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VARIATION IN STEREOACUITY IN THE HUMAN POPULATION INCLUDING FIXATION DISPARITY, AND THE ROLES OF AGING AND GENDER

by

CHARLES M. ZAROFF

A dissertation submitted to the Graduate Faculty in Psychology in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York.

2001

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The City University of New York

Abstract

VARIATION IN STEREOACUITY: NORMATIVE DESCRIPTION, FIXATION DISPARITY, AND THE ROLES OF AGING AND GENDER.

by Charles Zaroff

Advisor: Professor Thomas E. Frumkes

Stereoacuity functions were obtained with a forced-choice staircase procedure in observers whose corrected visual acuity in each eye was at least 20/30. Accordingly, threshold disparity for detecting a 2.78° x 2.28° rectangular test stimulus was determined as a function of the disparity (varied in 11 arcminute steps from 55 arcmin uncrossed to 55 arcmin crossed) of a 5.57° x 4.8° rectangular pedestal. Stimulus duration was 100 milliseconds (ms) preventing vergence eye movements. Ordinate and abscissa values of the nadir of stereoacuity functions are defined respectively as, the observer's *optimal stereoscopic threshold* and *fixation disparity*.

Optimal stereoacuity was examined in 160 observers ages 15-79 years. When plotted logarithmically, 100 ms duration thresholds for observers <60 years of age approximated a normal distribution (mean = 1.57 log arcsec [37 linear arcsec]; standard deviation = 0.227 log arcsec). Normal stereoacuity involves thresholds between ±2 standard deviations of the log mean (13-109 linear arcsec). For observers less than 60 years, 1% were supernormal, 88% were within the normal range, 2% had thresholds greater than 109 arcsec, 8% failed testing with 100 ms stereograms but had residual binocular depth discrimination, and 1% were stereoblind. For observers aged 60-69, 37% were stereo normal, 42% completed testing with

100 ms stimuli but with thresholds greater than 109 arcsec, while 21% were still more stereo impaired. For observers aged 70-79, 25% were stereo normal, 25% had thresholds with 100 ms stimuli greater than 109 arcsec, while 50% were still more stereo impaired. The correlation between optimal stereo threshold and age was statistically significant and involved no significant gender differences. Age-related deterioration in stereoacuity probably reflects: a). an underlying linear correlation between age and threshold; and additionally b). a catastrophic factor producing more marked deterioration whose incidence increases greatly after age 60.

Fixation disparity was examined in 151 observers with optimal stereo threshold values ≤108 arcsec. Approximately half were maximally sensitive with no pedestal disparity; 89% were maximally sensitive to disparities within 11 arcmin of the fixation plane. Males were more likely to be maximally sensitive to uncrossed-, while females were more likely to be maximally sensitive to crossed-disparities. All males were maximally sensitive to pedestals within 22 arcmin of the fixation plane, while 8% of female observers had fixation disparities >22 arcmin. These gender differences were statistically significant and unrelated to age.

Acknowledgments

I would like to thank Dr. Thomas E. Frumkes for all he has done for me during my time at Queens College. His guidance and support made this thesis possible. I would also like to thank the members of my dissertation committee, Drs. R. Johnson and R. Lanson, for their informative and instructive suggestions. I am also thankful for the help of my outside readers, Drs. K. Holopigian and J. E. Sturr.

I would like to thank Margaret Knutelska, both for her friendship and for the countless hours she spent not only as a subject, but also as a co-investigator. I am grateful to John Zhu for useful modifications he was able to perform in the software used in the current experiment. I would like to thank Gwinne Wyatt for devoting her time as an editor.

I would like to thank the faculty and graduate students in the department of psychology at Queens College as a whole who helped me by contributing their time and cooperation.

Lastly, I would like to thank my family. My brothers Samuel and Andrew were always there for me when I needed them. My parents, Rita and Irving, have always appreciated my efforts and were willing to provide whatever support I needed. This thesis is dedicated to them.

Table of Contents

List of Tables

List of Illustrations

Chapter 1

Introduction and Overview

Both eyes receive a slightly different view of the world because of their lateral separation in the head. As a result, object points may stimulate non-corresponding retinal positions in the two eyes leading to horizontal retinal disparity. Horizontal retinal disparity is the necessary and sufficient condition for stereopsis, the most salient cue for depth perception. Stereopsis-mediated depth acuity, or stereoacuity, is the minimum horizontal retinal disparity leading to a perception of depth based upon stereopsis; if retinal disparity is further reduced, an observer is unable to discriminate differences in depth between two objects or object points.

Howard (1919) was one of the first investigators to study the limits of stereoacuity. His observers were required to judge which of two rods appeared closer in depth. Howard's most accurate observers were able to indicate the difference in distance of the rods when the separation in depth between the two was less than 2 seconds of arc (arcsec). Numerous stereoacuity studies followed Howard, some using similar procedures, others utilizing more modern stereoacuity tasks. For a variety of reasons which include poorly designed methodological procedures and incidental additional involvement of non-stereoscopic cues for depth, the values obtained for stereoacuity varied from study to study. However, widely disparate values were also obtained within the observers examined in individual studies. For example, Howard obtained a range of 2 to 133 arcsec for what he called "depth difference thresholds" in the 106 observers he examined. Therefore, the variation in stereoacuity reported in the literature cannot be attributable solely to procedural differences.

While there are many claims in the literature (reviewed below) that stereo thresholds can be as low as 2 arcsec under optimal conditions, there is no consensus on what constitutes "normal" stereoacuity. As might be expected, the literature also provides no consensus on what constitutes a "stereoanomaly," "impaired stereopsis," or "stereoblindness." For example, Richards (1970) found that 30% of the 75 observers studied had difficulty perceiving depth. A few years later, Newhouse and Uttal (1982) reported that only 3 of 102 observers were stereoanomalous, as defined by an inability to perceive depth in a random-dot stereogram. More recent studies reviewed below have also failed to reach a clear conclusion. In lieu of a clear definition of stereoanomaly, the prevalence of impaired stereoacuity must be considered unknown.

Age and gender might also affect stereoacuity. While there has been little study of gender differences in stereopsis (Rubin et al., 1997), many prior studies have examined the influence of age on stereoacuity (reviewed below). Most studies purporting to assess depth perception using only stereopsis as a depth cue have suffered from methodological flaws. Some have failed to properly account for changes in visual acuity and other optical changes in the eye attributable to age. More commonly, many studies have failed to isolate stereopsis as the sole cue to depth.

The present study investigated variation in stereoacuity in a large group of observers having normal Snellen visual acuity with no history of eye disease. This large sample represented both genders and provided a homoscedastic representation of ages between 15 and 79 years. Testing involved tachistoscopic presentation of random-dot stereograms in order to isolate stereopsis as the only possible cue for depth. The stimulus characteristics of these stereograms enabled examination of sensitivity to increments of depth in front of and behind the plane of fixation. The ability to examine stereopsis at various intervals of depth from the plane of fixation was important, because stereoacuity is not always maximal at fixation, i.e., "fixation disparity" (Wick, 1985; Fogt & Jones, 1998). Results show a wide variation in stereoacuity in all age groups. Quantitative analysis of tachistoscopic stereoacuity values obtained from observers who completed all aspects of testing reveals a gradual decrease in mean stereoacuity over the entire age range examined, with a significant linear correlation between age and stereoacuity. However, analyses of data from all observers including those unable to complete all testing also reveal a marked increase in the incidence in stereo deficits in the 7th decade of life which cannot be attributable to changes in two dimensional visual acuity and/or optical factors.

The following portions of the *Introduction* first discuss depth perception with an emphasis on stereopsis and stereoacuity. Age-related changes in vision are then discussed with a brief mention of gender differences, followed by a section which analyzes the variation in stereoacuity in a normal population. The subsequent section contains a description of some commonly used clinical tests for stereopsis including a review of the findings concerning the incidence and types of stereopsis impairment. The final section reviews, in detail, the deficiencies of previous studies of the influence of age and gender on stereoacuity.

Depth Perception

The ability to discriminate differences in the distance of two objects from an observer is commonly called "depth perception." Even with only one-eye viewing, depth perception is readily experienced due to monocular cues for depth. As a result, difficult tasks such as maneuvering an automobile at high speeds can be carried out if one eye is closed. Monocular cues can be divided into static cues, which require no movement of the eyes or head, and dynamic cues, which do require observer or stimulus motion. Static monocular cues for depth perception include interposition, aerial perspective, shading and lighting, elevation, and texture gradient. Accommodation, a dynamic monocular depth cue, is the change in the shape of the lens required to focus clearly on objects at different distances. This cue is of use up to distances of 2 meters (Schiffman, 1990). The ability of the lens to focus deteriorates throughout adulthood so that by the 60s and 70s very little accommodative ability remains (Ogle, 1962). The other dynamic monocular depth cue is parallactic displacement, or monocular parallax. When an observer moves the head from side to side while viewing an array of objects, those nearer to the observer appear to move in a direction opposite to more distal objects.

Although these monocular cues have been described since the Renaissance era, it is also well known that depth perception improves dramatically with two-eyed viewing due to the role of the binocular depth cues, vergence and stereopsis. The eyes diverge to fixate upon objects further than the current point of fixation, and converge to fixate upon objects closer than fixation. Vergence can be a potent cue for depth but is only useful at distances less than about 6 meters (Mon-Williams & Tresilian, 1999); beyond this distance, the convergence angle formed by the two eyes becomes zero, a position of the eyes known as "straight ahead." Vergence eye movements, which are caused by horizontal retinal disparity, have a latency of approximately 150 milliseconds (ms) (Westheimer & Mitchell, 1969): therefore, stimulus exposure for less than 150 ms eliminates their involvement in depth perception.

Stereopsis, the focus of this thesis, is the other binocular cue for depth and results from horizontal retinal disparity. When an object point is fixated, it stimulates corresponding retinal elements in the two eyes (e.g., if the two eyes were removed from the head and placed directly on top of one another, a pin placed through a point in both retinae would pass through corresponding retinal elements). Such corresponding retinal elements are said to contain zero horizontal retinal disparity. When the signals from these stimulated retinal elements in the two eyes are combined in the cortex, the resulting percept is a point in space where the eyes are fixated. Object points that are not fixated stimulate retinal elements in the two eyes that are disparate. When the signals from these stimulated retinal elements are combined in the cortex, the resulting percept is placed at a point in space either behind, or in front of the point in space where the eyes are fixated. The impression of depth that results solely from retinal disparity is known as stereopsis.

The two types of horizontal retinal disparity are termed crossed and uncrossed. In Figure 1, the point of fixation is imaged on the left and right foveas and thus stimulates corresponding retinal elements. Object point A stimulates horizontally disparate retinal elements and is said to contain horizontally crossed retinal disparity (or more simply, crossed disparity). Objects with crossed disparity appear closer than the fixation point. Object point B stimulates horizontally disparate retinal elements and is said to contain horizontally uncrossed retinal disparity. Objects with uncrossed disparity appear further away than fixation.

At a given fixation distance, the locus of all points that are imaged on corresponding retinal elements is known as the longitudinal horopter, a term introduced by Aguilonius in 1613. These points are experienced as equidistant. Veith in 1818, and later Mueller in 1826, described what is known as the theoretical horopter, which has been extensively studied by more recent investigators (for a thorough review, see Ogle, 1964). The horopter is based on the theorem of inscribed circles (see Figure 2), which states that any lines drawn from two

Figure 1. Depiction of crossed and uncrossed horizontal retinal disparity derived from Howard and Rogers (1995). Point A represents crossed disparity while point B represents uncrossed disparity, with fixation as indicated by X.

