Variation in Stereoaucuity: Normative Description, Fixation Disparity, and the Roles of Aging and Gender

Charles M. Zaroff,1 Magosha Knutelska,2 and Thomas E. Frumkes2

PURPOSE. Variation in stereoaucuity was examined in a large group of observers with Snellen acuity of 20/30 or less.

METHODS. Threshold retinal disparity for 2.78° × 2.28° rectangular test stimuli was determined as a function of the retinal disparity (varied from 55 arcmin uncrossed to 55 arcmin crossed) of a 5.57° × 4.8° rectangular pedestal stimulus in 160 observers 15 to 79 years of age. In most cases, data were collected during viewing of random dot stereograms (RDSs) presented for 100 ms, which prevents involvement of vergence or monocular depth cues.

RESULTS. When plotted logaritically, 100-ms thresholds in 106 observers less than 60 years of age approximated a normal distribution (mean, 1.57 ± 0.227 [SD] log arcsec [37 linear arcsec]). Among these, one observer was supernormal, 88% were within the normal range (±2 SD of the log mean), 2% had elevated thresholds, and 8% failed testing with 100-ms stimuli but had residual binocular depth discrimination; 1 observer was stereoblind. In contrast, only 37% of the observers aged 60 to 69 and 25% of the observers aged 70 to 79 had stereoaucuity within the normal range. Moreover, the extent of the stereo deficiencies became more pronounced with age. Fixation disparity was operationally defined as optimal stereoscopic threshold with a nonzero retinal disparity pedestal. Of the 151 normal observers tested, 89% were maximally sensitive to disparities within 11 arcmin of fixation; all males were maximally sensitive to pedestals within 22 arcmin of fixation, whereas 8% of females had fixation disparities of more than 22 arcmin. Males were more likely to be sensitive with uncrossdispparity pedestals, whereas females were more likely to be sensitive with crossed disparity.

CONCLUSIONS. Age-related deterioration in stereoaucuity is reflected not only by a linear correlation between age and threshold but also by a catastrophic factor that produces more marked deterioration after age 60. Both factors are probably cerebral and not specifically related to stereopsis. The prevalence of fixation disparity in the normal population is probably more common than previously reported. (Invest Ophthalmol Vis Sci. 2003;44:891–900) DOI:10.1167/iovs.02-0361

A considerable amount of prior research has been devoted to the influence of aging on stereoaucuity in the general population. Table 1 summarizes the results of studies published since 1960. Most, but not all these studies conclude that stereoaucuity decreases with age. Before we conducted the present research, there was reason to believe that all prior studies shared at least one of the following limitations in the assessment of stereoaucuity. First, all tests used for stereoaucuity that failed to eliminate nonstereoscopic depth cues (for description of these tasks, see Howard and Rogers15). The listed dioptic stereoaucuity tasks (the Howard-Dolman apparatus, the Frisky Stereo Test [Richmond Products, Boca Raton, FL], and the Flashlight Diastereo Test) provide several monocular cues for depth, including accommodation, motion parallax resulting from head movements, perspective, and/or the relative widths of stimuli. This is also a criticism of stereoaucuity tests traditionally used in clinical practice,16 which is a likely reason that such tests are rarely used for research purposes, particularly when the question of anomalous stereopsis is an issue (i.e., because many individuals with stereo difficulties are not aware of the fact, a depth discrimination based on monocular cues might be made without any intention of doing so). Julesz’s statement that not only can stereopsis “occur in the total absence of monocular form, but also . . . if monocular form exists, stereopsis precedes perception of form and can scramble it”17 exemplifies the need to control for monocular cues when assessing stereopsis. This criticism does not apply to the tests that present separate stimuli to the two eyes stereoscopically (the TNO [Richmond Products], Randot [Stereo Optical, Chicago, IL], and Titmus [Occulus, Wetzlar, Germany] tests). However, the stereoscopic as well as the dioptic tasks fail to eliminate vergence, which can be a potent cue for depth.18 Consequently, the studies listed in Table 1 might more appropriately be designated as investigations of age-related changes in depth discrimination.

Second, most of the listed studies failed to control for visual acuity. For this reason, age-related changes in depth discrimination could reflect either ocular optical changes, changes in general neural pathways mediating many aspects of vision, or brain mechanisms restricted to depth discrimination or possibly just stereopsis. For example, Hagerstrom-Portnoy et al.14 propose that one common optical factor accounts for many different age-related changes in vision, only one of which is stereopsis. In contrast, the interest of the present study was restricted to age-related neural changes. Third, many of the listed studies failed to appropriately sample individuals of many different age groups. Some reported only results from older subjects, whereas most compared a young with an older age group. Fourth, none of the studies accounted in a systematic fashion for the importance of fixation disparities in determining stereoaucuity.

