Monocular Acuity Norms for the Teller Acuity Cards Between Ages One Month and Four Years


**Purpose.** To derive norms for monocular grating acuity and interocular acuity differences that are appropriate for clinical applications using the acuity card procedure (ACP) and Teller Acuity Cards (TAC).

**Methods.** Monocular acuities were measured in 460 children in 12 age groups between 1 month and 4 years. Inclusion criteria were term birth, good general health and normal development, normal eyes, and cycloplegic refraction within specific limits. Each child was tested by two ACP testers who were aware of TAC spatial frequency but not grating location during testing.

**Results.** Three monocular tests were completed in the first session in 99% of children. Median time to complete the tests of both eyes ranged from 3.2 to 8.4 minutes. Monocular acuity norms were calculated using 95% and 99% prediction limits. The new norms spanned higher spatial frequencies than the preliminary ACP norms between ages 1 month and 18 months but were similar between 24 and 36 months. The lower normal 2.5% limits were similar to lower limits of other normative studies. The interocular acuity difference was zero or 0.5 octave in 99% of subjects of all ages. Acuities obtained by the same tester on different days and by different testers on the same day were within 0.5 octave in at least 90% of subjects, comparable to previous studies.

**Conclusions.** This study provides monocular acuity norms that are appropriate for clinical settings in which the ACP and TAC are used and should replace the preliminary ACP norms.

the study had a complete eye examination that showed normal eyes and refractive error within specified limits. Demographics of the study subjects were surveyed. Prediction limits for monocular acuity, interocular acuity difference norms, and within- and between-tester test—retest reliability based on tests of 460 children between ages 1 month and 48 months are reported.

To ensure consistent clinical use of the method and because exact procedural details may affect the acuities tested, we describe the specific ACP we used in detail. In the interest of efficiency, we made two important choices when selecting the exact ACP with which to obtain norms. First, a single tester obtained the acuity of each eye of a subject, as would be the case in most clinical settings. As a consequence, the testers in the present study, in contrast to the preliminary norm studies, could have known the spatial frequency of the test gratings and, when testing the second eye, knew the acuity obtained in the first eye. Second, fixed spatial frequencies for each age were used to start the grating series, unlike the preliminary norm studies that used a range of start card spatial frequencies. We discuss the possible effects of these aspects of the ACP on the results. We compare the monocular acuity norms in this study to other ACP and FPL normative data sets intended for clinical use. Guidelines for interpreting ACP acuities of individual patients are also provided.

**METHODS**

**Study Design**

The study was intended to provide, using an ACP administered by a single examiner, norms for monocular acuity and interocular acuity differences, as well as data on test—retest reliability for within-tester and between-tester comparisons. To minimize variability yet also evaluate between-tester reliability, all subjects were tested by the same two testers. In the first session, one tester measured the acuity of each eye of a subject, and the other tester measured the acuity of only one of the subject’s eyes. The tester who obtained the acuity of each eye of a subject in the first session also tested each eye in the same order in a second session. Randomization of the first tester, the tester who tested each eye of the subject, and the eye tested first resulted in eight random orders of acuity tests. A sample random order is shown in Table 1 with data derived from the tests.

The two sessions were scheduled within a specified time interval. The maximum difference between sessions was 7 days for the 1- to 2.5-month group, 9 days for the 4- to 12-month group, and 25 days for the 18- to 48-month group.

**Eye Examination**

Study subjects received complete eye examinations by one of two study examiners, an ophthalmologist and an optometrist. The examination included evaluation of binocular alignment, extraocular motility, pupil and anterior segment, ophthalmoscopy of the media and posterior pole, and cycloplegic retinoscopy (1% cyclopentolate). The eye examination was scheduled immediately after the second test session or on a separate day within 9 days of the second session.

**Subjects**

**Recruitment.** Subjects were recruited through hospital birth records, advertisements in local publications, and referral from other sources. Hospital records were screened for normal birth weight. Apgar scores ≥8 at 1 and 5 minutes, and a normal neonatal course. Parents responding to recruitment efforts were questioned regarding their child’s general health, history of eye problems, and development. At the first test session, information on the child’s birth date, birth weight, estimated gestational age at birth, general health history, sex, race, family eye history, parents’ ages and education, and total family income was obtained from the parent or guardian.

**Eligibility Criteria.** To be eligible for inclusion in the study, subjects met the following criteria: (1) a difference between birth date and due date of no more than 10 days for ages 1 to 12 months and 14 days for ages 18 to 48 months; (2) birth weight between 5.5 and 10 pounds (2.5 to 4.5 kg); (3) no major medical problems; (4) normal development by parent report and observation; (5) completion of five monocular tests, three in the first test session and two in the second session; and (6) a complete eye examination showing no ocular problems or strabismus, and cycloplegic refractive error within specified limits.

Refractive error exclusion criteria were based on studies of cycloplegic refractive error in human infants. Subjects between 1 and 12 months of age were excluded if the spherical equivalent was greater than 3.5 D myopia or 4.5 D hyperopia, if the maximum cylinder power was greater than 2.25 D in either eye, or if there was anisometropia (difference between spherical equivalents of right and left eyes) greater than 2 D. Excluded from the study were subjects between ages 18 and 48 months with spherical equivalent greater than 2.5 D myopia or 2.75 D hyperopia, maximum cylinder power greater than 1.5 D in either eye, or anisometropia greater than 1.25 D.

**Age Groups and Sample Size.** Subjects were recruited for 12 discrete age groups to facilitate planning of recruitment and to ensure equal distribution of subjects across age. Intervals between ages were selected based on previous normative data to minimize
The extrapolation of norms between ages. The nominal age of each group in months (1 month = 30.4 days) with the acceptable window for the first test session was: 1 (±0.3), 1.5 (±0.3), 2.5 (±0.3), 4 (±0.3), 6 (±0.3), 9 (±0.3), 12 (±0.3), 18 (±0.5), 24 (±0.5), 30 (±0.5), 36 (±0.5) and 48 (±0.5).