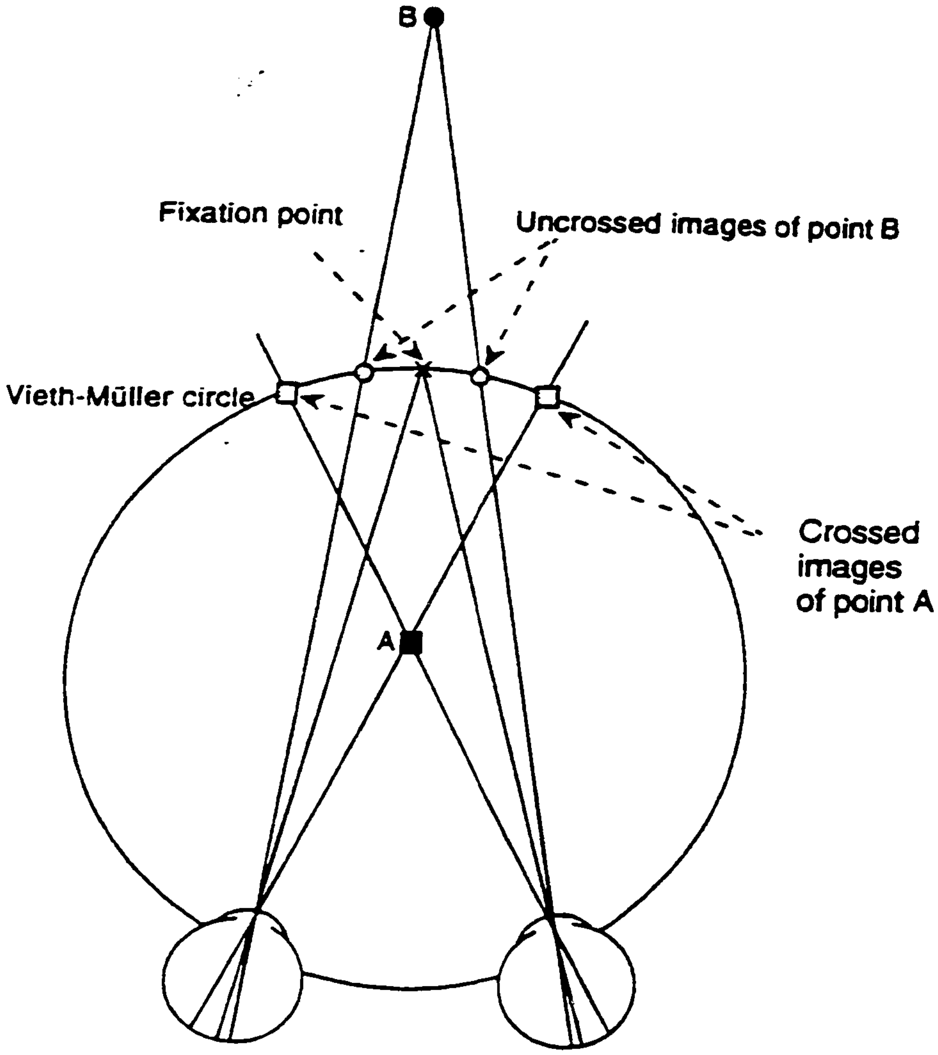
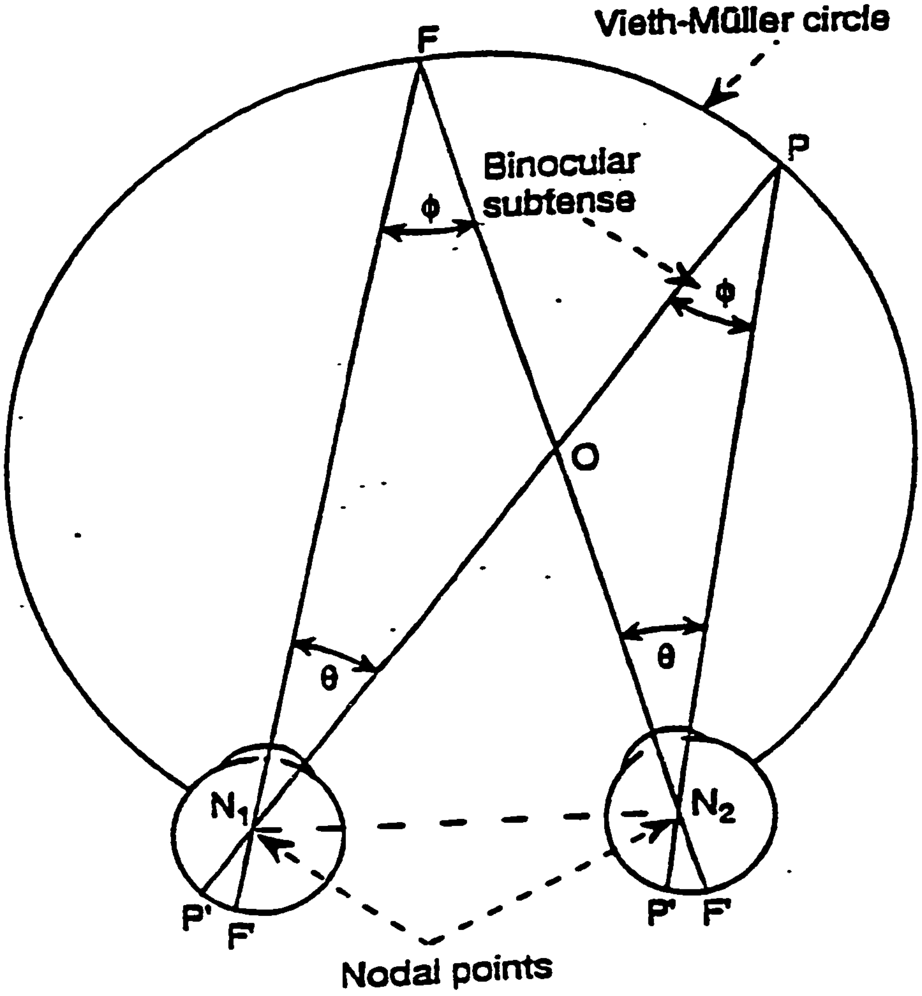

B
Fixation point
Uncrossed images of point B
Vieth-Müller circle
Crossed images of point A
A

Figure 2. Depiction of the horopter, based on the theorem of inscribed circles, derived from Howard and Rogers (1995), which states that any lines drawn from two points on a circle to any other two points on its circumference include equal angles. Thus, the angles subtended at points F and P on the horopter are equivalent.


Vieth-Müller circle
F
P
Binocular subtense
ϕ
ϕ
O
θ
θ
N1
N2
P'
F'
P'
F'
Nodal points

points on a circle to any other two points on its circumference include equal angles. Points located on the horopter result in a single, "fused" percept. Although object points not on the horopter should theoretically result in double images, or diplopia, within a certain area in front of or behind the horopter, object points are still perceptually fused. This area of space resulting in singleness of vision is known as Panum's fusional area.

Wheatstone, with his invention of the stereoscope (1838), first empirically demonstrated that horizontal retinal disparity was the cue necessary for the impression of depth called stereopsis. Wheatstone took separate photographs of a single scene from the vantage point of the left eye, and that of the right eye. He placed these in a "stereoscope," a device consisting of two mirrors at right angles and two vertical picture holders. When the two photographs (i.e., stereograms) were viewed, and subsequently fused into a single percept by an observer, a vivid impression of depth appeared. In 1841, Dove demonstrated that eye movements were not necessary for stereopsis to occur by illuminating a stereoscope with an electric spark. As a result, the duration that an observer was allowed to view the stereogram was much too brief for vergence eye movements to occur.

Julesz (1964) conclusively demonstrated that horizontal retinal disparity was the sole cue for stereopsis using random-dot stereograms (RDS). With such stimuli, each stereogram is composed of a matrix of equal sized elements or "dots." The individual dots are black and white and randomly selected. If the exact pattern in each member of the pair is identical, these "correlated dots" provide a zero disparity background. However, if a region of the random-dot array presented to one eye is shifted horizontally relative to the corresponding region presented to the other eye, the shifted region appears to "jump out" with vivid depth. On the other hand, if one eye is closed or occluded when viewing a random-dot stereogram, all that is visible is a random array of black and white dots containing no depth, thus proving that it is horizontal retinal disparity that is crucial for stereopsis. Depending upon whether the shift involves crossed or uncrossed retinal images, the shifted region will appear in front of or behind the array of dots in the unshifted region. Because the shape of the area that appears with depth is not evident in the monocular image, the perception of form with random-dot stereograms is reliant upon the perception of depth. Therefore, depth perception must occur prior to form along the hierarchy of cortical visual processing areas (Julesz, 1986). Random-dot stereograms also provide an example of global stereopsis in that any one individual dot in one member of a stereogram pair could conceivably be matched with any individual dot in the corresponding stereogram. In contrast, local stereopsis is a term used to define stereoscopic displays in which a finite number of matches between opposing members of a stereogram pair are possible.

Stereopsis as a cue for depth is innate, unequivocal, and inescapable, while at least some monocular cues are learned and their significance varies with individual experience (Von Noorden, 1996). Additionally, since stereopsis cannot be synthesized from other aspects of vision such as form, brightness, or color, it is said to occur in parallel with these other visual abilities. Its physiological basis was first shown by Barlow, Blakemore, and Pettigrew (1967), who found neurons in the striate cortex of the cat that responded selectively to retinal disparity. Fischer and Poggio (1979) found neurons in areas V1 and V2 in the rhesus monkey that responded selectively to the depth provided in random-dot stereograms. No such binocular interaction occurs at subcortical loci within the visual system of higher mammals and therefore, stereopsis is clearly a cortical phenomenon.

Stereoacuity

Two-dimensional visual acuity (usually referred to as simply "visual acuity") refers to the smallest visual angle that can just be discriminated. Typical visual acuity tasks measure the minimally detectable border separation such as the difference between two dark bars in the Letter **E** on a Snellen chart. Normal Snellen visual acuity (i.e., 6/6 or 20/20 vision) indicates an ability to detect one minute of arc. Border separation measures of visual acuity will vary somewhat with the technique used (Schiffman, 1990), and under optimal conditions are limited by the retinal mosaic (e.g., see Williams, 1988). However, other tasks, such as vernier acuity, result in much lower thresholds. Such tasks, because they result in such high acuities, have been referred to by Westheimer (1975) and later workers as *hyperacuity* tasks. Hyperacuity threshold values can be less than 1 second of arc (e.g., Hecht & Mintz, 1939).

Stereoacuity is the depth discrimination threshold expressed in angular terms. Stereoacuity is an example of hyperacuity since the 3-6 arcsec thresholds found in some studies (e.g., Westheimer & McKee, 1979) under optimal circumstances are considerably smaller than the *circa* 1' threshold for conventional acuity measures (while stereoacuity is considered an example of hyperacuity for the reasons described above, any particular individual's stereo threshold may fall outside of the range typically considered to be representative of hyperacuity). Stereoacuity thresholds of between 3 arcsec (Westheimer & McKee, 1979) and 15 arcsec (Westheimer & Pettet, 1990; Patterson, 1990) have been reported. However, the more typical threshold values approximate 30 arcsec (Coutant & Westheimer, 1993).

Vision, Aging, and Gender

Any investigation of the variation in perceptual ability within the normal population must take into account the effects of age. Stereopsis is a cortically mediated aspect of visual perception. Therefore, changes in stereoscopic performance may reflect alterations anywhere within the visual pathway prior to the cortex, including optical factors in the eye, as well as changes within the retina, the geniculo-striate pathway, or extra-striate cortical areas.

In general, changes in the visual system with age are classified as "optical," "neural," or both. Probably the best-known example of a largely optically related age change involves a loss of color discrimination along the blue-yellow axis, which can be attributed to the yellowing of the lens with age which results in decreased absorption of blue light (e.g., see Weale, 1992). Additionally, many age-related ocular diseases such as many maculopathies, glaucoma, and diabetic retinopathy are known to effect blue/yellow (as opposed to red/green) discriminations. However, this change in perception is also at least partially neural in origin. Sperling, Johnson, and Harwerth (1980) show that the short-wavelength sensitive cones, unlike cones sensitive to longer wavelengths, can be easily and permanently damaged by exposure to bright light. The amount of damage is cumulative with repeated exposure. As a consequence, older people are more likely to have a reduced sensitivity to blue light.