Fifth, the meaning of all the studies in Table 1, most particularly those using arbitrary pass–fail criteria rather than quantitatively measures of stereoaucuity, is limited because the possible are no established norms for stereoaucuity in any population. Consequently, there are no generally accepted norms that permit an accurate estimate of the prevalence of stereoneormally, stereoaomaly, or stereoblindness in the aging population. The
dearth of such norms is best illustrated by considering data from nonaging observers. Heron et al.\textsuperscript{19} reported that the definition of stereacuity in a group of subjects depends greatly on methodology. Mean stereacuity thresholds were 12.9 (the Frisby Test), 28.1 (the Randot Test), 26.6 (the Titmus Stereo Vision Test), or 88.7 arcsec (the TNO Test). They also reported that the prevalence of stereo impairment has varied from a low prevalence of 2%\textsuperscript{20} or 3%\textsuperscript{21} to as high as 30%.\textsuperscript{22,23} In lieu of normative data, it is impossible to specify the influence of aging on stereacuity.

In the present study, we investigated age-related changes in stereacuity in a large sample of subjects of both sexes, ranging in age from 15 to 79 years. All had corrected visual acuity of at least 20/30 in both eyes. Testing generally involved presentation of RDS for 100 ms. Because this duration is too short to permit vergence eye movements,\textsuperscript{24} it was ensured that stereopsis alone was the cue for depth discrimination. Subsequent to presentation of the stimuli, observers were allotted an unlimited time to make their responses because what has been shown by some to be crucial is the time provided to process the stimuli after its presentation.\textsuperscript{20,25} In addition, stereacuity was measured at many different planes of fixation, permitting consideration of the importance of fixation disparity in influencing optimal stereacuity. The results represent normative data for stereacuity as well as the prevalence of fixation disparity.

Portions of the present study have been presented previously in abstract form.\textsuperscript{26} A more complete presentation of the present study can be found in the doctoral dissertation of the first author.\textsuperscript{27}

**METHODS**

**Subjects**

All subjects had Snellen acuity (with corrective lenses if necessary) of at least 20/30 in each eye and were naive before testing regarding the purposes of experimentation. Sample 1 was used to obtain normative stereacuity data and to determine the influence of age on stereacuity. Sample 1 consisted of approximately 10 male and 10 female subjects in each of the age decades 20 to 29, 30 to 39, 40 to 49, 50 to 59, 60 to 69, and 70 to 79 years, as well as a less systematic sample of teenagers.

In the course of testing sample 1, it became evident that the prevalence of fixation disparity was much greater than had been reported in the literature. For this reason, sample 2 was used to measure the prevalence of fixation disparity. Sample 2 consisted of all subjects in sample 1 with optimal stereacuity of 114 arcsec or less (an approximation of the upper limit of what was defined as stereonormal), and approximately 50 additional stereonormal subjects, most of whom were less than 30 years of age. Because of the archival nature of these data, information from every subject represented in both samples 1 and 2 is listed in tabular fashion in the appendixes to Zaroff.\textsuperscript{27}

**Apparatus**

All stimuli were presented by means of a commercially available hardware and software package (VisionWorks 2; Vision Research Graphics, Inc., Durham, NH) on a 19-in. monochrome cathode ray display with a P46 phosphor with a refresh rate of 120 Hz, a display resolution of 1024 × 512 pixels, and a maximum luminance of 80 cd/m\textsuperscript{2}. Stereoscopic images were presented by the field-sequential procedure.\textsuperscript{28} Accordingly, separate images were provided to each eye by synchronizing the opening and closing of liquid crystal shutter glasses (at a rate equal to that of the refresh rate, 120 Hz) with the presentation of alternate sets of images on the display. A computerized program randomly arranged the matrix of dot elements from trial to trial, to eliminate transfer effects of practice.\textsuperscript{29}

**Procedure**

The complete testing procedure, which adhered to the tenets of the Declaration of Helsinki and was approved by the Queens College Committee for the Protection of Human Subjects, took approximately 1 hour. The subject first signed an informed consent form and completed a brief questionnaire providing biographical information including any history of eye disease. Subsequently, interpupillary distance was measured and Snellen acuity was assessed (with corrective lenses in place if necessary). Subjects with a history of eye disease or inadequate Snellen acuity were excluded. The range of interpupillary distances was approximately 9 mm, symmetrically distributed around a mean of 64 mm, which is consistent with the literature.\textsuperscript{30} At the 1-m viewing distance used for testing, variation in pupil size would produce an error in actual retinal disparity of less than 10%. Such an error is considerably smaller than the magnitude of the effects of concern, and so no correction was made for interpupillary distance.

