified PEST	PEST	Modified PEST	PEST	Modified PEST
12	6.8	7.1	6.1	5.9	33.8	27.7**	26.5	21.4*
24	5.1	3.9	4.9	4.8	34.6	29.6*	22.6	18.9***
36	1.9	1.6	2.4	2.0	40.8	28.2**	17.0	11.8**

Note.—Means include children for whom training phase and/or criterion phase were deleted (see text).
[a] $N = 16$ for each group.
* $p < .05$.
** $p \leq .01$.
*** $p < .10$.

$T(16) = 62.5$; all p's $> .10$, two-tailed—or to complete the criterion phase—12-month-olds, $T(10) = 25.5$; 24-month-olds, $T(9) = 21$; 36-month-olds, $T(15) = 52.5$, all p's $> .10$, two-tailed. This is not surprising, since the two procedures differed only during the subsequent acuity phase. However, children required more trials to complete the acuity phase of tests that used PEST rules than of tests that used the modified rules: 12-month-olds, $T(15) = 20$, $p = .01$; 24-month-olds, $T(16) = 34$, $p < .05$; 36-month-olds, $T(15) = 3$, $p < .001$; all one-tailed tests. Overall, 12- and 36-month-olds required significantly more time to complete tests that used PEST rules than tests that used the modified PEST rules—12-month-olds, $T(13) = 21$, $p < .05$, one-tailed; 36-month-olds, $T(16) = 13$, $p < .01$, one-tailed—and the 24-month-olds showed a trend in the same direction—$T(15) = 34.5$, $p = .07$, one-tailed.

Table 2 indicates that the median threshold values from the two tests were very similar to each other. More than 85% of the time, the thresholds obtained using PEST rules were within .5 octave of those obtained using the modified PEST rules, and children did not perform consistently better on one test than on the other. Wilcoxon tests of matched pairs confirmed that there was no significant difference between the threshold values obtained from the two tests: 12-month-olds, $T(8) = 13$; 24-month-olds, $T(9) = 19$; 36-month-olds, $T(4) = 3$; all p's $> .10$, two-tailed.

Discussion

Children required more trials and more time to complete tests of visual resolution that used Taylor and Creelman's (1967) PEST rules than to complete those that used our modified version of the rules. The entire test that used the modified rules took an average of only 37 trials and 17 min. Even inexperienced children (those who were tested first with the modified rules) usually completed the entire shorter version of the test (79% success rate), and they did so in only 41 trials and in only 19 min, on average. Yet the shorter version yielded values of visual resolution similar to those obtained with the longer PEST rules. This good reliability suggests that our alterations of the PEST rules did not bias the estimates of threshold.

The threshold values obtained in this study are very similar to those reported by Mayer and Dobson (1982), who used preferential looking combined with the classic method-of-constant stimuli. However, in that study only small groups of children were tested binocularly, whereas we tested larger groups of children monocularly. To compare adequately the method-of-constant stimuli with our staircase procedure, each child should be tested with both methods under the same conditions. In Experiment 2, we used preferential looking to test monocularly each of 48 children with both the method-of-constant stimuli and our modified PEST rules.

Experiment 2

Method

Subjects

The subjects were three new groups of children, similar to those described in Experiment 1. There were 18 12-month-olds (M age = 12.6 months, range 12.3–13.1 months), 16 24-month-olds (M age = 24.8 months, range 23.6–25.3 months), and 16 36-month-olds (M age = 36.9 months, range 35.7–37.5 months). (All ages refer to the child's age at the first testing session.) An additional 36 children

TABLE 2

A Comparison of Visual Resolution Estimated from Tests Using PEST Rules with That from Tests Using the Modified PEST Rules

	Median Visual Resolution (in Min of Arc)		% of Children for Whom the Two Estimates Were within:	
Age (Months)[a]	PEST	Modified PEST	.5 Octave	1 Octave
12	4.7	4.7	88	94
24	2.1	2.5	88	88
36	1.6	1.4	100	100

[a] N = 16 for each group.

were excluded from the final sample because they refused to wear an eye patch (N = 2) or to play the game (N = 5), because of procedural errors (N = 5), or because the parent would not return to complete the tests (N = 24). Of the 24 children whose parents would not return, seven of the nine tested first with the staircase procedure completed that test, but none of the 15 children tested first with the method-of-constant stimuli completed that test. We completed two tests of one eye for 18/36 (50%) 12-month-olds, 16/32 (50%) 24-month-olds, and 16/18 (89%) 36-month-olds (see Procedure section).