A sample size of 40 subjects per age group provides more than adequate power (80%) to detect a 0.5 octave difference (the approximate interval of Teller Acuity Cards [TACs]) between testers based on an average sample standard deviation of 0.8 octave, a conservative estimate derived from the preliminary normative data. Recruitment of the desired 40 subjects per age group meeting all eligibility criteria, however, was not possible for the 1- and 48-month-old groups. For the 1-month-old group, the delay in obtaining birth information and the time required for mailing limited the number of subjects available for recruitment. For the 48-month-old group, recruitment sources were limited. Consequently, these two groups contain 32 subjects, or four replications of the eight random orders. After the end of data collection, it was discovered that four subjects did not meet eligibility criteria. This resulted in fewer than the desired 40 subjects in three other age groups: 38 subjects at 2.5 months and 39 subjects each at 9 and 36 months.

Excluded Subjects. Five hundred sixty subjects were recruited (75% from hospital birth records and 25% from other sources) and tested in at least the first session. Of these, 100 were excluded either due to ocular disorder or refractive error (32), protocol violations, i.e., eye or tester order incorrect (29), no second session (20), replicates of random orders (9), monocular tests in both sessions not completed (7; in 6, monocular occlusion was refused and one refused testing in the second session), incomplete eye examination (2), and developmental delay (1).

Success in Testing. In all age groups, the success rate for completion of three monocular acuities in the first session was 99% (553/560). Between ages 1 and 12 months, the success rate was 100%, and for ages 18 to 48 months it was 97%. The success rate in all age groups for completion of two tests in the second session was also 99% (532/540).

Demographics of Study Sample. Distribution by sex was 50% (228/460) female. Study subjects were predominantly white (85%; 393/460). A four-year college education was attained by 73% (329/452) of mothers and 71% (316/443) of fathers. Total family income for 82% (348/423) of the subjects was $33,200 or greater, based on a categorical survey of family income.

Procedures

The tenets of the Declaration of Helsinki were followed, and the study was approved by the human subjects review committees of the hospitals involved. Written informed consent was obtained from the subject’s parent or guardian after demonstration of the tests and explanation of the eye examination. Compensation for participation included $5 per session and a free eye examination.

Monocular occlusion was achieved with an adhesive eye patch in all subjects up to age 12 months. Older subjects who resisted the patch were allowed to

<table>
<thead>
<tr>
<th>Test</th>
<th>Session 1</th>
<th>Session 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eye</td>
<td>RE/LE</td>
<td>RE/LE</td>
</tr>
<tr>
<td>Tester</td>
<td>1/1</td>
<td>2/1</td>
</tr>
</tbody>
</table>

**TABLE 1. Example of Random Order and Data Obtained**

RE = right eye; LE = left eye; IAD = interocular acuity difference.
choose between it and a pair of plastic lens frames with one eye piece occluded. The children who wore the lens frames were monitored carefully to ensure they did not peek around the occluder.

Testers

The two testers (EMP and KNR) were trained at the same time by two experts who had extensive experience in training acuity card testers and who were not otherwise involved in the study.

The testers had knowledge of each subject's name, test distance, and start card but were not informed of the subject's age. They were not present during each other's tests and were instructed not to discuss their experiences or the test results until data collection from all study participants was complete. A third person, the study coordinator (AFW), explained the test results to the parents after the child completed the second test session and also handled the test forms.

Test Materials

The TACs were provided by the manufacturer (Vistech Consultants, Dayton, OH) between September 1989 and April 1991. The TAC set contained 15 cards, 25.5 x 56 cm. Fourteen of them had high-contrast, vertical, black-and-white, square-wave gratings ranging from 0.32 to 26 cycles per centimeter (cyc/cm) in approximately half-octave steps (a halving or doubling of stimulus value). An additional card was blank, containing no grating. The grating was 12 x 12 cm overall and was displaced 7.5 cm from its edge to a small central peephole. The front surface of the cards was a homogeneous gray matched within 1% of the space-average luminance of the gratings (manufacturer's specifications).

Four sets of acuity cards were used during the period of data collection. Cards in each set were individually compared by eye to the previous cards to ensure a high degree of similarity across sets. Any cards that were not comparable or had obvious artifacts were rejected and replaced. The card with the highest spatial frequency grating, 38 cyc/cm, was not used because the grating location was readily identified by adult observers even when the grating could not be resolved because of an 'edge' or brightness artifact. No other cards were systematically rejected for edge or brightness artifacts.

The TAC apparatus (Vistech Consultants, Dayton, OH) was a three-panel hardboard screen painted gray; the central panel contained an opening behind which the acuity cards were presented. To enable comfortable testing of subjects at all ages and for stability of the apparatus, it was permanently attached to an ocular adjustment table. Side panels partially blocked the subject's view of the surround. A smaller panel blocked the person holding the subject from seeing the acuity card stimuli and was used to indicate the 38- and 55-cm test distances. At test distances of 84 cm or greater, the view of the holder of the few subjects who sat in their parent's lap was not blocked. A 40-watt desk lamp with voltage controlled by a potentiometer was attached to the back of the blocking panel to provide constant illumination of the acuity cards. Space-averaged luminance of the acuity cards in the apparatus was 1.75 log cd/m², measured with a J16 photometer and J6523 narrow angle probe (Tektronix, Beaverton, OR).

Test Procedure

All testing was done with the acuity cards placed behind the opening in the central panel of the TAC apparatus. Infants 1 to 4 months of age were held by the study coordinator and subjects 6 months of age and older were seated in the parent's lap or sat alone for testing.