All testing took place in a dimly lit room (save for desired stimuli, the luminance from all surfaces was less than 0.05 cd/m\textsuperscript{2}). Subjects were fitted with liquid crystal shutter spectacles provided by the stimulus presentation package over their corrective lenses (if necessary) and seated 1 m from the stimulus monitor. The initial demonstration RDS consisted of dots 0.04° × 0.02° with an individual dot luminance (as viewed through the shutters) of 6 cd/m\textsuperscript{2} and a dot density of 6.5%. To a normal viewer, this stereogram appeared vividly as a corrugated grating consisting of three wave-shaped cycles with a diameter of 11.37°. This grating was presented for as long a duration as desired with a space averaged overall uncrossed disparity of 33.45 arcmin at a spatial frequency of 0.25 c/deg. The word “demo” was superimposed on this grating. The subjects were asked to describe their perceptions of the grating and to move the “demo” from the “top of a mountain” to the “bottom of a valley,” at a three-dimensional trackball provided by the stimulus presentation package. The few subjects who did not perceive any depth and could not comply with these instructions were excluded from further testing. Although the possibility of residual stereoscopic vision in these subjects could not be excluded, these subjects were designated stereoblind. **General Psychophysical Procedure and Stimulus Description.** Subsequent testing involved several different sets of RDSs presented tachistoscopically. During periods when an RDS was not present, the stimulus monitor was unilluminated or had a fixation cross. Initially, the RDS consisted of 0.06° × 0.05° dots. In a 50/50 percentage, these consisted of 6 cd/m\textsuperscript{2} or unilluminated dots. A rectangular RDS (5.57° × 4.8°) was presented at 11 different retinal disparities (55, 44, 33, 22, 11, or 0 arcmin of either crossed or uncrossed retinal disparity). This rectangle is referred to as the pedestal stimulus. A second smaller rectangle, a test stimulus of 2.28° × 2.28°, was presented in the center of the pedestal stimulus at a different disparity value. Normal subjects perceived this grating to be a rectangle surrounded by the larger pedestal. The test stimulus either appeared to pop out in front of the surrounding pedestal or to recede into the monitor screen, forming a hole in the surrounding pedestal.

In any series of trials, testing began with a 250-ms presentation of a fixation cross, with its appearance signaled by a brief tone. The cross then disappeared and the test and pedestal rectangles appeared for one of the four durations described later. The subject then chose whether the test stimulus appeared in front of or behind the pedestal by depressing the appropriate button on the trackball. If the subject’s choice was correct, the fixation cross reappeared 250 ms after the keypress and the next trial began. If the subject’s choice was incorrect, three brief tones sounded and the fixation cross reappeared 1 second after the button was pressed. The subject was permitted unlimited time to make the choice.

Four series of experiments, each differing in stimulus duration, were used to collect data using a forced-choice staircase procedure. If
<table>
<thead>
<tr>
<th>Authors</th>
<th>Method</th>
<th>Ages</th>
<th>n</th>
<th>Visual Acuity</th>
<th>Scoring</th>
<th>Other Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allen¹</td>
<td>Flashlight Diastereo test</td>
<td>0-9 to 60+</td>
<td>2070</td>
<td>Measured; not controlled</td>
<td>Pass-fail</td>
<td>Many nonstereoscopic cues; fewer subjects aged ≥50 relative to younger ages</td>
</tr>
<tr>
<td>Baluyut and Hofstetter²</td>
<td>Optometrist report</td>
<td>0-9 to 80-89</td>
<td>1000</td>
<td>Not indicated; presumably not controlled</td>
<td>Pass-fail</td>
<td>No methodological detail; presumably many nonstereoscopic cues</td>
</tr>
<tr>
<td>Jani³</td>
<td>Flashlight Diastereo test</td>
<td>0-9 to 70-79</td>
<td>1207</td>
<td>Required 20/40 or better in each eye</td>
<td>Pass-fail</td>
<td>Many nonstereoscopic cues</td>
</tr>
<tr>
<td>Bell et al.⁴</td>
<td>Modified Verhoeff stereopter</td>
<td>20–70</td>
<td>164</td>
<td>Measured; not controlled</td>
<td>Percentage correct detections</td>
<td>Many nonstereoscopic cues</td>
</tr>
<tr>
<td>Hofstetter and Bertsch⁵</td>
<td>Diastereo test</td>
<td>8–46</td>
<td>242</td>
<td>Required 20/20 or better in each eye</td>
<td>Arcseconds</td>
<td>Many nonstereoscopic cues, no subjects aged ≥46</td>
</tr>
<tr>
<td>Greene and Madden⁶</td>
<td>RanDot test</td>
<td>17-25 vs. 60-75</td>
<td>24</td>
<td>Measured; not controlled</td>
<td>Arcseconds</td>
<td>Nonstereoscopic binocular cues</td>
</tr>
<tr>
<td>Yekta et al⁷</td>
<td>TNO test</td>
<td>10-65</td>
<td>187</td>
<td>Not measured or controlled</td>
<td>Arcseconds</td>
<td>Relatively few subjects in the 60-65 age group</td>
</tr>
<tr>
<td>Wright and Womald⁸</td>
<td>Frisby test</td>
<td>65 to 80+</td>
<td>728</td>
<td>Measured; not controlled</td>
<td>Pass-fail</td>
<td>Many nonstereoscopic cues; inclusion of older aged subjects (no younger aged control subjects)</td>
</tr>
<tr>
<td>Rumsey⁹</td>
<td>Four different tests</td>
<td>40-60</td>
<td>20</td>
<td>Measured; not controlled</td>
<td>Pass-fail</td>
<td>Used different tests at near vs. far distances</td>
</tr>
<tr>
<td>Brown et al.¹⁰</td>
<td>Modified Howard-Dolman apparatus</td>
<td>21-70</td>
<td>41</td>
<td>Required 20/20 or better in each eye</td>
<td>Arcseconds</td>
<td>Many nonstereoscopic cues; low stimulus luminance selectively disadvantages older subjects</td>
</tr>
<tr>
<td>Rubin et al.¹¹</td>
<td>RanDot test</td>
<td>65-90</td>
<td>222</td>
<td>Measured; not controlled</td>
<td>Mild vs. moderate vs. severe impairment</td>
<td>Contours evident with monocular viewing; no younger control group</td>
</tr>
<tr>
<td>Yap et al¹²</td>
<td>Modified Howard-Dolman apparatus</td>
<td>21-67</td>
<td>35</td>
<td>Required 20/20 or better in each eye</td>
<td>Arcseconds</td>
<td>Many nonstereoscopic cues; low test stimulus contrast selectively disadvantages older subjects</td>
</tr>
<tr>
<td>Rubin et al.¹³</td>
<td>RanDot test</td>
<td>65-84</td>
<td>2520</td>
<td>Measured; not controlled</td>
<td>Arcseconds</td>
<td>Contours evident with monocular viewing; no young control group; median (not mean) data reported</td>
</tr>
<tr>
<td>Hagertext-Portnoy et al.¹⁴</td>
<td>Frisby test</td>
<td>58-102</td>
<td>900</td>
<td>Measured; not controlled</td>
<td>Arcseconds</td>
<td>Many nonstereoscopic cues; no younger control group</td>
</tr>
</tbody>
</table>
the subject’s keypress indicated a correct response, the difference in retinal disparity between the test and pedestal stimuli was reduced 0.04 log units. With an incorrect response, the relative disparity was increased four of these 0.04-log-unit steps. Although the disparity between test and pedestal stimulus changed as such, the direction (i.e., crossed or uncrossed) of the disparity also changed randomly from trial to trial, as did the direction of the disparity of the pedestal stimulus itself.