To be sure, some of the age differences in visual capacity can be attributed to optical changes within the eye including sclerosis of the optic lens (which results in reduced lens accommodation such that by age 70, very little accommodative ability remains), increased light absorption by ocular structures along the visual axis, and increased interocular light scatter. Senile miosis refers to age related reduction in pupil size. That is, the average "fully dilated" pupil size for a 70 year-old observer is about 4 mm, as opposed to 6 mm for an observer in their 20s (Sloane, Owsley, & Alvarez, 1988). This decrease in pupillary diameter would reduce retinal illumination by about 56%, or approximately 0.36 log units. However, these optical factors account for only a small percentage of the large differences in sensitivity observed with aging (Pitts, 1982; Morrison & McGrath,1985; Elliot, 1987; Sloane, Owsley, & Jackson, 1988). That is, even with optimal spectacle correction, spatial vision in healthy older individuals with no history of eye disease is poorer than in younger adults (for review see Owsley, 1987; Fozard, 1990; Owsley & Sloane, 1990).

Additionally, visual acuity studies indicate that the elderly have particularly poor spatial resolution under dimmer levels of illumination (for review, see Pitts, 1982; Owsley, 1987; Fozard, 1990; Owsley & Sloane, 1990). More extensive studies which used contrast sensitivity functions (contrast sensitivity measured as a function of the spatial frequency of a sinewave grating) strongly support these acuity data. They show that sensitivity to middle- and high-spatial frequencies in the elderly is particularly poor at dim luminance levels (Derefeldt, Lennerstrand, & Lundh, 1979; Owsley, Sekuler, & Siemson, 1983; Sloane, Owsley, & Alvarez, 1988; Haegerstrom-Pornoy, Schneck, & Brabyn, 1999). On the other hand, much less reported is an age-related change in sensitivity to low-spatial frequencies (see Zhang & Sturr, 1995). Most of the aforementioned authors emphasize that optical factors alone can account for <1 $\log_{10}$ unit age-related change in spatial sensitivity, while in fact at dim photopic light levels, differences >2 $\log_{10}$ unit are observed.

A decline in temporal sensitivity also occurs with age. Temporal resolution decreases with age, as was first indicated by reductions in critical flicker frequency (Misiak, 1947). More recent studies of temporal sensitivity measure an individual's sensitivity to the contrast of temporally modulated stimuli. A decrease in sensitivity occurs for all temporal frequencies with age, but is greatest for high (>20 hz) temporal frequencies (Tyler, 1989). When compensation is made for decreases in area of the elderly pupil, these changes persist. The changes also remain when light scatter and absorption by the aging ocular media are minimized by testing with a long-wavelength stimulus (Tyler, 1989). Thus, neural factors would also appear to play some role in the age-related decline in temporal sensitivity.

Thus, it must be concluded that neural changes account for much of the age-related reduction in visual sensitivity. The functional characteristics of these neural changes have not been specified by usual psychophysical procedures, by electroretinography or other evoked potential procedures, or postmortem histological examination (for references, see Weale, 1982; Weale, 1986; Owsley & Sloane, 1990). It should be noted, however, that change in the response properties of individual visual cortical neurons with age have just begun to be studied by single unit physiological techniques in subhuman primates. For example, Schmolesky, Wang, Mingliang, and Leventhal (2000) have shown that a large number of visual cortical neurons in rhesus monkeys >20 years of age have a degradation of orientation and direction selectivity in comparison with the sensitivity of corresponding neurons in younger animals. Of the 187 neurons recorded from 4 older rhesus monkeys, only 107 (42%) were biased for orientation selectivity, whereas in 4 younger rhesus monkeys, 169 of 187 (90%) were biased for orientation selectivity.

In general, gender-related changes in the aging visual system are relatively uncommon. One notable exception is a study by Sturr, Zhang, Taub, Hannon, and Jackowski (1977) which showed evidence for a large age-related change in scotopic absolute threshold with age, but only in men. Such an age-related gender difference has not been seen in many other studies of the human visual system.

Variation in Stereoacuity

1. Measures of Stereoacuity

Much of what has been designated "stereoacuity" in the literature would be better labeled depth discrimination, as almost all investigations into the nature of stereoacuity have failed to eliminate other cues for depth. For example, Howard's (1919) apparatus, which has since come to be known as the Howard-Dolman apparatus (Woodworth, 1938), requires an observer to set a vertical rod to appear in the same frontal plane as two equidistant flanking rods. There are several monocular cues in this test, including the relative widths of the images of the rods and motion parallax resulting from head movement. More modern dioptic stereoacuity tasks, such as the Frisby Stereo Test and the Flashlight Diastereo Test, also suffer from such flaws. The Frisby Stereo Test consists of clear plastic plates of varying thickness containing 4 squares on one side. In the center of one square on each of the plates is a 3 cm circle printed on the opposite surface, giving the impression of either a "hole" or a circle "sticking out," which the observer is required to identify. While this task is relatively easy to administer, an observer may also use vergence, accommodation, parallax and perspective to provide cues for depth (Howard & Rogers, 1995). In fact, Cooper and Feldman (1979) described an observer who was able to perform above chance level when completing the Frisby task with monocular viewing! The Flashlight Diastereo consists of a flashlight whose outer surface has two opaque aluminum discs along with a third disc raised on a transparent plastic rod. The examiner points the flashlight at the observer and asks which disc appears raised. In such a device intended to measure stereopsis, the additional non-stereoscopic cues are obvious, including both monocular cues (accommodation, changing width of the stimuli, and motion parallax) and vergence eye movements.

In order to eliminate monocular cues, stimuli should be physically separated and viewed stereoscopically. The TNO Stereo Test presents random-dot displays printed as red/green anaglyphs, which are basically two views of a display, one viewed through a red filter and one through a green filter, which are then overlaid at some lateral distance. When an observer, who is fitted with spectacles containing a red filter covering one eye and a green filter covering the other, views the display, depth is apparent. On the TNO Test, an observer views plates which contain discs with retinal disparity: each disc has a missing sector in one of four positions and the disparity in the discs ranges from 15 to 480 arcsec. Other stereoscopic tasks include the Randot Stereo Test and the Titmus Stereo Test. The Randot Test contains random-dot stereograms arranged into three sets of different stimuli and requires the observer to wear polarizing spectacles. The first set contains six shapes to be identified and provides a measure of gross stereopsis. The other two sets consist of circles and animals; in each set there are rows of stimuli and the observer must indicate which stimulus in each row contains stereoscopic depth. The Titmus stereo test is similar to the TNO Stereo Test. Wearing polarizing spectacles, an observer views sets of stimuli labeled the Animal Test and the Circles Test. The Animal Test consists of three rows of animals with one animal in each row having a disparity of 100, 200, or 300 arcsec. The Circles Test consists of nine numbered diamonds, each containing four circles. One of the circles in each diamond contains anywhere from 40 to 400 arcsec retinal disparity.

Even these measures are not free of contamination by non-stereoscopic cues. On the Titmus Test, the lateral displacement of the stimuli can provide monocular cues (Cooper & Warshowsky, 1977), while contours are evident when viewing the Circles test of the Randot Stereo Test with only one eye open. Additionally, none of the tests mentioned above are free of depth cues resulting from vergence eye movements. Nonetheless, a much more valid assessment of stereopsis can be obtained using tests that employ polarizing lenses as a means of viewing dichoptic stimuli than can be had using measures such as the Frisby Test, Howard-Dolman apparatus, and the Flashlight Diastereo Test.

As a result of the aforementioned methodological differences, threshold values on some depth discrimination tasks do not correlate well with those obtained using dichoptic measures of stereopsis. For example, Harwerth and Rawlings (1977) found a range of stereoacuity values from 3 to 8 arcsec using a Howard-Dolman apparatus. When they used random-dot stereograms as test stimuli, however, the range of values changed to 15 to 200 arcsec.

2. <u>The Incidence of Stereoanomalies</u>

Studies that are able to isolate retinal disparity as the sole cue to depth often find great individual differences in stereoacuity. For instance, Heron, Dholakia, Collins, and McLaughlan (1985) measured stereoacuity in a population of 51 young adults between the ages of 18 to 22 and was able to examine the effects of stimulus variables by testing each observer on four separate measures: the Frisby Stereo Test, the TNO Stereo Test, the Titmus Stereo Test, and the Randot Stereo Test. Key features of the results are summarized in Table 1. Not surprisingly, the test most susceptible to monocular cues (the Frisby Test) produced the lowest mean threshold, while that least susceptible to monocular cues (the TNO Test) produced the highest thresholds. Parenthetically, it should be noted that the Randot Test, while considerably free from monocular cues, has been criticized because of the fine texture of the random-dot elements which needs to be differentiated before the discrimination of figure from ground is possible (Walraven, 1975). Because of the asymmetrical and decidedly

Table 1

Summary of Results from Heron et al. (1985). (All numbers represent seconds of arc)

Stereo test	Median	Mean	Standard deviation	Range
Frisby	8.0	12.9	23.1	>5 to 170
Randot	20.0	28.1	30.6	5-10 to 100-200
Titmus	18.0	36.6	58.5	10-15 to 200-400
TNO	32.0	88.7	121.4	>10 to 400-500

non normal distribution of the threshold scores which make-up these data, it is difficult to come up with any statistical definition of "stereo-impairment." However, the Frisby Test revealed one observer with an exceedingly high (a score >2 standard deviations above the mean) threshold (170 arcsec), while two of the other more valid tests (Randot and Titmus) revealed at least three observers with thresholds several standard deviations above the mean (up to 500 arcsec). Close to 20 observers on the TNO Test produced thresholds several standard deviations above the mean. If impairment can be tentatively defined as acuity several standard deviations below (i.e., worse) than the mean, based upon Heron's data, it would seem likely that at least 5% of the population is stereo-impaired.

The incidence of stereo-impairment varies considerably in other studies. For example, Richards (1970) found that approximately 30% of the 75 observers he studied were stereo-impaired. In Richards' study, observers who perceived stereoscopically presented vertical lines containing retinal disparity as if they were lying in the plane of fixation were designated as stereo-impaired, although his methodology has been criticized. In the same paper, however, he mentioned that a survey of 150 individuals revealed only 4% who were unable to see depth in a random-dot stereogram, while an additional 10% had difficulty detecting the depth of a figure relative to its background. This 14% total is considerably smaller than 30%.

Hering and Bechtoldt (1981) replicated the results of Richards (1970), finding a 30% incidence of stereo-impairment. Most other studies, however, report a much lower incidence of stereoanomaly. For example, approximately 80% of the 188 observers examined by Coutant and Westheimer (1993) were able to detect depth differences between two objects separated by 30 arcsec of retinal disparity. This percentage increased to 97.3% when retinal disparity between two objects was increased to 2.3 minutes of arc. Newhouse and Uttal

(1982) criticized Richards, proposing that sequence effects (i.e., difficulty detecting crossed disparities after initially being exposed to uncrossed disparities, and vice versa) artificially elevated his estimate of stereoanomaly prevalence. In their sample of 102 observers, only 3 had initial difficulty detecting depth in an anaglyphic random-dot stereogram. However, if they tested observers with the polarity of the lenses reversed, 12 observers had difficulty detecting the depth in the stereograms. While this finding might appear to be evidence for a sequence effect, 6 of these 12 observers still had difficulty detecting the depth in the reversed stereograms several days later. Thus, whether their results were due to real stereo-impairment or to stimulus presentation artifacts cannot be definitively stated. Unfortunately, Newhouse and Uttal utilized random-dot stereograms published by Julesz (1971), which were intended for demonstration purposes and contain an unspecified amount of retinal disparity. Thus, it is possible that if the stimuli contained enough retinal disparity, some observers were stereo-impaired yet still possessed enough stereoacuity to view the stimuli presented. Patterson and Fox (1984) also found much lower rates of stereoanomaly (i.e., 3%). Patterson and Fox were able to eliminate vergence eye movements as cues to depth by presenting stimuli as induced afterimages on the eyes of observers.