To ensure that sufficiently high spatial frequencies were tested, the following procedure was used. If the tester judged that the subject detected the 26 cyc/cm card (the highest spatial frequency card used) at any distance, the subject was moved a specified distance farther away from the apparatus (from 55 to 84 cm, 84 to 110 cm, 110 to 168 cm) until threshold could be determined. A total of 26 subjects (5 at 30 months; 7 at 36 months; 16 at 48 months) were tested at a distance farther than the initial distance on at least one test. An acuity estimate was obtained in all.

Before the test, the acuity cards were arranged in order of spatial frequency with the right–left location of the grating randomized. The tester presented the gratings in order of increasing spatial frequency. The card series began with a suprathreshold grating (start card) 1.5 to 3 octaves above the expected normal mean acuity for age, based on previous studies of normal acuity maturation.9,17,18 Table 2 lists the test distances and start cards for each age group.

Initially, the tester presented the cards in intervals of 1-octave (two cards) and in 0.5-octave (one card) steps when the subject appeared not to detect a grating (i.e., when nearing threshold). Previously presented cards could be shown again as necessary, in any order, at the discretion of the tester.

Presenting each card two or more times in succession with the right or left position of the grating varied, the tester decided whether the child responded consistently to the presumed grating location. For example, by a change in fixation or pointing. Older subjects were shown the blank card to demonstrate that some cards contain "no stripes."

The tester remained unaware of the right–left location of the grating until she judged that the child detected the grating; thereupon, she checked the front surface of the card to confirm its location. If the
Acuity Card Norms

TABLE 2. Mean Monocular Acuity (First Eye) With Test Distance and Start Card

<table>
<thead>
<tr>
<th>Age (months)</th>
<th>Test Distance (cm)</th>
<th>Start Card (cyc/deg)</th>
<th>N</th>
<th>Mean Acuity (cyc/deg)</th>
<th>SD (octaves)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38</td>
<td>0.22</td>
<td>32</td>
<td>0.94</td>
<td>0.44</td>
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<tr>
<td>1.5</td>
<td>38</td>
<td>0.22</td>
<td>40</td>
<td>1.11</td>
<td>0.42</td>
</tr>
<tr>
<td>2.5</td>
<td>38</td>
<td>0.44</td>
<td>38</td>
<td>2.16</td>
<td>0.43</td>
</tr>
<tr>
<td>4</td>
<td>38</td>
<td>0.44</td>
<td>40</td>
<td>2.68</td>
<td>0.47</td>
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<tr>
<td>6</td>
<td>55</td>
<td>0.86</td>
<td>39</td>
<td>5.65</td>
<td>0.47</td>
</tr>
<tr>
<td>9</td>
<td>55</td>
<td>0.86</td>
<td>40</td>
<td>6.79</td>
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</tr>
<tr>
<td>12</td>
<td>55</td>
<td>0.86</td>
<td>40</td>
<td>6.42</td>
<td>0.29</td>
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<tr>
<td>18</td>
<td>55</td>
<td>1.57</td>
<td>40</td>
<td>8.59</td>
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<td>84</td>
<td>3.55</td>
<td>32</td>
<td>24.81</td>
<td>0.31</td>
</tr>
</tbody>
</table>

* Standard deviation.

tester erred in judging grating location, that is, if the child consistently looked to the blank half of the card, a rare occurrence, this grating was not considered detected and could be retested. Gratings that the tester was unsure the subject resolved were not checked for location and usually were retested. The tester was required to present at least one grating the child was judged not to detect.

Testing was completed when the tester was ready to score the finest grating she was sure the child resolved. Immediately after the test of each eye, the tester recorded the subject's threshold card in cyc/cm. She also recorded the specific responses made by the subject upon which she had based her judgment of the child's acuity.

In summary, as described in the manual accompanying the TAC sets, acuity was scored as the finest grating the tester judged that the subject could detect. This judgment was the end point of an integrated series of decisions based on the subject's responses to a range of grating spatial frequencies.

The tester timed the test of each eye using a stopwatch; small breaks in testing, such as to reattach the patch, were included in the overall test time. The interval between eye tests, involving a change in tester for one half of the first two tests, was not recorded. Long breaks for diapering or feeding were taken between eye tests if possible, or, if taken during an eye test, were not recorded.

Data Analysis

Data analyses were performed over age groups unless a significant interaction indicated an analysis within age groups. For some analyses in which larger sample sizes were required for adequate statistical power, the age groups were collapsed into five classes according to test distance and start card (see Table 2). Class A included age groups 1 and 1.5 months (n = 72); class B, ages 2.5 and 4 months (n = 78); class C, ages 6, 9, and 12 months (n = 119); class D, 18, 24, and 30 months (n = 120); and class E, 36 and 48 months (n = 71).

Acuity Data

Acuity data in cycles per degree (cyc/deg) were transformed to an octave (log = $\log_{10}/0.301$) scale for statistical calculations and plotting of data. For reporting, acuities were reconverted into cyc/deg. Standard deviations and differences between acuities are reported in octaves.

Norms for monocular acuity were calculated from the acuity of the eye tested first in the first session. Norms were not based on data from both eyes or from one eye selected randomly because the fellow eye was tested second in half the subjects and third in the other half and because acuity of the eye tested second could be biased by the tester's knowledge of the acuity of the eye tested first. Normative acuities from half the subjects were obtained by each tester.