**Specific Testing with Different Duration Stimuli.** Stimulus duration was initially 2 seconds, and the pedestal stimulus contained either 44, 22, or 0 arcmin of crossed or uncrossed retinal disparity. For this condition only, the test stimulus was initially presented with a retinal disparity 500 arcsec different from the pedestal stimulus. If it became clear after a few minutes that the subject could make such discriminations, this set of trials was discontinued.

If performance was satisfactory with 2-second stimuli, a similar procedure was used with a 500-ms stimulus, save that the pedestal contained either 55, 44, 33, 22, 11, or 0 arcmin of either crossed or uncrossed retinal disparity, the initially presented difference between test and pedestal stimulus disparity was 750 arcsec, and dot size was changed. With stimuli shorter than 2 seconds, dots were 0.15° × 0.18°. Once again, if the subject could make such discriminations, the 500-ms sequence of data collection was discontinued. The successful subject than repeated the same procedure with 200-ms and finally 100-ms stimuli. Reversals were used to obtain mean thresholds at each pedestal disparity. With 200-ms stimuli, six reversals occurred at each pedestal. The first two reversals were considered practice, and data analysis was restricted to the last four reversals. For 100-ms stimuli, 10 reversals occurred at each pedestal. The first four reversals were considered practice, and data analysis (computation of mean of SE) was restricted to data collected during the 100-ms stimuli.

**RESULTS**

**Stereocuity Function Obtained with 100-ms Stimuli**

Figure 1, top, displays results obtained from a 20-year-old woman. Mean stereo threshold in arcseconds (±1 SE) is plotted, with logarithmic spacing as a function of pedestal disparity in arcminutes. In this figure and throughout the Results section, negative pedestal values indicate uncrossed retinal disparity and positive or unsigned values indicate crossed disparity. As was the case for approximately half of the subjects examined and as reported previously,51 lowest thresholds were obtained with zero pedestal disparity, and the threshold increased with increasing crossed or uncrossed pedestal disparity. The minimal threshold disparity, 24 arcsec, is also consistent with previous results obtained using RDSs as test stimuli.6,52,53

The data from the 20-year-old woman are replotted in Figure 1, bottom, but are superimposed on similarly obtained data from three other subjects. Results (open circles) were from an 18-year-old woman. the minimal threshold obtained, 35 arcsec, is relatively similar to that in the 20-year-old woman, but this occurred with a markedly crossed (+44 arcmin) pedestal disparity. The other two data sets were obtained from 60-year-old male and female observers. The nadir of such functions was used to characterize the results from most observers. The ordinate defines the optimal stereothreshold for observers in sample 1, and the abscissa defines the fixation disparity for observers in sample 2.