To summarize, the results of all of the foregoing studies suggest that the incidence of stereo-impairment, defined here as poor stereoacuity, is at least 3% (Newhouse & Uttal, 1982) and may be as high as 30% (Richards, 1970). Because of differences in methodology and criteria, it is impossible to give a definition of "normal" stereoacuity, and thereby provide a definitive limit over which a stereo threshold indicates an anomaly. If, however, the results obtained by Heron, Dholakia, Collins, and McLaughlan using the TNO Test are ignored for the moment (owing to the hard to resolve fine elements contained on the task), most of the afore cited authors would agree that a stereoacuity threshold greater than 100 arcsec is indicative of a deficiency.

3. Types of Stereoanomalies

Some research has suggested several different types of stereoanomalies rather than just one. For instance, Richards (1970; 1971) found that some of the stereo-impaired observers he studied had difficulty with uncrossed retinal disparity, while others had difficulty with crossed retinal disparity. With these stereoanomalous observers, stimuli containing disparity in the direction of difficulty (i.e., crossed or uncrossed) were not perceived as containing depth. Shortly after his study was published, Fischer and Poggio (1979) reported the existence of several different types of neurons in visual cortex of monkeys which they related to the types of deficits shown by Richards' observers.

Some individuals with otherwise good vision cannot properly converge upon a point in space. As a result of this *fixation disparity*, monocular images of an object are thought to fall on non-corresponding points within Panum's fusional area (Ogle, 1950). With changes in vergence, fixation disparities can be quite profound, particularly when measured objectively (i.e., the exact deviation of the visual axes from bifoveal fixation is measured by photographing the position of the eyes; Fogt & Jones, 1998). Whereas a normal observer's stereoacuity tends to decline with increasing distance from the fixation plane (Badcock & Schor, 1985), there are individuals whose region of maximal stereoscopic sensitivity lies off the plane of fixation (i.e., are most sensitive to stimuli that are presented with standing disparity, known as a “depth pedestal”). It has been theorized that these observers exhibit such qualitatively different stereoscopic sensitivity as a result of a fixation disparity (Schumer & Julesz, 1984). Unfortunately, most authors correct for this abnormality by automatically localizing an observer's region of maximal stereoscopic sensitivity to the horopter, regardless of their actual findings (Krekling, 1974). Subsequently, as with overall stereoanomaly, prevalence rates for this apparent "misaiming" are unknown.

4. The Influence of Gender and Age on Stereoanomalies

Gender apparently has a negligible influence upon stereoacuity (Yap, Browne, & Clarke,1994; Rubin et al., 1997). In contrast, most studies have indicated age-related deterioration in stereoacuity, although the specific age at which this may occur and the rate of the subsequent decline vary considerably between studies. Comparison of the rate of the decline between studies is often difficult as a result of the small number of observers typically examined.

A list of studies which have tried to relate age to stereoacuity are summarized in Table 2. As should be evident from Table 2, most prior studies suffer from serious methodological flaws. One limitation common to all of these studies is an inability to isolate stereopsis as the sole cue to depth. As a consequence, an age-related change in "stereoacuity" may or may not involve a change in the ability to utilize several different cues for depth discrimination, only one of which is stereopsis. A problem which is also common to most of these studies is an inability to control for changes in visual acuity with age (e.g., by either matching observers or analyzing observers in groups of similar acuity). As a consequence, reported age-related changes in "stereoacuity" may merely reflect age-related changes in the optical properties of the eyes. In addition relatively few studies provided an actual estimate of stereo thresholds in arcsec; instead, most reported incidence of "failures" on a specific stereo test which were often administered at various distances to overcome deficits in visual acuity.

It is worth mentioning several features of earlier studies which are not summarized in

Table 2.

Authors	Method	Ages	N	Visual Acuity	Scoring	Other limitations	Conclusions
Allen 1964	Flashlight Diastereo test	"0-9 to 60+"	2070	measured, not controlled	pass/fail	many nonstereoscopic cues, fewer subjects >50 relative to younger ages	increased rate of stereo test failure over age 50
Baluyut & Hofstetter 1964	"optometrist report"	"0-9 to 80-89"	1000	not indicated, presumably not controlled	pass/fail	no methodological detail, presumably many nonstereoscopic cues	increased rate of stereo test failure over age 50
Jani 1966	Flashlight Diastereo test	"0-9 to 70-79"	1207	required 20/40 or better in each eye	pass/fail	many nonstereoscopic cues	increased rate of stereo test failure over age 50
Bell et al. 1972	modified Verhoeff stereopter	20-70	164	measured, not controlled	percentage correct detections	many nonstereoscopic cues	increased rate of stereo test failure over age 50
Hofstetter & Bertsch 1976	Diastereo test	8-46	242	required 20/20 or better in each eye	arcsec	many nonstereoscopic cues, no subjects > 46	no influence of age on stereoacuity
Greene & Madden 1987	RanDot test	17-25 vs. 60-75	24 24	measured, not controlled	arcsec	nonstereoscopic binocular cues	4 older Ss could not complete testing. No age related difference in stereoacuity in completely tested Ss

Table 2.(Con't)

Authors	Method	Ages	N	Visual Acuity	Scoring	Other limitations	Conclusions
Yekta et al., 1989	TNO test	10-65	187	not measured or controlled	arcsec	relatively few Ss in the 60-69 decade age group	all decade age groups have threshold between 57.2 & 60 arcs. No significant age effect
Wright & Wormald 1992	Frisby test	"65 to 80+"	728	measured, not controlled	pass/fail	many nonstreoscopic cues, inclusion of only older aged no younger aged controls	significant increase in the incidence of test failure with age
Rumsey 1993	4 different tests	40-60 68-87	20 50	measured, not controlled	pass/fail	used different tests at near" vs. "far" distances	older group shows significantly greater incidence of test failure at near and far distances
Brown et al. 1993	modified Howard-Dolman	21-70	41	required 20/20 or better in each eye	arcsec	many nonstereoscopic cues, low stimulus luminance selectively disadvantages older Ss	thresholds higher in the older (60-70) than in the younger (21-28,41-49, 51-59) age groups (mean of 27 vs 16 arcsec)
Rubin et al. 1994	RanDot Circles test	65-90	222	measured, not controlled	mild vs. moderate vs. severe impairment	contours evident with monocular viewing, no younger control group	41% of these older Ss had thresholds higher than 60 arcsec, 18% had thresholds higher than 140 arcsec

Table 2. (Con't)

Authors	Method	Ages	N	Visual Acuity	Scoring	Other limitations	Conclusions
Yap et al. 1994	modifed Howard-Dolman	21-67	35	required 20/20 or better in each eye	arcsec	many nonstereoscopic cues, low test stimulus contrast selectively disadvantages older Ss	mean threshold increased from 8.37 (20-29 years) to 11.21 arcsec (over age 50)
Rubin et al. 1997	RanDot Circles test	65-84	2520	measured, not controlled	arcsec	contours evident with monocular viewing, no young control group, median (not mean) values reported	median stereoacuity remains constant into mid 70s, the prevalence of "stereo-blindness" increases from 10% (60-65 years) to 26.3% (80-85 years)
Haegerstro-Portnoy 1999	Frisby test	58-102	900	measured, not controlled	arcsec	many nonstereoscopic cues, no younger controls	stereoacuity decreases with age. 60% of 60 year olds vs. 20% of 90 year olds have thresholds <85 arcsec

Table 2. The only information on stereoacuity provided by Allen (1964) was given in the form of a single figure that showed that between the ages of 9 and 50, between 1 and 3% of observers failed the Flashlight Diastereo Test; for observers between 50-59, this incidence rose to 5% and rose to 6% for observers identified as "60+." Jani (1966) also recorded the incidence of failure on the Flashlight Diastereo Test and found a statistically significant increase between the ages of 20 and 79. Hofstetter and Bertsch (1976), using the Flashlight Diastereo Test, found no trend with age. However, they did not examine any observers over the age of 46. Baluyut and Hofstetter (1964) reported the percentage of "fusion" failures. However, no clear indication of the methods used to test for fusion was given.

More recently, Bell, Wolf, and Bernholz (1972) also found a decline in stereoacuity beginning at the age of 50 using the Verhoeff stereopter. This test is a modification of the Howard-Dolman apparatus in which three bars were viewed, two of which were 2.5 mm from a third. The bars were then presented at 4 discrete distances from an observer and the number of correct identifications at each distance and at the four total distances was measured. They reported a monotonic decrease in performance with age. Two more recent studies from the same laboratory (Brown, Yap, & Fan, 1993; Yap, Brown, & Clarke, 1994) also used the Howard-Dolman apparatus and found a deterioration in stereoacuity first beginning in the 7th decade of life. These were among the few studies which actually controlled for the visual acuity of the different aged observers; and their results, which show a clear age-related deterioration in performance, rule out an obvious role for most "optical" changes in determining their conclusions. Unfortunately, the results of Yap, et al. may have been biased by the very low contrast of the test stimuli used (12.7%), which can differentially affect an older observer's performance (Sloane, Owsley, & Jackson, 1988). In addition, the Howard-

Dolman apparatus used in these two studies is particularly susceptible to non-stereoscopic monocular and binocular depth cues.

Wright and Wormald (1992) and Haegerstrom-Portnoy, Schneck, and Brabyn (1999) evaluated stereopsis in large samples of older adults using the Frisby Stereo Test. Wright and Wormald (1992) tested 728 observers reported to vary in age from 65 to 80+ and found that only 27% of the observers examined had full stereopsis, seeing all three plates, while 23% had no stereopsis. With groups split according to age: 65 to 69, 70 to 74, 75 to 79, 80+, a statistically significant trend ($p < 0.001$) was found. Additional analyses showed that only half of the 65 to 69 year-old group could pass testing with the finest stereo plate. In contrast, only one of the 51 young adults between the ages of 18 and 22 tested by Heron, Dholakia, Collins, and McLaughlan (1985) was unable to see the finest Frisby plate. Haegerstrom-Portnoy, Schneck, and Brabyn (1999) controlled the distance at which the Frisby test was administered; hence, they were able to obtain rough stereoacuity estimates (observers were classified according to whether they possessed enough stereopsis to permit them to pass the 340, 170, or 85 arcsec plate) on a sample of 900 observers from 58 to 102 years of age. Unfortunately, as stereopsis was only one of several visual tasks on which each observer was tested, they did not elaborate on their stereoacuity results in great detail. They did report that no observer younger than 60 had a stereoacuity threshold greater than 340 arcsec (i.e., failed all Frisby plates). They also found that approximately 5% of observers from 60 to 70 years of age, and 15% of observers from 70 to 75 years of age had thresholds higher than 340 arcsec. Approximately 95% of observers from 55 to 60 years of age had stereoacuity thresholds lower than 85 arcsec, while 70% of observers from 60 to 65 years of age had stereoacuity thresholds lower than 85 arcsec.

Studies which utilized polarizing lenses as a means to view stereograms have also generally found an age-related decline in stereoacuity. Greene and Madden (1987) used the Randot Stereo Test to examine two groups of 24 observers, one aged 17-25, the other 60-75. Four of the older age group and none of the younger age group were unable to perceive depth even in the coarsest of test stimuli (the exact amount of disparity contained in these stimuli was not given, although typically the coarsest stimuli on this task contain approximately 250 arcsec retinal disparity). When the older observers who could not perceive depth in even the coarsest plate were excluded from further analysis, there was a negligible difference in the mean acuity values for the two aged groups. Thus, the data may represent two different types of influences of age upon stereoacuity: the incidence of extreme stereo deficiency (which their data indicates) versus a quantifiable decrease in stereoacuity. On the other hand, it is also possible that observers in Greene and Madden's study who were unable to perceive depth with the coarsest of stimuli simply represent extreme cases of the more mild forms of stereo-impairment.

Two studies published by authors working in the same laboratory used the Circles Test of the Randot Stereo Test. Rubin, Roche, Prasada-Rao, and Fried (1994) tested 222 observers between 65 and 90 years of age. In this study, stereoacuity was only one of several measures examined; therefore, the results of stereoacuity assessment provided by the authors were cursory at best. The number of observers with thresholds higher than 60 arcsec was 41%, while 18% of the observers had thresholds higher than 140 arcsec. Unfortunately, many of their observers had "ocular disorders" such as cataracts, macular drusen, or glaucoma. While observers were allowed to wear corrective lenses, no minimal value for visual acuity was required for participation. Therefore, their results are difficult to interpret. A later study by Rubin et al. (1997) measured visual changes in a population of 2520 observers ranging in age from 65 to 84. Again, they did not control for visual acuity, and median as opposed to mean scores were reported, although the distribution did not appear to be symmetrical. They found that 10% of observers aged 60 to 65 and 26.3% of observers aged 80 to 85 had stereoacuity thresholds greater than 450 arcsec. However, median stereoacuity scores remained constant with age up to the middle 70s.