Apparatus, Stimuli, and Procedure

The apparatus and stimuli were identical to those described in Experiment 1. For tests that used modified PEST rules, the procedure was the same as for tests in Experiment 1 that used that procedure. For tests that used method-of-constant stimuli, the training phase and criterion phase were identical to Experiment 1 except that during the criterion phase, 24-month-olds and 36-month-olds were shown stripes only 15.5 min wide. We chose a smaller width so that the stripes did not differ so greatly from the widths to be used during the acuity phase and because the results of Experiment 1 indicated that even this width would be well above threshold for 24- and 36-month-olds.

For the acuity phase of the method-of-constant stimuli, we chose a standard set of four test stimuli for each age group. Within a set, the stripes differed in width by approximately 1 octave. The widths chosen for each age group were determined from the results of Experiment 1 so that the observer's percent correct would be likely to vary from approximately 50%, or chance, for the narrowest stripes to approximately 100% for the widest stripes. The standard sets of four stimuli ranged in size from 3.1 min to 22.7 min for 12-month-olds and from .75 min to 5.2 min for 24- and 36-month-olds.

Trials were divided into blocks so that each block contained two presentations of each of the four stripe widths, presented in a random order. Within each block there were also three catch trials designed to check on the child's alertness. For catch trials, we used the same width as had been used during the criterion phase (i.e., 66-min stripes for 12-month-olds and 15.5-min stripes for the two older groups). These trials were inserted randomly into each block, and the observer was unaware of when they occurred. If the observer made an incorrect judgment on any catch trial within a block, that whole block was repeated, usually after a break and/or additional training. As in tests with modified PEST rules, the left-right position of the stripes varied according to Fellow's (1967) orders, with a training trial added after each sequence of three trials in a row with the stripes on one side. The stripe width used for training trials was the same as that used for catch trials.

Each child provided data on 10 blocks of trials (i.e., 20 trials per stripe width). If, after the first five blocks of trials, the observer's percent correct was 75% or higher for the narrowest stripes, stripes 1 octave narrower were added to the set, and the widest stripes were removed. If instead, the observer's percent correct was 75% or less for the widest stripes, stripes 1 octave wider were added to the set, and the narrowest stripes were removed. Added test stimuli were presented four times instead of twice during each of the remaining five blocks so that there would be 20 trials for that stripe width. Thus, each block consisted of eight trials with test stimuli (10 trials if a new width had been added to the series), three catch trials, and training trials when necessary.

To estimate a child's visual resolution, we calculated the observer's percent correct for each of the four stripe widths. We then plotted a logistic function (Berkson, 1953; Cox, 1970) with the logit of the observer's percent correct plotted as a function of log stripe width. From the best fitting straight line, we calculated the width corresponding to 75% correct judgments. This value was our estimate of the child's visual resolution.[4]

We tested each child's visual resolution twice, once with method-of-constant stimuli and once with modified PEST rules. As in Experiment 1, we counterbalanced between children, the eye that was tested, and the order of the tests. Children had to complete the entire PEST procedure during any one session but could take as many sessions as necessary to complete the method-of-constant stimuli. Children were included in the final sample only if they completed both tests within 2 months of their first appointment.

[4] We calculated thresholds from the logistic function rather than by probit analyses because logits are computationally simpler and may be theoretically superior (see Cox, 1970). Empirically, both analyses give virtually identical results (Cox, 1970).