**Variation in Optimal Stereothresholds in Sample 1**

**Normative Description of Stereocuity in Younger Subjects.** Preliminary analysis showed that results obtained from subjects ≥60 years of age were considerably different from those obtained from younger subjects. For this reason, normative data were obtained by using the optimal stereothresholds for the 106 subjects less than 60 years of age in sample 1 who could complete testing with 100-ms stimuli. Figure 2 is a relative frequency distribution of the optimal stereothresholds of these 106 individuals. Note that the stereothreshold is plotted in log10, arcsec, because a plot in linear units (not shown) would be markedly skewed. The plotted function has a mean of 1.57 log arcsec (which in linear units corresponds to a geometric mean of 37 arcsec) and an SD of 0.23 log arcsec; values that are in reasonable agreement with the literature.19 The coefficient of correlation between the plotted data points and the smooth function is 0.866, indicating a reasonably good Gaussian fit. Consequently, these data were used to define norms for z-scores (SD units), as presented in Table 2.

Incorporating the information presented in Figure 2 and Table 2, Table 3 divides all 160 subjects representing sample 1 into six categories, including those who could not complete

![Figure 1. Stereocuity functions with 100-ms stereograms for four different observers. Mean stereothreshold in arcseconds (±1 SE) is plotted with logarithmic spacing as a function of pedestal disparity in arcminutes. Negative pedestal values indicate uncrossed disparity, and positive or unsigned values indicate crossed disparity. Top: data from a typical 20-year-old female observer; bottom: data from the same observer replotted, along with less typical data from an 18-year-old female and 60-year-old male and female observers. The nadir of such functions was used to characterize the results from most observers. The ordinate defines the optimal stereothreshold for observers in sample 1, and the abscissa defines the fixation disparity for observers in sample 2.](https://iovs.arvojournals.org/pdfaccess.ashx?url=/data/journals/iovs/932919/)
Another way to analyze these data is to divide observers into the age-decade group that they represent. Figure 4 shows mean stereoacuity threshold (±1 SE) for both male (hatched bars) and female (open bars) observers in six different age groups. This is plotted with a logarithmic ordinate to include data from older age groups exhibiting poorer stereoacuity. A two-way analysis of variance shows that the influence of age is significant (F_{1,123} = 13.58, P < 0.0001), whereas gender has no significant effect (F_{1,123} = 1.71, P = 0.1929).

To summarize, the results from subjects who completed testing with 100-ms stimuli reveal a significant tendency for stereoacuity to deteriorate with age. This correlation is likely to account, in part, for findings in prior studies that suggest that the prevalence of stereoanomalies increases with age. To emphasize this point, a horizontal dashed line is shown at the 110-arcsec ordinate position in Figure 3, which, based on normative analysis of data from subjects less than 60 years of age (Table 3), approximates a value delineating stereonormality from stereointerference. As indicated earlier, all but two subjects less than 60 years of age who completed testing were in the normal category. In contrast, a large percentage of the subjects who were 60 years of age or older (Fig. 5) could not be included in this category, including 25% (11/44) who were mildly stereointerfered (thresholds between 110 and 300 arcsec) and 9% (4/44) who were moderately stereointerfered (thresholds between 301 and 1000 arcsec).

Analysis Including Data from Subjects Unable to Complete 100-ms Testing. Figure 5 summarizes results from all subjects, regardless of whether they completed testing with 100-ms stimuli. The six different sets of coordinates show for the different age brackets the percentage of male and female observers who failed to complete testing with the demo program; those who failed to complete with stereograms presented for 2 seconds, 500 ms, 200 ms, or 100 ms; or those who completed testing with all stimuli (the "none" category). The graphs for the four younger age categories show that most subjects younger than 60 years were in the "none" category, and most were able to complete testing with 100-ms stimuli. However, in the 60 to 69 and particularly the 70 to 79-year-old categories, a smaller percentage of subjects were classified in the "none" category, and a much larger percentage failed to complete testing with either 500-ms or 2-second stereograms or with the demo program. For example, by the criteria established in Table 3, almost 90% of subjects less than 60 years of age were classified as stereonormal. In contrast, less than 40% of subjects between the ages of 60 to 69 and less than 30% of subjects 70 to 79 could be classified as stereonormal. Further data analyses revealed not only an increase in the prevalence of stereo interference with age, but also an increase in the severity of interference with age. That is, less than 11% of the subjects between the ages of 15 and 59 were classified as anything other than stereonormal. However, of the subjects aged 60 to