Prediction limits formula for 95% prediction limits:

$$\text{mean} \pm t_{0.025} \left( \sqrt{\frac{1}{1 + 1/n}} \times \text{SD} \right)$$

with $t_{0.025}$ = two-tailed value from the Student's $t$ distribution, SD = standard deviation, and n = number of subjects in each age group) provide a method that is appropriate for determining whether an individual patient's acuity is within normal limits. We present 95% and 99% prediction limits, that is, the range of acuities in which acuity of an individual from the normal popu-
Interocular acuity difference (IAD) norms appropriate to the clinical use of the ACP are derived from the raw distributions of the IADs (unsigned) expressed in TAC card steps (Table 3). For all subjects, an unsigned IAD of zero (no difference between acuities of right and left eyes) was found in 72% (329/460) and an IAD of less than or equal to 0.5 octave (zero or 1 card difference) was found in 99% (455/460).

**Test—Retest Reliability**

To evaluate the test—retest reliability of acuities, we calculated the intraclass correlation coefficients (ICC). To investigate whether one tester differed systematically from the other and the extent to which acuity obtained by the same tester differed across days, signed differences between acuities of the same eye were analyzed using repeated measures analysis of variance. The model for the analysis included age group and interaction with the repeated measure. Separate

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**RESULTS**

**Norms for Monocular Acuity**

Monocular acuity results are shown as mean acuity and calculated 95% and 99% prediction limits for each age group in Figure 1. Mean acuity and standard deviation for each age group are listed in Table 2.

Mean acuity improved rapidly between 1 and 6 months of age and more slowly thereafter. Mean acuity at age 1 month was about 1 cyc/deg and at age 6 months was about 6 cyc/deg, a 2.6 octave increase. Acuity did not change appreciably between 6 and 12 months of age. By 48 months of age, mean acuity was about 25 cyc/deg. Acuity improved by 2.1 octaves between ages 6 and 48 months. The rate of improvement averaged 0.5 octave per month between 1 and 6 months and 0.05 octave per month between 6 and 48 months.

**Intercocular Acuity Differences**

Norms for the IAD appropriate to tests of individual patients using the TAC are derived from the raw distributions of the IADs (unsigned) expressed in TAC card steps (Table 3). For all subjects, an unsigned IAD of zero (no difference between acuities of right and left eyes) was found in 72% (329/460) and an IAD of less than or equal to 0.5 octave (zero or 1 card difference) was found in 99% (455/460).
Acuity Card Norms

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S

A. Within-Tester, Between-Day

1 1.5 2.5 4 6 9 12 18 24 30 36 48

AGE GROUP (months)

FIGURE 2. Distribution of differences between acuity tests in terms of TAC intervals for each age group. Age is scaled arbitrarily. No difference •; 1 card difference (approximately 0.5 octave) ▲; 2 cards difference (1 octave) ◇; 3 cards or more difference (> 1 octave) □. Panel A (top): Within-tester, between-day differences. Panel B (bottom): Between-tester, within-day differences.

Within-Tester, Between-Day. The correlation coefficient for the within-tester comparison across days was high across all ages (ICC = 0.96) and moderate within age groups (range, 0.38 to 0.62, median 0.50). Acuities did not differ significantly between days. The repeated measures analysis of variance revealed a marginally significant interaction (P = 0.07) between session and age group, suggesting possible differences across age groups. Paired t-tests showed no significant mean within-tester difference for any age group.

The distributions of within-tester differences between sessions for each age group are shown in Figure 2A. For the sample as a whole, 51% (235/460) of the acuities obtained by the same tester were identical, 95% (437/460) were within 0.5 octave (1 card), and 99% (455/460) were within 1 octave (2 cards).

IAD Test-Retest Reliability. There was no relationship in any age group between the distribution of unsigned IADs in sessions one and two investigated using transitional probabilities. Thus, an IAD obtained in the second session was not contingent upon an IAD in the first session, which is not surprising given that 72% of the IADs in session one were zero.

Between-Tester, Within-Day. The correlation coefficient for the between-tester comparison was high over all ages combined (ICC = 0.95), and ICCs were low to moderate within age groups (range, 0.06 to 0.65, median 0.29). Tester 2 obtained slightly higher mean acuities than tester 1 over all ages combined (difference = 0.07 octave, SD = 0.48 octave, P < 0.01). The repeated measures analysis of variance yielded a significant interaction (P < 0.001) between tester and age group. Significant (P < 0.01) differences in mean acuity between testers were found in three age groups. Tester 2 obtained significantly higher mean acuity than tester 1 at age 1 month (0.32 octave) and 2.5 months (0.26 octave), and tester 1 obtained significantly higher mean acuity than tester 2 at age 24 months (0.22 octave).

The distribution of differences in acuity between testers is shown in Figure 2B. Over all ages, the testers' results agreed perfectly in 45% of subjects (207/460), to within 0.5 octave (1 card) in 90% (414/460), and to within 1 octave (two cards) in 98% (451/460) of subjects. Reliability between testers was lower in the younger than in the older age groups. For example, in the age range 1 to 12 months, the testers agreed to within 0.5 octave in 82% (221/269) and to within 1 octave in 97% (261/269), whereas, for ages 18 to 48 months, agreement to within 0.5 octave occurred in 95% (182/191) and to within 1 octave in 100% (191/191) of subjects.

Between-Tester, Between-Day. The distribution of differences between acuities obtained by each tester between sessions showed perfect agreement in 38% (175/460) of subjects overall, to within 0.5 octave in 88% (403/460), and to within 1 octave in 99% (455/460). This distribution is only slightly more variable than the between-tester, within-day distribution.

Effect of the Tester's Knowledge of Acuity. To evaluate the effect of the tester's knowledge of the acuity of the eye tested first on the acuity of the eye tested second, we conducted the following analyses. We calculated ICCs within age classes for two within-tester comparisons—acuities of the eye tested first and the eye tested second in session one and acuities of the eye tested first in session one and the same eye tested in session two. For the age group 1 to 30 months, the ICCs of acuities of each eye tested in the first session ranged from 0.77 to 0.84, higher than the range of ICCs of acuities of same eye compared between sessions of 0.47 to 0.64. However, for the 36- and 48-month-old class, the ICCs of between-eye and withi-
Ancillary Analyses

Demographics. The effect of demographic variables on mean acuities of the eye tested first was analyzed within the five age classes using univariate analysis of variance and linear regression models. Acuity did not differ significantly according to any of the subject demographic variables—sex, race, parent’s age, parent’s education, and family income—when analyzed within the five age classes.