As in Experiment 1, the training and/or criterion phases were eliminated from the second test whenever possible. The training phase was eliminated from the second test for four 12-month-olds, seven 24-month-olds, and 14 36-month-olds. In addition, the criterion phase was eliminated from the second test for six 24-month-olds and 13 36-month-olds. These phases were eliminated about twice as often for tests that used the modified PEST rules than for tests that used method-of-constant stimuli.

RESULTS

Table 3 shows, for each age, the mean number of trials and the mean amount of time required to complete a test, both for tests that used our modified PEST rules and for tests that used method-of-constant stimuli. We included only each child's first test in this analysis because for the second test we had eliminated the training and/or criterion phases more often for tests that used the modified PEST rules than for tests that used method-of-constant stimuli. Mann-Whitney U tests showed that at each age, children required more trials—12-month-olds, $U = 0$, $p < .001$; 24-month-olds, $U = 0$, $p < .0001$; 36-month-olds, $U = 0$, $p < .0001$; all one-tailed tests—and more time—12-month-olds, $U = 2$, $p < .001$; 24-month-olds, $U = 0$, $p < .0001$; 36-month-olds, $U = 5.5$, $p < .002$; all one-tailed tests—to complete tests that used method-of-constant stimuli than tests that used modified PEST rules. In fact, every child required more trials, and all but one child required more time to complete tests that used method-of-constant stimuli than tests that used modified PEST rules.

Two-tailed Wilcoxon tests of matched pairs used to compare the visual resolution estimated from the two tests for each child showed that neither 12-month-olds, $T(18) = 55$, $p > .10$, nor 36-month-olds, $T(14) = 3.5$, $p > .10$, performed better on one test than on the other. Table 4 shows that more than 80% of the time the estimates from modified PEST rules and the method-of-constant stimuli were within 1 octave of each other, and at both ages the median visual resolution from the two tests was very similar.

For 24-month-olds, visual resolution estimated from method-of-constant stimuli was significantly better than that estimated from tests that used the modified PEST rules, $T(14) = 17.5$, $p < .05$, two-tailed. This was so because 12 out of 16 children at this age showed a lower threshold with method-of-constant stimuli than with modified PEST rules. However, in all but three of these cases, the thresholds were less than .5 octave apart. In fact, for 2-year-olds, the estimates from one test were within .5 octave of those from the other test 81% of the time (see Table 4).

DISCUSSION

Children took more than three times longer and more than three times the number of trials to complete tests that used the method-of-constant stimuli than tests that used the modified PEST rules. Yet, we found good agreement in visual resolution estimated by the two procedures. Although for 24-month-olds, tests that used the modified PEST rules tended to produce poorer values than did the method-of-constant stimuli, the differences in scores between the two procedures were very small. These small differences do not warrant using the longer method-of-constant stimuli, particularly in a clinical setting where patients must often be tested quickly.

TABLE 3

MEAN NUMBER OF TRIALS AND MEAN AMOUNT OF TIME REQUIRED TO COMPLETE TESTS USING THE MODIFIED PEST RULES AND TESTS USING METHOD-OF-CONSTANT STIMULI (MCS)

	No. of Trials		Time (Min)	
Age (Months)	Modified PEST	MCS	Modified PEST	MCS
12 (N = 18)	56.8	183.0**	27.7	77.3**
24 (N = 16)	42.0	163.1***	20.3	76.1***
36 (N = 16)	37.3	156.5***	16.3	51.8*

NOTE.—Data are for the first test completed by each child (see text).
* $p < .01$.
** $p < .001$.
*** $p < .0001$.