**Table 2. Normative Table**

<table>
<thead>
<tr>
<th>Deviation from Mean (z-scores)</th>
<th>Threshold (log arcsec)</th>
<th>Threshold (arcsec)</th>
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<tbody>
<tr>
<td>-3</td>
<td>0.88866</td>
<td>8</td>
</tr>
<tr>
<td>-2</td>
<td>1.11592</td>
<td>13</td>
</tr>
<tr>
<td>-1</td>
<td>1.34518</td>
<td>22</td>
</tr>
<tr>
<td>0</td>
<td>1.57044</td>
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<td>1</td>
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</tr>
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<td>2</td>
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<td>106</td>
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<td>3</td>
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<tr>
<td>4</td>
<td>2.47948</td>
<td>302</td>
</tr>
<tr>
<td>5</td>
<td>2.70674</td>
<td>509</td>
</tr>
<tr>
<td>6</td>
<td>2.95400</td>
<td>859</td>
</tr>
</tbody>
</table>

Figure 2. The relative frequency distribution of stereothreshold for the 106 observers in sample 1 who completed testing with 100-ms stereograms. To normalize the shape of this function, the abscissa is plotted in logarithmic rather than linear units. The fitted curve is a Gaussian function with a mean of 1.534 ± 0.2409 (SD), whereas the indicated numerical values are numerically calculated.

100-ms testing and/or those who were 60 or more years of age. The one subject whose threshold was more than 2 SDs below the mean (threshold, less than 13 arcsec) was designated acutely stereosensitive. Subjects within the mean (threshold, less than 13 arcsec) was designated normal. Subjects with stereoacuity thresholds from approximately 2 to 4 arcsec (thresholds between 301 and 1000 arcsec) were designated mildly stereointerfered. Subjects who failed to perceive depth in the initial demonstration stereogram; those who failed to complete with stereograms presented for 2 seconds, 500 ms, 200 ms, or 100 ms; or those who completed testing with all stimuli (the "none" category). The graphs for the four younger age categories show that most subjects younger than 60 years were in the "none" category, and most were able to complete testing with 100-ms stimuli. However, in the 60 to 69 and particularly the 70 to 79-year-old categories, a smaller percentage of subjects were classified in the "none" category, and a much larger percentage failed to complete testing with either 500-ms or 2-second stereograms or with the demo program. For example, by the criteria established in Table 3, almost 90% of subjects less than 60 years of age were classified as stereonormal. In contrast, less than 40% of subjects between the ages of 60 to 69 and less than 30% of subjects 70 to 79 could be classified as stereonormal. Further data analyses revealed not only an increase in the prevalence of stereo interference with age, but also an increase in the severity of interference with age. That is, less than 11% of the subjects between the ages of 15 and 59 were classified as anything other than stereonormal. However, of the subjects aged 60 to
Table 3. Stereoacuity Categories

<table>
<thead>
<tr>
<th>Designation</th>
<th>Approximate Variation from Mean in Standard Deviation Units</th>
<th>Range (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acutely stereosensitive</td>
<td>&lt; -2</td>
<td>&lt;13</td>
</tr>
<tr>
<td>Stereonormal</td>
<td>±2</td>
<td>13-109</td>
</tr>
<tr>
<td>Mildly stereoimpaired</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moderately stereoimpaired</td>
<td>&gt; +2 &lt; +4</td>
<td>110-300</td>
</tr>
<tr>
<td>Markedly stereoimpaired</td>
<td>&gt; +4</td>
<td>301-1000</td>
</tr>
<tr>
<td>Stereo blind</td>
<td>Detected demo, but could not complete 100-ms Testing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Could not detect demo</td>
<td></td>
</tr>
</tbody>
</table>

69, 29% were mildly stereoimpaired, approximately 13% were moderately stereoimpaired, and 21% were severely stereoimpaired. In subjects aged 70 to 79, the prevalence of mild and moderate stereoiimpairment decreased, but the prevalence of marked stereoiimpairment increased to approximately 40%.

To better illustrate the meaning of the data in Figure 5, the six categories of test failures (i.e., failure to complete testing with the demo program, stereograms of 2-second, 500-ms, 200-ms, or 100-ms duration) were collapsed into the dichotomous classes: “failing to complete” or “completion” of 100-ms testing. Figure 6 illustrates the percentage of male and female subjects failing to complete testing and shows that a trend toward failure to complete testing increased with age decade. A Spearman rank order correlation shows that this relationship is statistically significant when male and female subjects are considered together ($r_s = 0.429, P = 0.0083$ with a one-tailed test). A considerable number of additional statistical analyses verify the conclusion that the prevalence of more extreme stereodeficits increases significantly with age and is not related to gender.$^{27}$

**Contribution of Education, Differential Practice Effects, and Senile Meiosis to the Influence of Age on Stereopsis**. We considered three factors that do not specifically involve neural visual pathways and that may account for poorer stereosensitivity in older subjects. First, some older subjects were less well educated and less experienced with computers than younger subjects. For this reason, some of the elderly could have been less able to comply with the demands of testing. However, in the 25 subjects unable to complete testing with the 100-ms stimuli, the relationship between education (as indicated by years of schooling) and performance (i.e., optimal stereo threshold with 200-ms stereograms or exposure duration of stereogram perceived) was negligible (Spearman $r_s = 0.0201$, $P = 0.9257$ with a two-tailed test). Considering just subjects aged 70 or more years, the individual with the highest stereoaucity had only a 10th-grade education and was computer illiterate, whereas subjects designated markedly stereoimpaired included active college professors with years of computer experience.