Yekta, Pickwell, and Jenkins (1989) used the TNO test to measure stereoacuity in 187 observers ranging in age from 10-65 and found no difference in mean threshold among 10-19 (57.20 arcsec), 20-29 (57.95 arcsec), 30-39 (59 arcsec), 40-49 (58.28 arcsec), 50-59 (58.84 arcsec), and 60-65 (60 arcsec) year-old groups. There are at least two possible reasons for their failure to find any age-related change in stereoacuity. First, their age samples were not equal. That is, they only studied 7 observers aged 60-69, while every other group contained between 26 and 45 observers. Second, all observers were reported to have "good" visual acuity in each eye, although a precise definition of "good" was not reported.

To summarize, most of the studies referred to above indicate some age-related deterioration in depth discrimination which is most obvious when comparing results from observers who are over the age of 60 with younger age-groups. This result is obtained in two (Brown, Yap, & Fan, 1993; Yap, Brown, & Clarke, 1994) of the three studies which adequately controlled for age-related changes in visual acuity. Unfortunately, there are a sufficient number of methodological problems with these studies such that a quantitative definition of stereo-impairment is difficult, if not impossible.

Purpose of the Present Study

The present study investigated age-related changes in stereoacuity in a large sample of male and female observers ranging in age from 15 to 79. All observers had corrected visual acuity greater than 20/30 in each eye. The experimental procedure used tachistoscopically presented random-dot stereograms which completely eliminated contamination by cues for depth other than retinal disparity. In addition, specific stimulus characteristics and the use of a forced choice staircase procedure permitted measurement of stereoacuity at many different planes of fixation. Therefore, a reliable measure of stereoscopic acuity could be obtained at many different planes of fixation for male and female observers of all ages. The results clarify several previously unresolved issues pertaining to the stereopsis literature:

1. They provide normative stereoacuity data in a carefully chosen population of observers with normal visual acuity using a technique that definitively ruled out the involvement of non-stereoscopic depth cues. These norms permit an archival description of variation of stereoacuity in a non clinical population and, hence, provide a reasonable definition of stereo deficiency.
2. They definitively show that aging has two influences upon stereopsis. Stereoacuity gradually decreases with age, but in addition, the incidence of extreme stereo deficiency increases markedly beginning in the 7th decade of life.
3. The results show that stereoacuity, defined as the minimum horizontal retinal disparity leading to a perception of depth based upon stereopsis, is not influenced by gender.
4. They provide, for the first time, normative data related to the incidence and type of fixation disparities.

Chapter 2

Methods

Overview

The overall goal was to measure variation in stereoscopic vision of both male and female observers of varying ages having unimpaired Snellen visual acuity. Several precautions were taken to ensure that discrimination of relative depth depended solely upon retinal disparity. Vergence eye movements can provide potent cues for depth (Mon-Williams & Tresilian, 1999). Since the latency of vergence eye movements is approximately 150 milliseconds (ms) (Westheimer & Mitchell, 1969), stimulus exposure was limited to 100 ms. Additionally, experience with random-dot stereograms (RDS) is known to influence an observer's sensitivity (O'Toole & Kersten, 1992). Most potential observers had not been exposed to RDS, and therefore, it was necessary to provide experience with tachistoscopically exposed RDS of decreasing duration prior to presentation of 100 ms stimuli to familiarize them with the task. Furthermore, to assess sensitivity to increments of depth some distance in front of or behind the plane of fixation, 11 different levels of standing retinal disparity were utilized. Although stereoacuity is usually optimal at the plane of fixation, some individuals are anomalously more sensitive to change in depth superimposed upon a fixed level of crossed or uncrossed disparity (i.e., presented on a *depth pedestal*) (e.g., Fogt & Jones, 1998). Since the standing level of disparity was varied randomly from trial to trial, this also made it impossible for observers to develop a response set to one specific depth plane.

The procedure described below took about one hour for most observers who completed all aspects of testing. The protocol for this experiment was approved by the

Queens College Committee for the Protection of Human Observers and adheres to all guidelines for human experimentation established by the National Institutes of Health.

Population of Observers

Approximately 10 male and 10 female observers in each of the age decades 20-29, 30-39, 40-49, 50-59, 60-69, and 70-79 were examined. Observers were unpaid with the exception of some elderly (age 60s and 70s) observers who were paid $10 to cover the cost of their transportation. All but three of the observers had at least a high school education, none were noticeably cognitively impaired. The results reported below show that education level negligibly influenced stereoscopic sensitivity.

During initial data collection (prior to May 27, 1998), no experimenter was present during testing procedures which were entirely computerized. At that time, many of the younger observers had very high (i.e., >1000 arcsec) stereoacuity thresholds; such gross stereo-impairment was exceedingly rare among the observers tested between 33-55 years of age. This surprising finding appeared to have been likely caused by a strategy that was adopted by many of the younger observers, i.e., random responding without attending to the stimuli to minimize the time it took to complete experimentation and the course requirement. The incidence of such high stereoacuity thresholds dramatically decreased when the experimenter (always the author) remained in the room during testing. For these reasons, the examiner was present at all times during all aspects of data collection with all observers after May 27, 1998. Additionally, prior to May 27, 1998, less stringent visual acuity criteria for participation were in place (i.e., 20/40). The visual acuity criteria for experiment participation subsequently adopted (20/30) eliminated observers' complaints of difficulty viewing test stimuli. The following observers were not included in data analysis for the two reasons mentioned above: age 80 to 89 = 1 observer; age 70 to 79 = 4; age 60 to 69 = 7; age 50 to 59 = 10; age 40 to 49 = 5; age 30 to 39 = 14; age 20 to 29 = 22; age 17 to 19 = 19.

As a consequence of the foregoing anomaly, results from this thesis consist of an analysis of data drawn from two overlapping populations. Population 1 contains all observers tested after May 27, 1998, and approximately adheres to the original number of observers desired in each age-gender group. For a variety of different reasons, data was sometimes obtained from more than 10 observers in the various age/decade groups. Data was also obtained from a few observers younger than 20 years of age. Population 1 was used to obtain normative, age-related data. The incidence of cases in which individuals showed superior sensitivity to changes in perceived depth at non-zero (rather than zero) retinal disparity values is shown in Population 2; which consists of all observers tested with 100 ms duration stimuli who had optimal stereoacuity values less than 114 arcsec (the upper limit of what is defined here as "stereo normal"), regardless of whether they were tested before or after May 27, 1998.

Apparatus

All stimuli used to assess stereoacuity were presented by means of "VisionWorks 2," a hardware/software package sold by Vision Research Graphics, Inc. (VRG) located in Durham, NH. This device is capable of presenting an extremely large variety of visual stimuli with 32-bit control over stimulus luminance. Stimuli were presented on a cathode ray display specifically designed for the purposes of the current study by VRG: a 19" monochrome cathode ray display with a P46 phosphor with a refresh rate of 120 hz, a display resolution of 1024 x 512 pixels, and a maximum luminance of 80 cd/m^2. The wavelength distribution of this phosphor is such that brighter stimuli appeared a greenish white to observers with normal color vision. For most testing, the image was limited to the central area of the screen to minimize nonlinearities, maintain image geometry, and maximize luminance uniformity. In addition, a GC Electronics (Rockford, IL) degaussing coil was used periodically to demagnetize the cathode ray display.

In a Wheatstone type stereoscope, stereoscopic viewing is achieved by presenting a different visual stimulus to each eye (for a comprehensive review see Hubel, 1987). VRG achieves this end using a procedure referred to as the "field-sequential" or "time-multiplexing method" of stereoscopic presentation (Patterson & Martin, 1992). Accordingly, two sets of images were alternately presented at a frequency of 60 Hz. This alternation of stimuli on the display occurred in tandem with the "opening" and "closing" (i.e., the alternation of optical density from low to high) of a set of liquid crystal shutter glasses. Taking into account the high flicker rate, the dim illumination level used in the testing room (which is well known to reduce critical flicker frequency), the ultra-short persistence of the P46 phosphor tube, and the large (approximately 1 log unit) change in optical density provided by the shutter glasses, each eye was presented a distinct stimulus which appeared to the observer to be simultaneous. The difference in stimuli presented to each eye can readily be appreciated by any individual with normal binocular vision by having him/her view the same sort of stimulus used in experimentation without the shutter glasses present (in which case he/she sees a blurry stimulus), viewing the stimulus with the shutter in place and both eyes viewing the stimulus (in which case he/she experiences striking depth), or viewing the stimulus with the shutter glasses in place but one eye or the other eye closed (in which case he/she sees non-blurred random-dot pattern providing no hint of any depth effect).

Procedure

1. Non-Stereoscopic Testing Procedure

Prior to experimentation, all observers were naive regarding the experiment save that it had something to do with aging and vision and involved being tested with an elaborate computerized procedure. All observers were asked to sign an informed consent form and complete a brief questionnaire involving biographical information (e.g., information about name, age, gender, level of education), any past or present history of eye disease, and the use of corrective lenses. In order to maintain confidentiality, each observer's data were encoded by an alphanumeric sequence known only to the author and research sponsor. Snellen acuity was then assessed with corrective lenses in place if necessary. Individuals not having 20/30 (6/9) acuity or better in each eye separately were at this point excluded from the study. Individuals with past or current history of eye disease were also excluded from participation. Observers with poor visual acuity or a history of eye disease were excluded because deficits in visual acuity which could degrade perception of the test stimuli could in turn affect stereoacuity (Levy & Glick, 1974).

Interpupillary distance was then measured with a millimeter ruler. The determination of interpupillary distance was at first deemed necessary since stereoacuity depends upon interpupillary distance (e.g., Howard & Rogers, 1995). That is

$$\text{stereoacuity} = a\Delta d/d^2,$$

where a is the interpupillary distance, Δd is the depth difference, and d^2 is the square of the viewing distance (Howard & Rogers, 1995). While there is a degree of error when computing interpupillary distance in this manner, the mean value obtained, 64 mm, agrees with values in the literature (Woodson, 1981). In fact, interpupillary distance was not factored into the stereoacuity values obtained since the range of values of a was 9 mm and symmetrically distributed around the mean value. According to formula (1) above, this means that the most deviant score from the mean would involve an error of less than 10% in stereoacuity value. Such an error is smaller than the magnitude of the effects and is of negligible concern.

2. Initial Stereoscopic Testing Procedure

All subsequent data collection took place in a dimly lit room with an ambient luminance level of 0.05 cd/m^2. As indicated above, the ambient illumination was used to reduce sensitivity to flicker. The observer viewed the stimulus display at a distance of 1 meter (m), a distance involving relatively little optical challenge for most observers, regardless of age and optical correction. No device was employed to stabilize the position of each observer's head because head movements would not provide depth cues with a stimulus exposure of only 100 ms. Nonetheless, observers were instructed to limit head movement as much as possible. In addition, each observer was asked to use his/her personal spectacle corrective device (if necessary) to optimize sensitivity at this viewing distance. The observer was then fitted with the liquid crystal shutter spectacles provided by the VRG apparatus which could easily fit over prescription glasses if worn.