TABLE 4

A COMPARISON OF VISUAL RESOLUTION ESTIMATED FROM TESTS USING MODIFIED PEST RULES WITH VISUAL RESOLUTION ESTIMATED FROM THE METHOD-OF-CONSTANT STIMULI (MCS)

	MEDIAN VISUAL RESOLUTION (in Min of Arc)		% OF CHILDREN FOR WHOM THE TWO ESTIMATES WERE WITHIN:	
AGE (Months)	Modified PEST	MCS	.5 Octave	1 Octave
12 (N = 18)	4.7	5.9	78	94
24 (N = 16)	2.5	1.9	81	94
36 (N = 16)	1.4	1.6	63	81

Only two other studies (Gwiazda, Wolfe, Brill, Mohindra, and Held, 1980; Mayer et al., 1982) have compared visual resolution tested both by the method-of-constant stimuli and by a staircase procedure in the same children. Like us, the authors obtained similar results from their two methods. However, they used two other staircase procedures and tested only a few children at each age, all of whom were less than 1 year old.

The visual resolution estimated for children in this study was similar to that reported in previous studies that used preferential looking (see, e.g., Mayer & Dobson, 1982) and to that found in Experiment 1. However, the results of Experiments 1 and 2 are not suitable as normative estimates of visual resolution because the children were not screened for ocular abnormalities. Moreover, in neither experiment did we evaluate the reliability of thresholds obtained from the modified PEST procedure.

The purpose of Experiment 3 was to evaluate the reliability of the modified PEST procedure and to obtain norms for groups of children, 6–36 months of age. To measure reliability, we obtained two independent estimates of each child's monocular visual resolution using the modified PEST rules. Those children who met our criteria on a standard ophthalmological examination were also included in the calculation of norms.

Experiment 3

METHOD

Subjects

The subjects were 192 children similar to those described in Experiment 1. There were 30 6-month-olds, 27 12-month-olds, 26 18-month-olds, 51 24-month-olds, 27 30-month-olds, and 31 36-month-olds, all of whom were within 1 month of the specified age at their first appointment. An additional 89 children were excluded from the sample because they refused to wear an eye patch (N = 18) or to play the game (N = 22), because the parent would not return to complete the tests (N = 47), because of procedural errors (N = 1), or because the child was taking heavy doses of medication (N = 1). We completed two tests of one eye for 30/43 (70%) 6-month-olds, 27/36 (75%) 12-month-olds, 26/45 (58%) 18-month-olds, 51/90 (57%) 24-month-olds, 27/34 (79%) 30-month-olds, and 31/33 (94%) 36-month-olds. We completed at least one test of one eye for 34/43 (79%) 6-month-olds, 30/36 (83%) 12-month-olds, 33/45 (73%) 18-month-olds, 66/90 (73%) 24-month-olds, 28/34 (82%) 30-month-olds, and 32/33 (97%) 36-month-olds.

Stimuli, Apparatus, and Procedure

The stimuli, apparatus, and procedure were identical to those described in tests that used the modified PEST rules in Experiment 1, with the following exceptions. We obtained two independent estimates of each child's visual resolution, in both cases using the modified PEST rules. Following the tests, each child was given a full eye examination, including cycloplegic refraction, by an ophthalmologist. Children were excluded from the normative data (see Results section) if their parents refused the eye examination or if the results of the eye examination revealed a spherical error of 2 diopters or more in the eye that we had tested, a cylindrical error of 1.5 diopters or more in the eye that we had tested, a difference between the two eyes of 1 diopter or more of equivalent spherical error,[5]

[5] The equivalent spherical error is the algebraic sum of the spherical error plus half the cylindrical error.

or any other abnormality that might interfere with visual acuity (e.g., strabismus, ptosis, etc.).

RESULTS

The 192 children required a mean of 46 trials and a mean of 20 min to complete the first test of visual resolution (see Table 5). Because many children required little or no training for the second test, it was somewhat shorter than the first (M number of trials = 40, M amount of time = 17 min). Wilcoxon tests of matched pairs confirmed that the second test was completed in significantly fewer trials and/or in significantly less time than the first test for children between 12 and 36 months of age (all p's $< .05$, one-tailed). Only for 6-month-olds were there no significant differences between tests in the number of trials, $T(29) = 189.5$, N.S., or in the amount of time required, $T(29) = 173.5$, N.S.