It is well known that practice with stereoscopic tasks can subsequently improve stereoaucity.$^{34}$ Thus, it might seem possible that younger subjects may have been better able to use additional practice trials to produce lower stereo thresholds, whereas older subjects may have eventually produced stereo thresholds equivalent to younger subjects with additional practice. However, a comparison of 200-ms stereogram data (which as indicated in the Methods section, were obtained before 100-ms data) versus 100-ms stereogram data revealed no influence of age on such practice effects.$^{27}$

A third factor that could account for the decreased stereoaucity in older subjects is the decrease in pupil size with age (senile meiosis). Because the undilated pupil size of subjects in their 70s is approximately 4 mm, as opposed to 6 mm in the young adult,$^{35}$ retinal illuminance provided by a fixed-illuminance target would be reduced by approximately 44%. This reduction in retinal illuminance might be expected to produce reduced sensitivity. The efficacy of such an explanation was tested in three young adults by comparing stereosensitivity, using dots that were 6 cd/m$^2$ (as used throughout the remainder of this study) and dots that were 0.6 cd/m$^2$. Obviously, this reduction in stimulus luminance by 90% would reduce retinal illuminance by 90%, a reduction greater than that attributable
to senile meiosis. Results under both luminance conditions were nearly the same (a slightly lower mean threshold was obtained under the conditions of reduced luminance in comparison with that obtained with the typical luminance level used) ruling out a "retinal illuminance" explanation for age-related change in stereoacuity.

**Figure 4.** Mean stereoacuity threshold (±1 SE) for both male and female observers of six age groups. The ordinate is plotted with logarithmic spacing to include data from older age groups exhibiting poorer stereoacuity.

**Figure 5.** Percentage of male and female observers who failed to complete testing with the demo program; failed to complete testing with stereograms of 2-second, 500-ms, 200-ms, or 100-ms duration; or completed testing with all procedures (none), according to age.
We conclude that the age-related changes in stereosensitivity are due to neural changes within the visual pathways. 

**Influence of Gender on Stereoacuity.** Differences in the results from the two genders were carefully considered. Some comparisons are illustrated graphically in Figures 3, 4, and 5. Analyses revealed no statistically significant gender differences in optimal stereoacuity or in age-related influences on stereoacuity.27

**Prevalence of Fixation Disparities in Sample 2**
The pedestal value that resulted in maximum stereosensitivity served as an index of fixation disparity. Variation in fixation alignment in sample 2 is illustrated in Figure 7, top. This is a plot of the relative frequency distribution of different pedestal values producing optimal stereosensitivity and shows that approximately 50% of subjects in sample 2 were most sensitive with no (zero) pedestal disparity and approximately 40% more were maximally sensitive to both crossed and uncrossed pedestal disparities of 11 arcmin. In other words, approximately 90% of the subjects were maximally sensitive to disparities of 11 arcmin or less. The prevalence of still larger fixation disparities is more common for crossed (positive abscissa values) than for uncrossed pedestal values. Although not illustrated, Zaroff27 showed that the data obtained from subjects who were most sensitive to disparity values more than 11 arcmin were as reliable as the data obtained from subjects with no evident fixation disparity. In addition, the prevalence of fixation disparity did not relate to either the age or the optimal stereo threshold of a subject.

Figure 7, bottom, illustrates the alignment distribution for male and female subjects separately. Although approximately 50% of both male and female subjects were maximally sensitive to stereograms with no disparity pedestal, this plot reveals three different types of gender differences related to the prevalence and severity of fixation disparity. First, whereas more males seemed to be misaligned to uncrossed disparities, more females were misaligned to crossed disparities. As analyzed by a $2 \times 2 \chi^2$ analysis using a Yates correction factor, this difference was statistically significant ($\chi^2 = 4.662, P = 0.0308$). Second, no male was misaligned to pedestal disparities greater than 22 arcmin, whereas approximately 8% of female subjects exhibited optimal stereoacuity thresholds with pedestals greater than 22 arcmin from the plane of fixation. As analyzed by the Fisher exact test, this difference was also statistically significant ($P = 0.0413$). Third, for female subjects, the prevalence of disparity values of more than 22 arcmin was much greater for crossed ($n = 6$) than uncrossed ($n = 1$) pedestal values.