After the observer became accustomed to the dim light, a random-dot stereogram was presented consisting of dots 0.04° (width) by 0.02° (height) in size, with an individual dot luminance of 60 cd/m^2 for green dots and 0 cd/m^2 for the black dots. Mean luminance was thus 30 cd/m^2 (3.0 cd/m^2 through the glasses), while contrast was 100%. Dot density was 6.32%. To a normal individual, the stereogram appeared to be a corrugated grating consisting of three wave-shaped cycles with three parallel "mountains and valleys" which were contained in a circular-shaped window with a diameter of 11.37°. This grating was presented for as long a time period as desired by the observer with a space averaged overall uncrossed disparity of 33.43 minutes of arc at a spatial frequency of 0.25 cycles per degree. The word "demo" was superimposed upon this grating. Observers were asked to describe their perception of the grating to indicate whether stereoscopic depth was perceived. Additionally, to allow observers to become familiar with the test stimuli in a condition with minimal task demands, no fixation point was provided with the demonstration stimulus. The three-dimensional position of the word "demo" could be changed by experimenter and/or observer by adjustment with a special "three-dimensional track ball" provided by VRG, which was also used in later phases of experimentation: the two-dimensional position of "demo" was adjusted with the position of a conventional track ball, while its apparent depth was controlled by a separate adjustable "wheel." Thus, either the observer could be asked if the word "demo" appeared to be moving and in what direction if adjusted by the experimenter, or the observer could be asked to set the word "demo" on the "bottom of a valley" or "top of a mountain." No further testing took place with observers who had difficulty viewing the grating and the three-dimensional motion of the word "demo." Although it is possible that such observers had some residual stereoscopic vision, they had to be markedly stereoscopically impaired. These observers comprise part of Population 1.

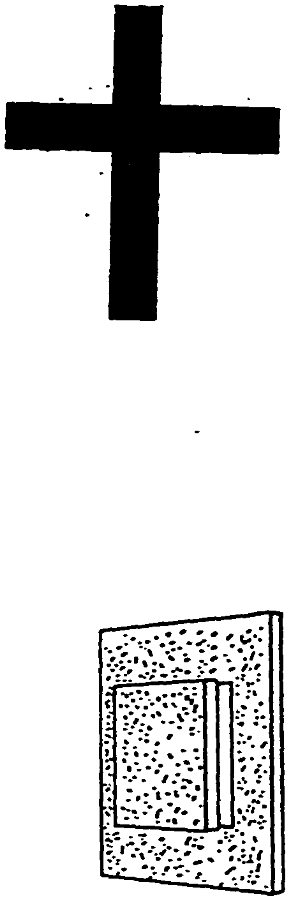
Formal Stereoscopic Testing Procedure

1. Description of Stimuli

Subsequently, more formal experimentation involved a much different series of RDS which were presented tachistoscopically. During time periods when a RDS was not present, the stimulus monitor was blank or had a fixation cross described below (see Figure 3). The

Figure 3. An observer first viewed a fixation cross (A), presented for 250 ms, with a mean luminance of 3 cd/m^2 accompanied by a brief tone. Simultaneous with extinction of the fixation cross, a random-dot stereogram was presented (B) for 100 ms consisting of a large, rectangular shaped random-dot stereogram (i.e., the pedestal stimulus) which was 5.57° (width) by 4.8° (height) and presented at 11 different, randomly chosen retinal disparity values. A second, smaller rectangle, 2.78° (width) by 2.28° (height) (i.e., the test stimulus) was presented in the center of the pedestal stimulus at a different disparity. Both test and pedestal stimuli consisted of green and black dots in 50/50 percentage, measuring 0.06° (width) by 0.05° (height). Green dot luminance was 3 cd/m^2 while the luminance of the black dots was 0 cd/m^2.

After the stimulus disappeared from the screen, the observer was permitted an unlimited amount of time to determine the relative positioning of the two stimuli and indicate their choice on a trackball. The observer indicated whether the central square appeared to "pop out" in front of the larger surrounding square or appeared to "form a hole" in the larger surrounding square. With a correct response, the fixation cross would reappear 0.25 seconds after the observer's key press and the next trial would begin. With an incorrect response, three brief tones sounded and the fixation cross reappeared with a one second delay following the observer's keypress. During the sequences between the disappearance of the stimuli from the screen and the appearance of the next stimulus, a blank screen was displayed with a mean luminance of 0 cd/m^2. (Stereogram from Julesz, 1971).



A random-dot stereogram. The two halves are identical, except that a central subset of dots has been shifted laterally. (The middle panel outlines the section of shifted dots.) This lateral displacement creates retinal disparity and, thus, stereoscopic depth (bottom panel). (Stereogram from Julesz, 1971.)

RDS consisted of greenish and black "dots" in 50/50 percentage. These "dots" were, in fact, 0.06° (width) by 0.05° (height) in size; the luminance of the green dots was 60 cd/m^2. Luminance of the black dots was 0 cd/m^2. Mean luminance was therefore 30 cd/m^2 (3 cd/m^2 through the stereoscopic glasses) and contrast was 100%.

The tachistoscopically presented stimulus consisted of two rectangles. A larger, rectangular shaped RDS which was 5.57° (width) by 4.8° (height) was presented at 11 different, randomly chosen retinal disparity values: 55, 44, 33, 22, 11, or 0 arcmin of either crossed or uncrossed disparity. This rectangle is referred to below as the *pedestal stimulus*. Hence, depending upon this level of disparity, the *pedestal stimulus* appeared "in front of" or "behind" the depth plane of the fixation cross. A second, smaller rectangle, 2.78° (width) by 2.28° (height), referred to as the *test stimulus,* was presented in the center of the *pedestal* stimulus at a different disparity. Thus, observers with normal binocular vision who could perceive depth viewed a smaller *test stimulus* rectangle surrounded by the larger, *pedestal stimulus* rectangle. The *test stimulus* either appeared to "pop out" in front of the *pedestal stimulus*, or the *test stimulus* appeared to recede into the screen forming a "hole" in the large surrounding *pedestal stimulus.* Once again, with either the left or right eye closed, the observer merely perceived a flat screen containing random green and black dots.

2. Psychophysical Procedure

The three buttons on the VRG trackball were used by the observer to signal his/her perception of the stimulus to the computer, and additionally determine the time of onset of the next stimulus. The following instructions were given to the observer prior to each trial: "the cross you see in the center of the screen will disappear. You will then see two squares; a larger surrounding square here, and a smaller square in the middle. The smaller central square will appear to either pop out in front of the larger surrounding square, or it will appear to form a hole in the larger surrounding square. If the central square appears to pop out in front of the larger surrounding square, press the left button. If the central square appears to form a hole in the larger surrounding square, press the middle button. If you are unable to tell the difference, press the button on the right, which is the retry button. You may only press the retry button once. If after pressing the retry button once, you are still unable to tell the difference in the squares, guess and then go onto the next one. Although the squares will only flash on the screen for a short period of time, you have as much time as you need to make your choice by pressing the button. The next square will only come on the screen after you have made your choice for the last square."

Thus, the observer was instructed to depress the left button if the *test stimulus* appeared behind the *pedestal stimulus*, the middle button if it appeared in front: the right, "retest" button was to be depressed if the observer could not discern the relative depth of the two stimuli. Individuals were only allowed to depress the "retest" button once; if still unable to discern relative depth of the two stimuli, they were instructed to guess and proceed to the next trial. A subsequent stimulus presentation always occurred 0.25 seconds after the observer made his/her choice.

Trials with 2 s, 500 ms, and 200 ms duration stimuli served to familiarize observers with random-dot stereograms and to allow them to practice responses on the trackball. After testing was begun, observers were allowed to rest whenever and for however long they required. However, on no occasion did an observer rest for longer than 1 minute.

In any series of stimulus presentations, trials began with the presentation of a fixation cross, which appeared for 0.25 seconds and was accompanied by a brief tone. Simultaneous with extinction of the cross, the stimulus (the test and pedestal rectangles) appeared for one of the four durations described below. If the observer's choice was correct, the fixation cross would reappear 0.25 seconds after the observer's key press and the next trial would begin. With an incorrect response, three brief tones sounded and the fixation cross reappeared with a one second delay following the observer's keypress. During the sequences between the disappearance of the stimuli from the screen and the appearance of the next stimulus, a blank screen was displayed with a mean luminance of 0 cd/m^2. After the stimulus disappeared from the screen, the observer was permitted an unlimited amount of time to determine the relative positioning of the two stimuli and indicate his/her choice on the trackball. Additionally, although the stimulus had a specific exposure time, observers were informed that because their keypress would initiate the next trial, they could control the rate of stimulus presentation by delaying their responses. Informing observers that the rate of stimulus presentation was controlled by their responses, served to prevent observers, particularly those in the older age groups, from becoming overwhelmed by the speed of the stimulus presentation.

Four series of experiments, each differing in stimulus duration, were used to collect data according to a forced-choice staircase method. If the observer's keypress indicated a correct response, the difference in the retinal disparity between *test stimulus* and *pedestal stimulus* was reduced in 0.04 log unit steps. With an incorrect response, the relative disparity between the two objects was increased by four 0.04 log unit steps. While the disparity between the *test stimulus* and *pedestal stimulus* changed as such, the direction (i.e., crossed or uncrossed retinal disparity) of the disparity between the *test stimulus* and *pedestal stimulus* also changed randomly from trial to trial. Additionally, after each trial, the disparity of the *pedestal stimulus* itself was randomly changed.

For initial trials, stimulus duration was 2 s 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 of 500 arcseconds relative to that of the *pedestal stimulus.* If it became clear after a few minutes (as was the case with most observers) that the observer could make such discriminations, this particular "run" of data collection was interrupted. Under the relatively rare circumstance when an observer could not readily make such discriminations, data collection proceeded as specified below for the other stimulus durations, or terminated after approximately 10 minutes; in either of these two unusual circumstances, the experiment was then terminated.

If (as was the case with most observers) performance was satisfactory with 2 s duration stimuli, a similar procedure was then used with 500 ms duration stimuli, save that the *pedestal stimulus* 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 a different dot size was used. With stimuli less than 2 s in duration, dots were 0.15° (width) by 0.18° (height), with a luminance of 30 cd/m^2 (3.0 cd/m^2 through the glasses). The particular size of the dots (and as a result, dot density and numerosity) was chosen on the basis of preliminary experimentation with three laboratory members well practiced in viewing stereoscopic RDS and several naive observers. That is, although the salience or perceived "reality" of the depth effect achieved with RDS is much greater with smaller sized dots (which consequently increases dot density per unit area), lower stereoacuity thresholds were produced with the dots used than with either larger or smaller dots. This value roughly corresponds to values reported in the literature (Uttal et al., 1975). Once again, if after a few minutes the observer could make such discriminations, the 500 ms "run" of data collection was also interrupted; otherwise, data collection continued as specified for the shorter duration stimuli below. Then, the successful observer repeated the same procedure with 200 ms and finally 100 ms duration stimuli.

For the 200 and 100 ms duration stimuli, reversals were used to obtain mean thresholds at each of the pedestal disparities. Each initial incorrect response at a specific pedestal was counted as a reversal. The first correct response after that initial error at that particular pedestal was marked as the second reversal. The next incorrect response at that pedestal was counted as a third reversal, and this continued until the specified number of reversals was achieved at each particular pedestal. For 200 ms duration stimuli, 6 reversals occurred at each individual pedestal. A threshold was obtained by taking the mean of the values at each of the last 4 reversals. For 100 ms duration stimuli, testing proceeded until 10 reversals occurred at each individual pedestal. The number of reversals with 100 ms stimuli was increased in order to further ensure the reliability of the data and eliminate practice effects. The "Visionworks" apparatus recorded every key press as well as the latency of the response (in ms) to make this response. In general, the first four presentations of the 100 ms stimulus were taken to be practice and the data presented in the results section below are the mean of the last 6 reversals obtained with a particular *pedestal stimulus*. For both the 200 and 100 ms duration stimuli, the observers' thresholds were typically based on reversals made after several hundreds to thousands of individual responses.

Additional testing was also conducted in order to determine if an age-related reduction in stimulus luminance (owing to senile meiosis) was the cause of any age-related deterioration in stereoacuity. Thus, three younger observers (age 25, 29, and 31) were tested with normal stimulus luminance and stimulus luminance reduced by 75%. Stimulus contrast was 100%

in all conditions, and thus no testing was conducted with contrast altered.