A comparison of the threshold estimates from the two tests showed that the modified PEST rules yielded reliable results: the threshold values from the second test were within .5 octave of those from the first test in more than 80% of the cases (see Table 6). Data from the first and second tests are shown as a scatter-plot in Figure 1. In general, the two tests agreed closely, and children did not perform consistently better on one test than on the other. Wilcoxon tests of matched pairs confirmed that there was no significant difference at any age between the thresholds obtained from the two tests (all p's $> .10$, two-tailed).

Of the 192 children who completed the test twice, the data from 24 were excluded from the normative sample because the parents refused the eye examination ($N = 6$) or because the examination revealed problems that might interfere with normal vision ($N = 18$). Seventeen of these children had a hypermetropia of at least 2 diopters in the tested eye (M spherical equivalent = 2.9 diopters, range 2.0–4.25) and one had hypotropia (a constant vertical deviation) in the tested eye.

The normative data were based on two tests of an eye for each of the remaining 168 children (24 6-month-olds, 25 12-month-olds, 24 18-month-olds, 47 24-month-olds, 24 30-month-olds, and 24 36-month-olds). We calculated each child's threshold by taking the mean of the two tests, and then at each age we calculated the median of these values for all children and the range from the best 95% of the sample. The bottom of the normal range is the value against which results are compared in the clinic. We defined this value as that obtained by at least 95% of children at an age so as to include virtually all of the results, yet

TABLE 6

RELIABILITY OF ESTIMATES OF VISUAL RESOLUTION BASED ON THE MODIFIED PEST RULES

	% OF CHILDREN FOR WHOM THE TWO ESTIMATES WERE WITHIN:	
AGE (Months)	.5 Octave	1 Octave
6 (N = 30)	87	97
12 (N = 27)	85	89
18 (N = 26)	85	88
24 (N = 51)	84	98
30 (N = 27)	89	96
36 (N = 31)	87	100

TABLE 5

MEAN NUMBER OF TRIALS AND MEAN AMOUNT OF TIME REQUIRED TO COMPLETE TESTS USING THE MODIFIED PEST RULES

	NO. OF TRIALS		TIME (Min)	
AGE (Months)	Test 1	Test 2	Test 1	Test 2
6 (N = 30)	50.1	47.9	22.6	19.7
12 (N = 27)	44.7	37.5	22.8	20.5*
18 (N = 26)	58.9	52.1*	27.8	22.7**
24 (N = 51)	40.0	31.9**	16.8	14.1*
30 (N = 27)	47.2	39.9**	15.7	13.4
36 (N = 31)	31.9	28.5**	12.8	11.9*
Mean	45.5	39.6	19.8	17.1

* $p < .05$.
** $p < .01$.

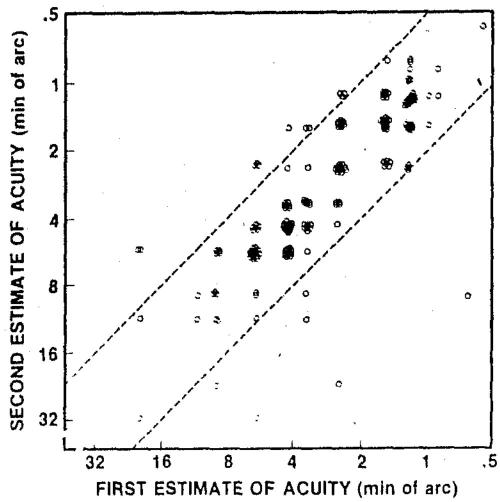

FIG. 1.—Scatter-plot showing the relation between the first and second estimates of acuity in Experiment 3. Each point represents the results from one child tested twice within a 2-month period. Points falling between the diagonal lines represent values within 1 octave of each other.