**DISCUSSION**

**Normative Nonaging Data**
The present study found that for observers less than 60 years of age, the logarithm of stereothreshold is normally distributed. The mean of this distribution is 1.57 log arcsec, corresponding to a geometric mean of 57 linear arcsec, a value consistent with average values from previous studies using the RDS.6,32,33 Although none of these prior studies considered the shape of the population distribution, all reported SDs considerably larger than the arithmetic mean, indicating positive skewing. This was certainly the case when the present data were considered in linear units.27 We emphasize that studies reporting much
smaller average stereoaucity used tests that did not eliminate nonstereoscopic depth cues.

In the present study, approximately 1% (1/106) of observers less than 60 years of age were stereoblind, and an additional 8% were considered stereoimpaired. These results are lower than those previously reported, which indicated a prevalence of stereoblindness as low as 2% or 3% or a prevalence of stereoeimpairment as high as 30%. This discrepancy can be accounted for by the exclusion of subjects with any history of eye disease and with substandard Snellen acuity in the present study, a rigorously defined technique for measuring stereoblindness (rather than depending on pass-fail criteria), and the use of many different pedestal disparities, which are likely to compensate for fixation disparities. Obviously, the reported prevalence of stereoeimpairment becomes much higher if results from older observers are considered.

Influence of Aging on Stereopsis

We believe that the present study indicates two different types of influence of aging on stereopsis. The first factor involves the correlation between stereoeacuity and aging. In Figure 3, the least-squares regression line crosses the demarcating value between what was designated as stereonormal and mildly stereoeimpairred at approximately age 65. As a consequence of this correlation and keeping in mind the scatter around the regression line, the greater the age the smaller the percentage of observers that would fall into the stereonormal category. However, the scatter around the regression line is not sufficiently great to account for the large number of observers in their 60s and particularly their 70s (e.g., Fig. 4) that could not complete testing with 100-ms stereograms and fall into the markedly stereoeimpairred or stereoblind categories. This result suggests the importance of a second, age-related catachlysmic factor that causes a deterioration in stereoscopic vision. Although rarely considered in visual science, such a two-factor theory is not unknown in a neurologic context. For example, both motor coordination and various types of memory decrease in the normal aging population, but the majority of individuals do not experience the development of either Parkinson’s or Alzheimer’s disease.

Exactly which factors account for age-related changes in stereoeacuity remains unclear. Haegerstrom-Portnoy et al. describe a single age-related metric related to optical factors that predicts a general deterioration in several aspects of vision, including visual acuity and stereopsis. Because all the observers in the present study were equal in Snellen acuity, it is unlikely that such an optical factor could account for the reported age-related deterioration in stereoeacuity. Because of the cerebral basis for stereopsis, it is much more likely that age-related deterioration can be attributed to neural factors. The present data alone cannot be used to determine whether these neural factors represent a general deterioration in the brain (e.g., see Lindenberger and Baltes), factors related generally to vision (somewhat specifically to depth perception) or very specifically to stereopsis. However, the present findings are similar to those from 12 of the 14 previous studies on age-related effects on depth perception summarized in Table 1, which did not rigorously rule out a role for nonstereoscopic depth cues. This similarity strongly suggests that the presently reported age-related deterioration perhaps in a very general way, it is the noise inherent to and introduced by the visual system that increases with age. In an assessment of stereoeacuity, this increased noise would then be further magnified by the involvement of and the precise interaction required between the two eyes that must occur before an observer is able to precede with even the beginning steps of stereopsis (i.e., fusing two retinal images). This would in turn result in a greater aging of stereoeacuity relative to that of other hyperacuity abilities.

Variation in Stereoealignment and Qualitatively Different Types of Stereooanomalies

Stereoeacuity has been reported to be maximal at the plane of fixation and to decline with increasing distance from fixation. Except with peripheral stimulus presentation and/or lack of adequate fixation, disparities of more than 30 arcmin have been unreported (e.g., see Carter). In fact, neither of these factors could account for the existence of fixation disparities of more than 22 arcmin in 6% of the observers who constituted sample 2. It is possible that these instances of extreme fixation disparities correlate with two of the types of stereoealignment reported by Richards that strongly influenced the subsequent binocular vision literature (e.g., Fischer and Poggio). However, it should be mentioned that in the present study, fixation disparity was determined, not by the usual optical procedures, but rather was taken to be the non-zero disparity pedestal at which optimal stereoeacuity occurred. Although individual phorias (i.e., latent strabismus evident when both eyes are not given a fusible stimulus) may have affected measurement of fixation disparity, rarely did more than several hundred milliseconds elapse before an observer was presented with a salient stimulus. In contrast, it takes approximately 20 seconds for an eye to come to rest in its position of phoria. Thus, it is unlikely that estimates of fixation disparity were affected by undetected phorias.

The present results showed no relationship between the prevalence of fixation disparity and age, in contrast to findings of Yekta et al. Perhaps the operational definition of fixation disparity used by Yekta et al., as opposed to that used in the present study, is responsible for the contrasting results. We are unaware of any precedent for the unexpected gender differences in fixation disparity, nor do we have any explanation.

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References