Refractive Error. Because there were no significant differences between eyes for either acuity or refractive error, the correlation between acuity and refractive error is reported for the right eye, as is traditional. For simplicity of calculation and because so few eyes were myopic (n = 16), acuity was analyzed in relation to the spherical equivalent and maximum cylinder for all nonmyopic eyes (n = 444). Small but significant correlations were found between acuity and the spherical equivalent (r = −0.38, P < 0.001), and between acuity and maximum cylinder power (r = −0.16, P < 0.001) over all ages. However, when analyzed within age classes, no significant correlations were found between acuity and either refractive component in any age class. A relation between refractive error and acuity might not be expected in any case because of the purposefully restricted range of refractive errors.

Test Duration. Appropriate to the use of the ACP clinically, we report the sum of the duration of the tests of fellow eyes of all subjects obtained by the same tester. The median duration of the two tests ranged from 3.2 to 8.4 minutes across age groups. The minimum duration of the two tests ranged from 1.6 to 3.8 minutes and the maximum duration ranged from 7.9 to 20.8 minutes. Durations were longest in the two youngest age groups. For example, the median duration of both tests was 8.4 minutes for 1-month-olds and 7 minutes for 1.5-month-olds. The median duration of the two tests in all other age groups did not exceed 5.2 minutes.

Responses of Subjects. The subjects’ responses shifted from less mature to more mature with increasing age. Table 4 shows the relative proportion of the responses of subjects in each age group used by the testers to judge the subject’s acuity. The responses are ordered by their presumed maturity. In the 1- and 1.5-month-old groups, involuntary eye movements elicited by the holder’s rotation of the infant in front of the acuity cards predominated. From age 4 months to 18 months, reflexive eye movements from a central position constituted the majority of responses scored. Scanning or searching eye movements became more prevalent after age 4 months. At age 24 months, reflexive and scanning eye movements were distributed approximately equally. At 30 and 36 months, subjects’ responses were more widely distributed than at previous ages, with more mature responses at age 36 months than at 30 months. Pointing to the grating was scored increasingly frequently between ages 24 and 48 months. However, pointing by the younger subjects was inaccurate or inconsistent, and, for most subjects under age 48 months, the testers used looking responses to score acuity. Only at age 48 months did accurate pointing and verbal responses predominate.

DISCUSSION

Monocular Norms and Prediction Limits

The maturation of monocular grating acuity represented in this study follows the familiar course described in numerous previous studies: rapid improvement in the first 6 to 12 months after birth and more gradual improvement thereafter.5,6,17,18 The main purpose of the present study, however, was not to describe the normal maturation of acuity but to provide norms for pediatric ophthalmic applications using the ACP and TAC.

For the normal range with which to compare an individual patient’s monocular acuity, we provided two sets of prediction limits, in part because choice of a single set is arbitrary. In addition, different limits may be useful to optimize the balance between positive and negative predictive values for specific populations and different applications. For example, in patients with known ocular disorders tested in a clinical setting, 95% or narrower limits may be preferred to ensure sensitivity (the ability of a test to detect true abnormality) to small deviations from normal. On the other hand, broader limits, for example, 99%, may be preferred for vision screening of an unselected population because of an unacceptably high cost of increased false-positive referrals (normals identified as abnormal on the test) resulting from narrower prediction limits.

Smoothed, Adjusted Prediction Limits

The raw prediction limits shown in Figure 1 were derived using means and standard deviations and therefore were not constrained to coincide with the available spatial frequencies of the TAC gratings. Because optimal clinical usefulness requires limiting acuity estimates to the values of the individual TAC stimuli, we propose an adjustment of the raw prediction limits corresponding to the exact spatial frequencies of the TAC gratings at the appropriate test distance. Figure 3 shows these adjusted 95% and 99% prediction limits.

First, the 95% prediction limits were adjusted to the nearest card spatial frequency that minimized the limits without excluding any data points within the
TABLE 4. Responses of Subjects at Threshold on First Acuity Test

<table>
<thead>
<tr>
<th>Responses</th>
<th>1</th>
<th>1.5</th>
<th>2.5</th>
<th>4</th>
<th>6</th>
<th>9</th>
<th>12</th>
<th>18</th>
<th>24</th>
<th>30</th>
<th>36</th>
<th>48</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raised eyebrows</td>
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<td>8</td>
<td>0</td>
<td>0</td>
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<td>Involuntary EM, child rotated</td>
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<td>76</td>
<td>32</td>
<td>19</td>
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<tr>
<td>Reflexive EM, child centered</td>
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<td>Pointing, inaccur.</td>
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<td>0</td>
<td>3</td>
<td>8</td>
<td>6</td>
<td>0</td>
<td>13</td>
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<td>39</td>
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<td></td>
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<tr>
<td>Pointing to grating position</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>18</td>
<td>18</td>
<td>47</td>
<td></td>
</tr>
<tr>
<td>Says “stripes/no stripes” with pointing/looking</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Says “right/left”</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</table>

* Percent of subjects scored by age group.
EM = eye movements.
† Inaccurate or unreliable.

raw 95% limits. Where indicated, we adjusted the 95% limits further to avoid the nonmonotonics of the raw limits (see Fig. 1) that make the interpretation of change in acuity between ages relative to the norms problematic. Next, the raw 99% prediction limits were adjusted to the next higher or lower available TAC spatial frequency relative to the adjusted 95% limits, except at 48 months, where the next higher spatial frequency is unreasonably high (55 cyc/deg). We emphasize that the adjusted 95% and 99% limits include the same individual data points as the raw 95% and 99% limits. Table A in the appendix provides the raw and adjusted lower 95% and 99% prediction limits in cyc/deg for each age group.