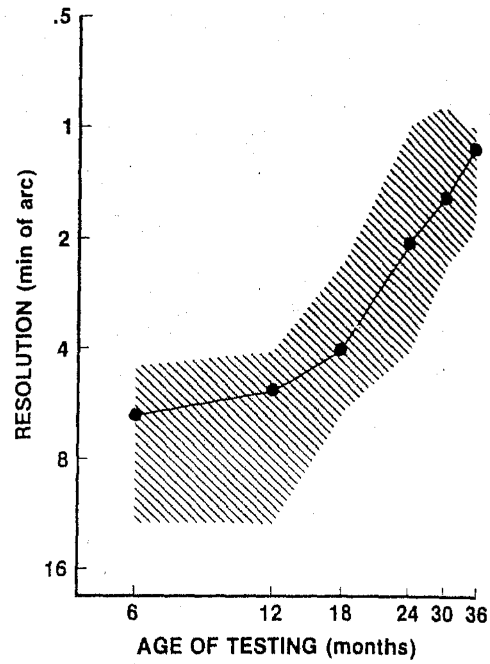

FIG. 2.—The monocular visual resolution of 168 6–36-month-olds with normal eyes tested in Experiment 3 with the modified PEST rules. Dots represent the median visual resolution as a function of age. The shaded area represents the range of values from the best 95% of the thresholds.

not bias them by occasional highly deviant values. Figure 2 shows the median and range of visual resolution at each age, plotted in log units. Note the considerable variation at each age: the range extends about 2 octaves. Note also that the median visual resolution increases more slowly between 6 and 12 months of age than at later ages.

Of the 18 children who were excluded from the norms on the basis of the eye examination, 15 had visual resolution within the normal range. This suggests that moderate amounts of hypermetropia do not interfere with visual resolution during early childhood.

Discussion

The results of Experiment 3 show that most children 6–36 months of age can be tested successfully using preferential looking combined with a modified PEST procedure: 72% of the children completed two tests of an eye under monocular viewing conditions, and 81% completed at least one test. Although the poorest success was with 18–24-month-olds, even at that age over half of the children completed two monocular tests. It is interesting to note that in one-third of the cases in which the child did not complete the two tests, the reason was that the child never began testing because he or she refused to wear an eye patch. Perhaps because they tested children binocularly and because they required each child to complete only one test, Birch et al. (1983) were able to test successfully over 90% of their 18- and 24-month-olds. Only two other studies have reported their success in testing normal children of this age with preferential looking. Both were less successful than we were in getting toddlers to complete even one test either because they used a lengthy psychophysical procedure (Mayer & Dobson, 1982) or because they did not use an operant procedure (Sokol et al., 1983).

Children in Experiment 3, like those tested with the modified PEST procedure in Experiments 1 and 2, usually completed an entire test in 20 min. This is similar to the amount of time required to complete a test monocularly using other staircase procedures (Sokol et al., 1983) but considerably less than the amount of time for method-of-constant stimuli with 20 trials per stimulus and four stimuli (Experiment 2; Mayer & Dobson, 1982). Using method-of-constant stimuli with eight trials per stimulus and eight stimuli, Birch et al. (1983) found that it took 15–20 min to test children binocularly who were at least 2 years old, but 1 hour to test younger children. Note that their task was more difficult than ours: children had to touch the stripes for reinforcement, rather than just look at them. Obviously, short tests are desirable, particularly in a clinical setting.

The modified PEST procedure also yielded reliable results: independent tests of the same eye yielded values within .5 octave of each other 86% of the time, and within 1 octave, 96% of the time. Thus, we found that two tests of the same eye yielded values more than 1 octave apart less than 5% of the time. This suggests that a change of more than 1 octave in a child's visual resolution over time or a difference between the right and left eye of more than 1 octave is likely to reflect a real difference in visual resolution. Previous reports on the reliability of preferential looking all used different psychophysical procedures, either a "quick assessment" (Gwiazda, Brill, Mohindra, & Held, 1980), the Cornsweet staircase (Atkinson et al., 1982), or the method-of-constant stimuli (Birch et al., 1983). Moreover, in two of these studies (Atkinson et al., 1982; Gwiazda, Brill, Mohindra, & Held, 1980), reliability was evaluated in very few children (fewer than 15), all of whom were less than 1 year old, and in only one study were the children tested monocularly (Atkinson et al., 1982). Nonetheless, like us, these investigators found that repeated tests of the same eye yielded values within .5 octave of each other 85%–100% of the time and within 1 octave of each other 95%–100% of the time.