The testing procedure provided three types of measures used to compare results from different groups. First, with 100 ms duration stimuli, the lowest stereoscopic threshold value obtained, regardless of the *pedestal stimulus* value at which it occurred, was used to compare the different individuals in Population 1. Second, with 100 ms duration stimuli, the specific *pedestal stimulus* value producing this minimal threshold value was used to compare the different individuals in Population 2. Third, an ordinal measure was obtained distinguishing different observers who were unable to satisfactorily complete all aspects of testing: all observers making up Population 1 were put into ordinal categories indicating which procedure they failed to complete: failure to see the "*demo*," failure to complete 2 s testing, failure to complete 500 ms testing, failure to complete 200 ms testing, failure to complete 100 ms testing, and finally, no failure.

Chapter 3

Results

PART I: GENERAL CONSIDERATIONS

A. Overall Organization of the Results

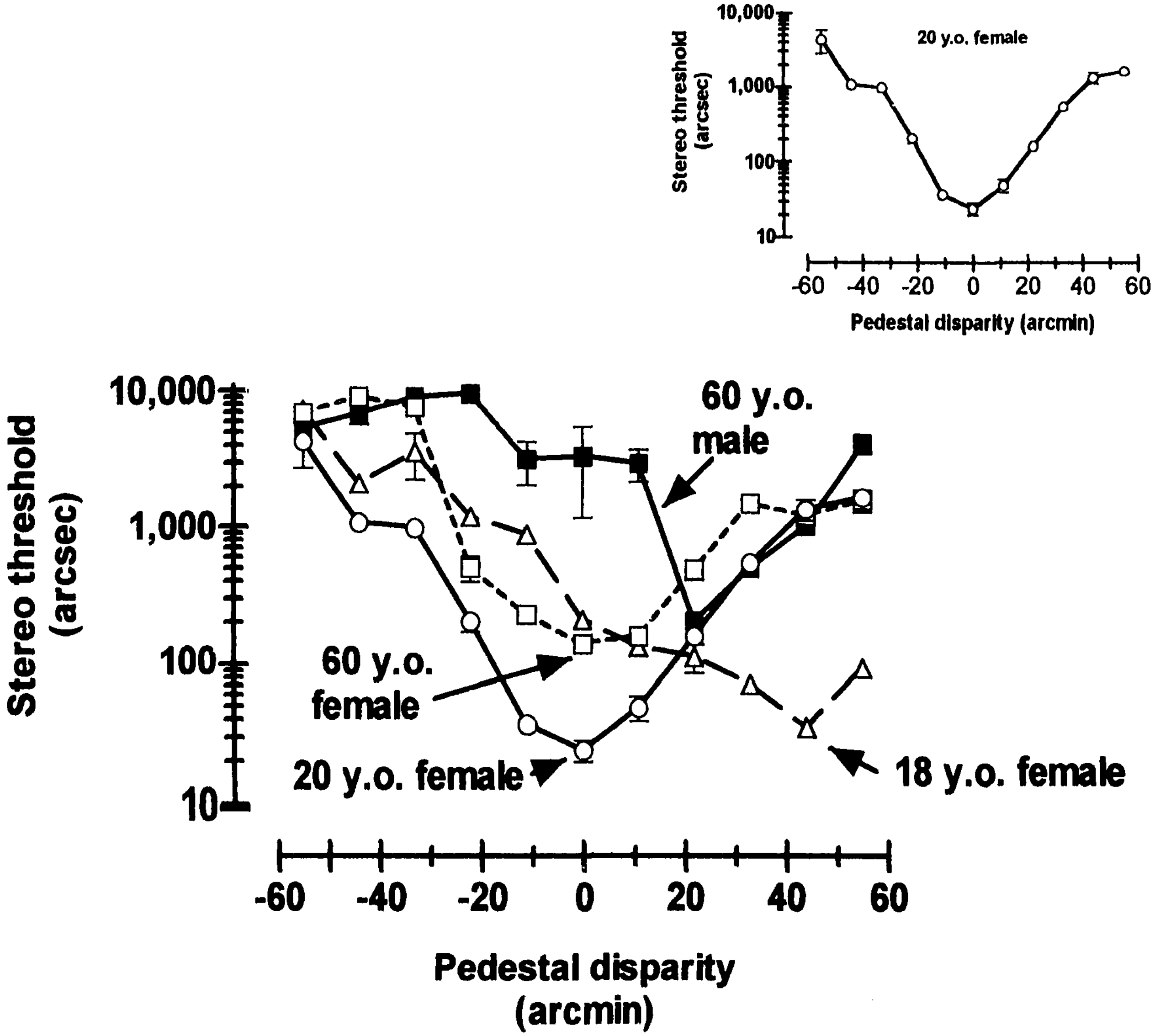
Population 1 was used to characterize the optimal stereo threshold value. Because of their archival value, some data from all observers in Population 1 who completed testing with 100 ms stimuli are listed in tabular fashion in Appendix A. This list includes a code to identify each individual observer followed by his/her gender, age, mean stereoacuity threshold at each of the 11 pedestal values, and an indication of whether this observer was also included in Population 2. Appendix B lists some results (i.e., stereoacuity values from trials the observers were able to complete, or the stimulus duration at which the observer could not meet criteria) from the 25 observers included in Population 1 who could *not* complete testing with 100 ms stereograms. Critical features of data summarized in Appendices A and B are analyzed in detail in Part II of this results section.

Population 2 was used to characterize the incidence of fixation disparity. Because of the archival nature of these data, they are presented in Appendix C, which includes a code to identify each individual observer followed by his/her gender, age, mean stereoacuity threshold at each of the 11 pedestal values, and an indication of whether this observer was also included in Population 1. Critical features of data summarized in Appendix C are analyzed in detail in Part III of this results section.

B. Stereoacuity Function Obtained with 100 ms Stimuli

The upper portion of Figure 4 displays results obtained from a 20 year-old female

Figure 4. Mean stereo threshold in arcsec (±1 standard error) for detecting a 2.78° x 2.28° rectangular test stimulus presented for 100 ms is plotted with logarithmic spacing as a function of pedestal disparity (varied in 11 arcminute steps from 55 arcmin uncrossed to 55 arcmin crossed) of a 5.57° x 4.8° rectangular pedestal. Negative pedestal values indicate uncrossed retinal disparity while positive or unsigned values indicate crossed retinal disparity. Stereoacuity functions were obtained with a forced-choice staircase procedure. Observer #04228f20, a 20 year-old female (top plot) is presented. Mean stereo threshold is similarly plotted for observer #04228f20 and three other observers (bottom plot).


10,000
1,000
100
10
Stereo threshold (arcsec)
20 y.o. female
-60
-40
-20
0
20
40
60
Pedestal disparity (arcmin)
10,000
1,000
100
10
Stereo threshold (arcsec)
60 y.o. male
60 y.o. female
20 y.o. female
18 y.o. female
-60
-40
-20
0
20
40
60
Pedestal disparity (arcmin)

observer using 100 ms duration stimuli. Mean stereo threshold in arcsec (±1 standard error) is plotted with logarithmic spacing as a function of pedestal disparity (in arcmin). In this figure and throughout this *Results* section, negative pedestal values indicate uncrossed retinal disparity while positive or unsigned values indicate crossed retinal disparity. As is the case for about half of the observers examined (see below), lowest thresholds were obtained with zero pedestal disparity; thresholds increased with increasing crossed or uncrossed disparity.

Several features of these data should be noted. Firstly, although results from the majority of observers had a clear minimum, functions from most are not quite as symmetrical as those for the observer illustrated in Figure 4. Secondly, the validity of the testing procedure was assessed in several mock experimental sessions by randomly pressing either the "closer than" or "further than" response button (as described in the *Methods* section) without viewing stimuli: resulting "threshold values" were never less than 1000 arcsec, but were often between 1500 and 2500 arcsec. For this reason, "real data" involving threshold values exceeding 1000 arcsec were not analyzed.

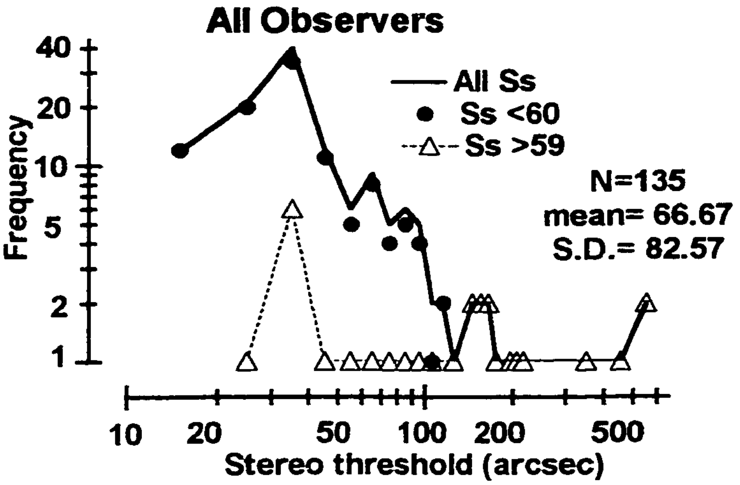
The lower portion of Figure 4 replots the same results from observer #04228f20, but superimposes them upon comparable data obtained from three other observers to illustrate ways in which stereoacuity functions varied between observers. The two features that were used to characterize these functions were the ordinate (threshold) and abscissa (pedestal disparity) values of the nadir. The results plotted with open triangles were obtained from an 18-year-old female (#05078f18): the minimal threshold value obtained, 35 arcsec, is slightly greater than that from #04228f20. However, the optimal stereoacuity threshold for observer #05078f18 (i.e., 35 arcsec) was obtained with a crossed disparity pedestal of 44 arcmin. The other two sets of data were obtained from 60-year-old male and female observers. In these particular cases, the female (#04228f60) is most sensitive with a zero disparity pedestal while the male (#09159m60) is most sensitive with a crossed disparity pedestal of 22 arcmin. The nadir of the functions from these two older observers is considerably greater than 100 arcsec. This increase in threshold value with age is consistent with results from previously reported studies, as noted in the *Introduction* section. The data obtained from observer #09159m60, a 60-year-old male, showed greater variability than results from the other three observers. Although never formally analyzed, data from many of the older observers showed more variability than was typical for that of younger observers.

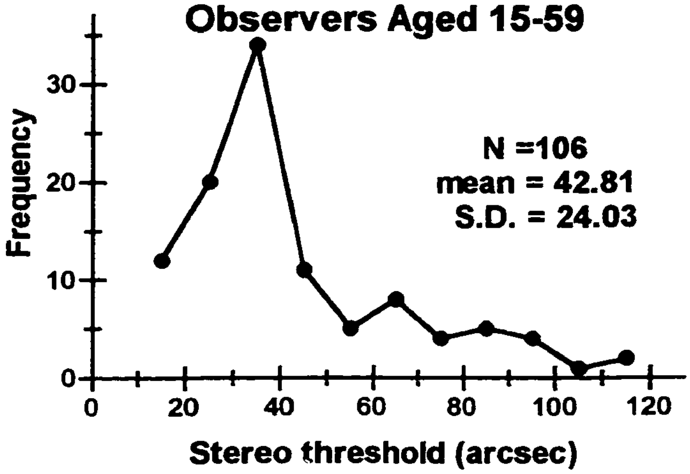
PART II: VARIATION IN OPTIMAL STEREO THRESHOLDS IN POPULATION 1

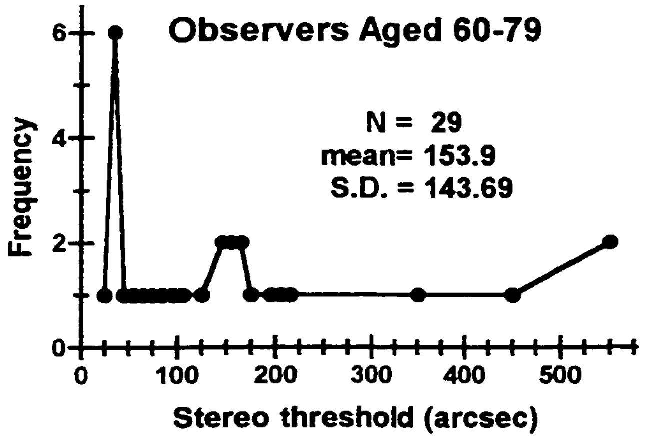
A. Normative Description of Stereoacuity in the General Population

The top set of frequency histograms in Figure 5 portrays optimal stereoacuity thresholds from the 135 observers comprising Population 1 who were able to complete testing using the 100 ms duration stimuli. All three plotted functions show the frequency of values which fall within a 10 arcsec window (i.e., between 10-19, 20-29, 30-39, etc.) as a function of the stereoacuity threshold value as plotted on logarithmic coordinates. The function plotted with heavy solid lines without symbols represents data from all 135 observers: the mode (i.e., most common stereoacuity threshold value) is between 30 and 39 arcsec. However, this function is positively skewed with a "tail" extending considerably to the right to very high threshold values (i.e., > 100 arcsec). The extent of this skew is evident even with logarithmic spacing on the abscissa and is also evidenced by the much larger value for the standard deviation (82.57 arcsec) than the mean (66.67 arcsec); additionally, the mean is markedly greater than the mode or median (both of which fall between 30-39 arcsec). Most

Figure 5. Optimal stereoacuity thresholds (in arcsec) from the 135 observers comprising Population 1 who were able to complete testing using the 100 ms duration stimuli (top plot). The function plotted with heavy solid lines without symbols represents data from all 135 observers. The three plotted functions show the frequency of values which fall within a 10 arcsec window (i.e., between 10-19, 20-29, 30-39, etc.) as a function of the stereoacuity threshold value as plotted on logarithmic coordinates for all observers (top plot), observers between the ages of 15 and 59 (middle plot), and observers between the ages of 60 and 79 (bottom plot).