New Versus Preliminary ACP Norms

Figure 4 compares the raw and adjusted 95% prediction limits of monocular acuity obtained in the present study with the preliminary ACP norms in current use, which encompassed 90% of the acuities measured (Dobson V, personal communication, 1994). The new normal limits span higher spatial frequencies than do the preliminary norms between ages 1 and 18 months, whereas the normative data sets overlap between ages 24 and 36 months. The 95% prediction limits we obtained are narrower generally than the preliminary norms at ages 1 to 18 months but are similar at older ages.

Possible factors leading to a shift of acuities to higher spatial frequencies include sampling variability due to the small number of subjects tested in the pre-
FIGURE 5. Lower prediction limit of normal monocular acuity (raw, lower 2.5%, –•–) from the present study compared to lower limits of normal obtained in five other studies using either ACP or clinical FPL methods. Birch and Hale,3 FPL, calculated lower 2.5% prediction limit, —–; Chandna,29 ACP, reported lower 2.5% limit, — – • – ; Heersema and van Hof-van Duin,28 ACP, calculated lower 2.5% prediction limit, —•—; Lewis and Maurer,4 reported lower 2.5% limit, FPL, —Δ—; Salomao and Ventura,30 ACP, reported lower 5% tolerance limit with 95% confidence, —–.

Comparisons with Other Normative Studies

Lower Limits of Normal

Figure 5 compares the lower normal limits of the present study with data from five other large-scale studies of normal subjects in which the ACP or clinical FPL methods were used. For simplicity and clinical relevance, a single set of lower limits of normal monocular acuity from each study is shown. We calculated the lower 95% prediction limits from reported data (solid symbols), where possible.

Agreement among the six studies in the estimation of the lower normal limits is very good; the estimates are within 1.5 octave of each other at most ages. The lower 95% limits obtained in our study fall near the center of the range defined by the other data sets at comparable ages. The level of agreement among these studies is striking considering the use of different statistical criteria, methods of testing grating acuity (ACP in the present study and ref. 28; FPL staircase;4 and hybrids of FPL staircases and ACP29,30), stimulus configurations (TAC in the present study and ref. 30; TAC in cutout surrounds,29 photographically produced gratings4 and slide-projected gratings3), luminances (1.0 to 2.5 log cd/m²), and numbers of testers.

Of particular note among these studies is the large-scale study of Salomao and Ventura. Agreement between the data of Salomao and Ventura and the present study is excellent at all ages except 18, 24 months, and 36 months. Coincidentally, the 95% prediction limits that we used to determine acuity norms and the 90% tolerance limits with 95% confidence used by Salomao and Ventura for their norms are nearly identical for the same data sets. Our study and the Salomao and Ventura study used TAC and similar start card spatial frequencies but different variants of ACP.

Interocular Acuity Differences

The distributions of IADs in this study are comparable to those reported in other ACP studies of normal subjects in which the tester had knowledge of card spatial frequencies, and presumably, of the acuities scored in each eye as well.11-14 IADs were slightly more variable in ACP and FPL studies in which testers were unaware of grating spatial frequencies.3,30,31-33 Notably, however, in virtually all ACP and FPL studies of normal subjects, at least 95% of the IADs are less than or equal to one octave.

In our study, the testers were aware that they were testing presumptively normal subjects and, thus, they may have expected that the acuities of fellow eyes should be identical. This could have influenced them to obtain a similar acuity in the eye tested second as the acuity of the eye tested first. Indeed, within-tester reliability was higher for between-eye comparisons on the same day than between-day comparisons on the same eye. However, our study design did not allow us to analyze within-tester reliability separately for between-eye and between-day comparisons. Prior knowledge of the acuity of the eye tested first may be unique to tests of presumptively normal subjects for whom no difference between eyes would be expected, whereas, differences between eyes would be expected in many patients. Thus, the possible influence of ACP testers’ expectations on acuities of patients should be studied.

Test–Retest Reliability

Agreement between acuities tested by the same tester on different days in this study is better than in the preliminary ACP norm study in which 1- to 12-month-olds were tested (99% within 1 octave versus 84% within 1 octave).6 However, the 1-octave interval between cards used in this preliminary norm study may have increased the variability of acuities compared to our and other studies in which 0.5-octave intervals were used.24 In the single other study reporting within-tester reliability, obtained with an FPL staircase, the 99% normal limit of agreement was slightly less than
1 octave between ages 6 and 60 months, similar to our findings.

In fact, the within-tester, between-day differences we obtained are remarkably similar to test–retest differences in letter recognition acuity of adults. In a study of adults tested with the Bailey-Lovie logMAR chart on different days, the standard deviation of the difference in acuity between days was 0.10 logMAR, or 0.33 octave. In our study, the standard deviation of the within-tester difference between days over all age groups is 0.42 octave or 0.13 logMAR.

Between-tester differences in our study are higher at younger ages than at older ages. Considering all age groups, our between-tester differences of 90% within 0.5 octave are similar to those found in the two other studies of normals in which between-tester reliability was obtained. In the preliminary norm study of 18- to 36-month-olds using 0.5-octave intervals, 88% were within 0.5 octave,7 and, in a study using an FPL staircase, 86% were within 0.5 octave.4 Our between-tester differences are also similar to those obtained in an ACP study of 20 patients with ocular disorders,37 but smaller than differences obtained in other ACP and FPL studies in clinical populations.31-34

It should be noted that in the ACP we used and the ACP of the preliminary norm studies, acuities are scored as discrete spatial frequencies, whereas in studies using FPL staircases, acuities can take intermediate values between spatial frequency steps. Discrete values could result in lower variability of acuities obtained with ACP than with FPL. However, the similar lower limits of normal acuity and similar test–retest variability of ACP and FPL studies5,4,10,29,30 suggest that other factors are more important contributors to variability in acuity measured with these procedures.