The results of Experiment 3 also showed that the median monocular visual resolution of children with no eye problems increased from 6.5 min at 6 months of age to 1.2 min at 36 months of age. To our knowledge, there have been only three previously published reports on the development of monocular visual resolution, as measured by preferential looking. One study (Manning et al., 1982) measured monocular visual resolution in only seven normal children, ranging in age from 2 to 30 months, and a second study (Mayer et al., 1982) included only 16 normal children, between 11 weeks and 5 years of age. A third study (Dobson, 1983) had a much larger sample (43 children), but all were tested only during the first year of life. Nonetheless, the values reported in all these studies were very similar to ours, despite the fact that all used psychophysical procedures that were different from ours.

There are several possible explanations for the observed improvement in visual resolution during early childhood. First, motivation to play the game and attention span might increase with age. This is an unlikely explanation, since children of all ages were rewarded for correct responses, and we included catch trials to ensure that they were attentive throughout the procedure. Second, improvements in accommodation or the clarity of the ocular media might underlie the changes. However, this is an unlikely explanation, since the optical quality of the infant's eye is very good shortly after birth and accommodative error does not appear to affect the infant's visual resolution (Banks, 1980; reviewed in Boothe, Dobson, & Teller, 1985, and in Odom & Green, 1984). Rather, the most likely explanation for improved visual resolution is neural maturation. Between 6 and 36 months of age there is significant development in the fovea (Hendrickson & Yuodelis, 1984), optic nerve (Magoon & Robb, 1981), lateral geniculate nucleus (Hickey, 1977), and striate cortex (Huttenlocher, deCourten, Garey, & van der Loos, 1982; reviewed in Boothe et al., 1985, and in Odom & Green, 1984). For example, Hendrickson and Yuodelis (1984) showed that the density of foveal cones increases markedly after birth and is still not adultlike at 15 months of age. Such changes could account, at least in part, for the observed improvement in visual resolution during early childhood.

Although monocular visual resolution improved almost 2.5 octaves between 6 and 36 months of age, there was little change between 6 and 12 months. Previous studies that used preferential looking to measure visual resolution have reported little or no improvement between 6 and 12 months, whether infants viewed the stimuli monocularly (Dobson, 1983) or binocularly (Bauer, Birch, Gwiazda, Shimojo, & Held, 1984; Gwiazda, Brill, Mohindra, & Held, 1980; Mayer & Dobson, 1980, 1982; Shimojo, Birch, Gwiazda, & Held, 1984; Sireteanu, Keller, & Boergen, 1984). The reason for the slow development at this age is unclear. However, its presence suggests that one best fitting function will not accurately represent the development of visual resolution (as measured by preferential looking) throughout infancy and childhood.

In summary, these studies show that preferential looking combined with the modified PEST procedure yields values of visual resolution very similar to those found in the same children using the method-of-constant stimuli (Experiment 2) and to those using Taylor and Creelman's (1967) PEST rules (Experiment 1). Moreover, the modified PEST procedure yielded reliable estimates of visual resolution at all ages between 6 and 36 months (Experiment 3). Most children in this age range could be tested successfully with the procedure, even when they were required to complete the test twice while viewing monocularly (Experiment 3). The main advantage of the modified PEST procedure is that tests that use this staircase can be completed in fewer trials and in less time than tests that use Taylor and Creelman's (1967) rules (Experiment 1) or tests that use the method-of-constant stimuli (Experiment 2). Taken together, these findings suggest that preferential looking combined with the modified PEST procedure would be a useful way to measure visual resolution in clinical settings.

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