Thus, despite methodologic differences between our study and other ACP and FPL studies, test–retest reliabilities for within- and between-tester comparisons of acuities in normal subjects are similar across studies.

Effect of Start Card
To make the ACP as efficient as possible for clinical applications, we selected fixed start cards for different age classes. Start card spatial frequencies were chosen to be lower in spatial frequency than previous normative acuity data2,17,18 by a similar magnitude across age. Therefore, it is not surprising that the mean acuities we obtained are higher than the start card spatial frequencies by a similar magnitude across age (median 2.6 octaves; range, 2.2 to 3 octaves).

However, the start card in the ACP, like the stimulus value that starts an adaptive test procedure, may bias the measured threshold6,42,43 such that higher spatial frequencies could lead to higher acuities. Direct evidence for an influence of start card on acuity for at least some ACP testers was reported in a study of preterm infants using the same ACP method as in the preliminary norm study.20 The magnitude of the overall effect of start card on mean acuities averaged 0.15 octave per 0.5-octave card step over a wide age range, although the effect varied with age. The generality of this effect over testers, however, is unknown.

It might be suggested that the spatial frequency of the start cards accounts for the maturation of acuity with age shown in this study. This explanation is sufficient, however, only if both testers used a similar strategy of presenting cards and the same strategy across age. Moreover, the predicted effect on acuity of start cards based on the previous study20 over the 4-octave range of start cards we used is only 1.2 octaves, whereas measured acuity means ranged over 4.6 octaves between 1 month and 48 months.

The higher acuity ranges obtained in the present study compared to the ranges of the preliminary norm studies (Fig. 4) could be due to differences in start cards at some ages. Start card spatial frequencies in our study are identical at ages 1 to 2.5 months, higher by an average 0.4 to 1.2 octaves at ages 4 to 24 months, lower by 0.7 octave at age 30 months, and 0.6 octave higher at age 36 months. Notably, however, start card effects of the magnitude shown in the previous ACP study account for a maximum of only 0.4 octave higher acuity in the present data compared to the preliminary norm data. Thus, start card differences might explain the slightly higher normal limits in the present study at certain ages but not the markedly higher limits (0.8 to 1.5 octaves) between 6 and 12 months. Notably, in all the large scale normative studies shown in Figure 5, the lower limits are at least 0.5 octave higher than the preliminary norms at 6 to 12 months of age. Thus, other factors, such as small sample variability, may be responsible for the difference between the preliminary norms and other normative data sets at 6 to 12 months.

The good agreement of the lower limits of normal between our study and other ACP and clinical FPL studies also argues that the acuity data we obtained accurately represent the normal maturation of acuity. Thus, although a small effect of start cards on acuities in this study is possible, we think it is more likely that the children’s visual responses guided the tester’s presentation strategies and the acuities scored.

Test variability within age groups might be predicted to be reduced using fixed start cards for age, also assuming similar strategies of testing across testers. Again, the good agreement of our lower normal limits with other ACP and FPL data argues that estimates of population variability across studies of acuity in infants, including the present study, are similar. Moreover, test–retest variability in our study was similar to that obtained in ACP and FPL studies of normal
Assuming symmetrical increments or decrements over normative data alone should be used with caution, fit considerations. Although recommendations based of interest, the application of the test, and cost-bene-

offs between normal and abnormal test results will—of ACP acuity criteria. Choice of cut-
offs between normal and abnormal test results will depend on relevant data from the clinical population of interest, the application of the test, and cost—benefit considerations. Although recommendations based on normative data alone should be used with caution, until there are appropriate data from patients, we make the following tentative suggestions based on the results of this study.

Decrements of Acuity

Assuming symmetrical increments or decrements over the age range of slow change in acuity, a 1-octave (or 3-card) decrement in acuity, whether obtained by the same or different testers, should occur in no more than 0.5% of children with normal eyes. An even lower false-positive rate, 0.5%, would result if the 99% prediction limit was used. Of course, data from specific patient groups are required to derive the sensitivity side—the detection of true positives and false negatives or misses—of ACP acuity criteria. Choice of cutoffs between normal and abnormal test results will depend on relevant data from the clinical population of interest, the application of the test, and cost—benefit considerations. Although recommendations based on normative data alone should be used with caution, until there are appropriate data from patients, we make the following tentative suggestions based on the results of this study.

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Guidelines for Interpreting ACP Acuities of Patients

The adjusted prediction limits of monocular acuity shown in Figure 3 can be used to interpret a patient’s acuity relative to normal. Acuity that falls on the 95% or 99% limit should be considered within the respective normal limit. Acuities of patients tested at different test distances than those used in this study may fall at values intermediate between the TAC spatial frequencies. When tests are conducted at different test distances, acuities that fall just below the normal limit should be interpreted with caution.

The data from this study can be used to provide predictions of test specificity—the detection of false positives and true negatives—for ACP tests in a presumptively normal population. In terms of false positives, an acuity value lower than the lower 95% prediction limit, for example, would be expected to occur in only 2.5% of children with normal eyes. An even lower false-positive rate, 0.5%, would result if the 99% prediction limit was used. Of course, data from specific patient groups are required to derive the sensitivity side—the detection of true positives and false negatives or misses—of ACP acuity criteria. Choice of cutoffs between normal and abnormal test results will depend on relevant data from the clinical population of interest, the application of the test, and cost—benefit considerations. Although recommendations based on normative data alone should be used with caution, until there are appropriate data from patients, we make the following tentative suggestions based on the results of this study.

Interocular Acuity Differences

Interpreting an unsigned IAD of 1 octave to indicate asymmetrical ocular or refractive status or amblyopia would result in overreferral of only 1% of children with normal eyes across age. The average overreferral rate in a normal population for an unsigned IAD of 0.5 octave (1 card) is predicted to be 28%. In our clinical experience, however, an IAD of 0.5 octave may indicate abnormality in some patients.65

Given the low frequency of IADs of 1 octave or greater in the first and second sessions, and the lack of relationship between IADs on sessions one and two, a 1-octave (2-card) change in the IAD between visits, either an increment or decrement, can be considered a significant change. But we caution that IADs obtained by different testers on different days would be expected to show greater variability than IADs obtained by the same tester.59

Validity of the New Norms for Wide Use

Three monocular tests were completed in the first session in 100% of subjects between 1 and 12 months of age and 97% of subjects between 18 and 48 months of age, for an overall success rate of 99%. These rates of completing monocular tests are among the highest reported previously in tests of normal subjects using ACP variants7,8,14,28 or clinical FPL procedures.3,4,33,46 Norms derived from a relatively low proportion of children who cooperate for monocular tests may be biased for more cooperative children. The present norms are virtually unbiased with respect to subject cooperation. The new norms were derived only from subjects meeting criteria for cycloplegic refractive error and normal ocular status. We excluded children with high refractive errors. Several reports suggest that infants with hyperopic refractions within the inclusion limits of this study, +3.5 to +4.5 D, may be at later risk of strabismus and amblyopia.65,66 However, had we excluded subjects between 1 and 12 months with refractive error of +3.5 D or greater, the exclusion rate for overreferral of 0.5 octave or greater would have increased from 6% to 19%. In fact, when age was controlled, acuity and refractive error were uncorrelated within the range of refractive errors allowed. Hence, the refractive error limits we chose appear to be appropriate for the population sampled.

No relationship between acuity and any demographic variable, including sex, race, and parents’ socioeconomic status (SES) was shown in this study.
However, because of the relative homogeneity of the sample, the study had limited power to detect race or SES-based differences. Evidence that race and SES do not play a major role in explaining acuity variations is provided by the good agreement between the lower normal limits in our study and those from the study of Salomao and Ventura of a large sample of nonwhite, Brazilian subjects of predominantly low SES (see Fig. 5). Nevertheless, systematic studies are needed to establish the independence of acuity and various demographic variables, particularly across a wider range of races and SES.

We conclude that the new norms should be useful and accurate because they were obtained from virtually all subjects who met our inclusion criteria, the ocular status of all subjects was normal, and the limits of refractive error of the sample were defined. In addition, evidence to date suggests that ACP acuities are relatively unaffected by subject demographics.

The new norms should be considered valid for the exact ACP we used, although different ACPs and FPL staircase methods provide surprisingly similar lower normal limits. Some aspects of our study design may have minimized variability of measured acuities and test–retest differences. These factors include the use of only two testers who were trained concurrently by the same two experts, the use of the same start cards at a given age, and the narrow range of ages tested in each age group. Clinical studies are required to determine the accuracy of the ACP for detecting abnormality and the applicability of the new norms to various clinical populations.

Modifications of the standard method of presenting TAC gratings in an apparatus have been reported to improve testing of patients, in particular, those with nystagmus, esotropia and cross-fixation, or visual inattention. One study reported that using TAC in a vertical orientation (horizontal gratings) markedly improved the acuity of infants with coarse, horizontal nystagmus. It may be questioned, therefore, whether the new norms are appropriate for tests in which modifications of the standard TAC presentation are used. Although establishing completely new norms for nonstandard TAC presentation modes does not seem economically feasible, determining the validity of modified TAC testing modes in selected age groups of normal subjects is warranted.

Several studies have reported relatively greater variability and poorer acuities in developmentally abnormal than in normal populations. Despite these findings, in our view, obtaining monocular acuity norms for nonnormal populations is not necessary because plotting any patient's acuity on a normative horizontal nystagmus. It may be questioned, therefore, whether the new norms are appropriate for tests in which modifications of the standard TAC presentation are used. Although establishing completely new norms for nonstandard TAC presentation modes does not seem economically feasible, determining the validity of modified TAC testing modes in selected age groups of normal subjects is warranted.

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Several studies have reported relatively greater variability and poorer acuities in developmentally abnormal than in normal populations. Despite these findings, in our view, obtaining monocular acuity norms for nonnormal populations is not necessary because plotting any patient's acuity on a normative age graph provides valuable information regarding that patient's performance. On the other hand, indices that are important for the management of ocular disorders, such as IADs and test–retest differences between visits, may not be valid if the test–retest variability in nonnormal populations is greater than in normal subjects. Therefore, investigating these indices in selected age ranges of well-defined, nonnormal populations is indicated.

Ultimately, the clinical usefulness of any diagnostic test depends on its sensitivity and specificity for detecting disease and guiding treatment. Although some information is available, determining the clinical usefulness of the ACP awaits the accumulation of much more extensive data from pediatric patients.


Acuity Card Norms


APPENDIX

TABLE A. Raw and Adjusted Lower 2.5% and 0.5% Prediction Limits for the ACP Using TAC

<table>
<thead>
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<th>Age (months)</th>
<th>Raw Lower Limits*</th>
<th>Adjusted Lower Limits*+</th>
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ACP = acuity card procedure; TAC = Teller Acuity Cards.
* Spatial frequency (cyc/deg).
+ Exact TAC grating in cyc/cm can be determined by reference to Teller Acuity Card Handbook.†