All Observers
— All Ss
● Ss <60
--△-- Ss >59
N=135
mean= 66.67
S.D.= 82.57
Frequency
40
20
10
5
2
1
10
20
50
100
200
500
Stereo threshold (arcsec)


Observers Aged 15-59
N =106
mean = 42.81
S.D. = 24.03
Frequency
30
20
10
0
0
20
40
60
80
100
120
Stereo threshold (arcsec)

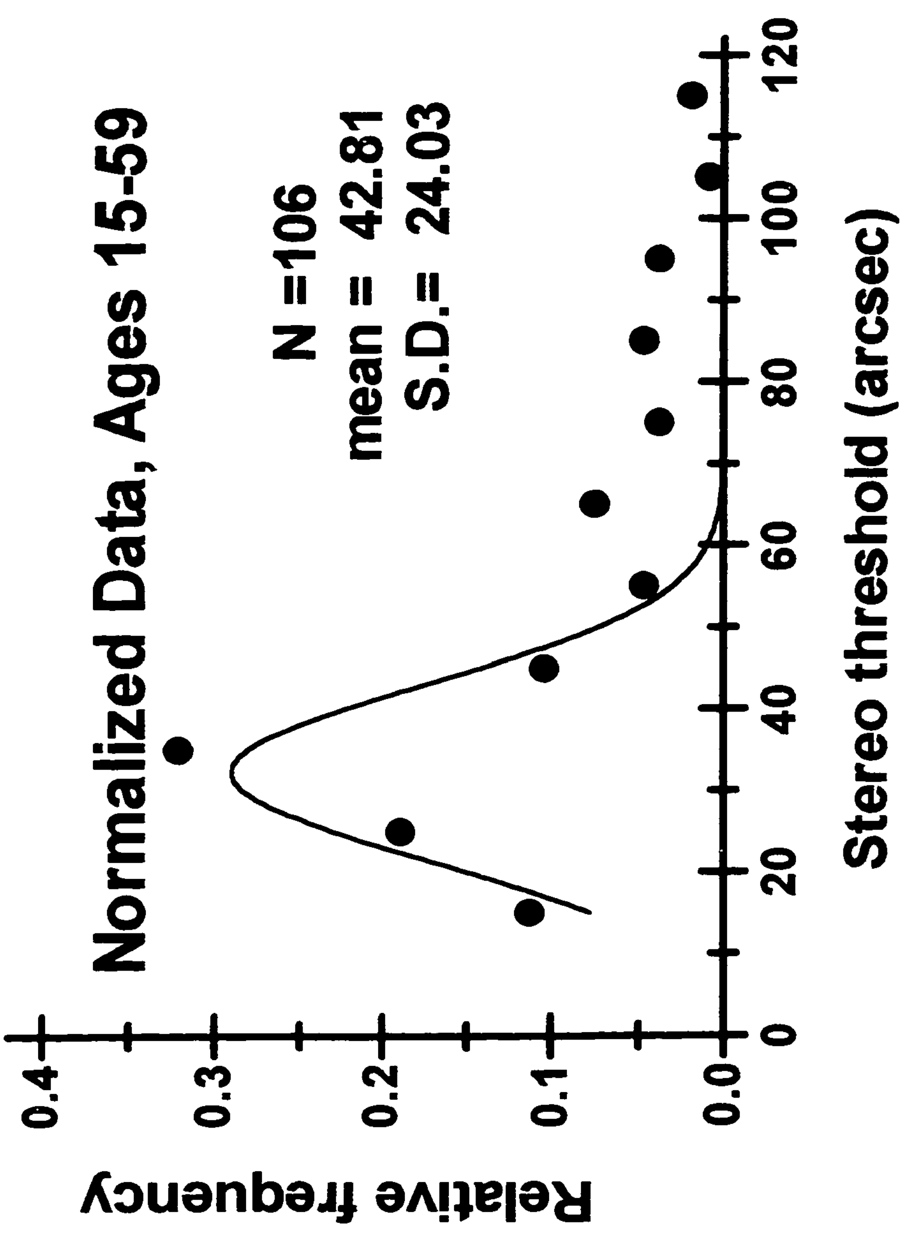

Observers Aged 60-79
N = 29
mean= 153.9
S.D. = 143.69
Frequency
6
4
2
0
0
100
200
300
400
500
Stereo threshold (arcsec)

of the very high stereoacuity threshold values were obtained by observers between 60 and 79 years of age. That the highest thresholds were obtained by observers age 60 or over can be seen by examining separately the frequency of scores for observers less than 60 years of age (closed circles), and for observers greater than or equal to 60 years of age (open triangles): the absence of a symbol indicates that no observer had thresholds falling within the indicated 10 arcsec window. Clearly, the highest thresholds were obtained by older observers.

To further illustrate the influence of age, the middle and bottom sets of data in Figure 5 plot respectively on linear coordinates, the distribution of stereoacuity thresholds for all observers in Population 1 who were less than 60 years of age, or between 60 and 79 years of age. The mode of both data sets falls within the 30-39 arcsec window and both of these functions are skewed to higher threshold values. However, the extent of this skew is much greater for the older than younger observers. In addition, both the mean and standard deviation of the data for the group of older observers (153.9 arcsec and 143.69 arcsec, respectively) are grossly larger than for the younger group of observers (42.81 arcsec and 24.03 arcsec, respectively). The influence of age on stereoacuity is considered in more detail below.

The mean value for stereoacuity for observers age 60 or older (mean = 153.9 arcsec; standard deviation = 143.69 arcsec) fell in a range generally acknowledged as indicative of stereo-impairment. For this reason, normative data, as represented by values obtained in the current study, were established using stereoacuity values from observers younger than 60 years of age. As a first step in establishing norms for stereoacuity, the middle set of coordinates in Figure 5 is replotted in Figure 6 according to relative frequency. This plot clearly shows that for younger observers this distribution is markedly positively skewed and,

Figure 6. Relative frequency of values which fall within a 10 arcsec window (i.e., between 10-19, 20-29, 30-39, etc.) as a function of the stereoacuity threshold value (in arcsec) for observers age 15-59. The smooth function represents a normal distribution fit to the mode of the plotted data.

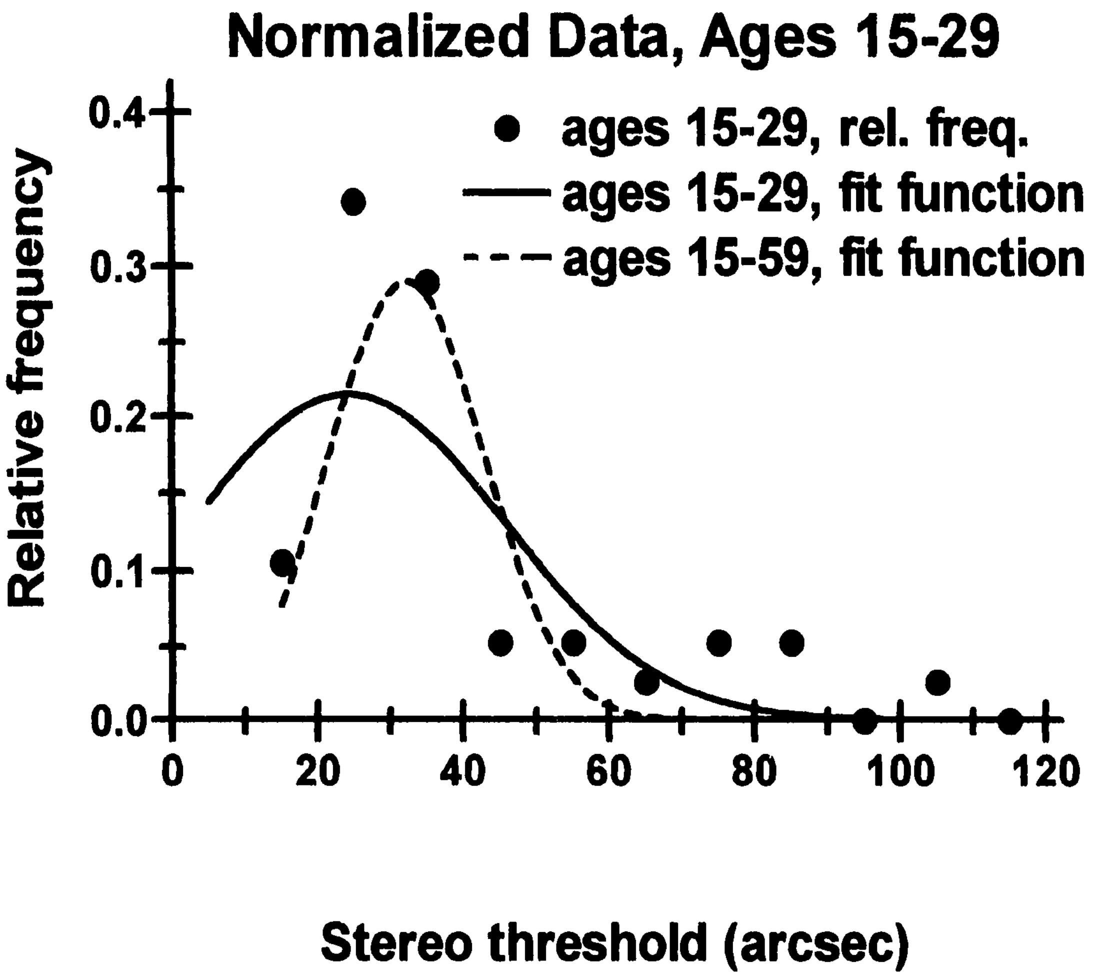

Normalized Data, Ages 15-59
N =106
mean = 42.81
S.D.= 24.03
Relative frequency
0.0
0.1
0.2
0.3
0.4
0
20
40
60
80
100
120
Stereo threshold (arcsec)

therefore, is not Gaussian (normal) in shape. A normal distribution with the calculated mean (42.81 arcsec) and standard deviation (24.03 arcsec) appeared so grossly different from the plotted data points that it is not illustrated. In fact, the smooth function represents a normal distribution with a different mean and standard deviation fit to the mode of the plotted data and which ignores the positively skewed tail (the smooth function describes approximately 80% of the variance of the data; $R^2 = 0.7991$).

It is very likely that the overall shape of the data illustrated in Figure 6 is representative of the general population less than 60 years of age, as shown by similar plots created for restricted age groups within Population 1. Providing that the N was large enough and that data from observers older than 59 years of age were ignored, the shape appeared more or less constant and resembled Figure 6. For example, Figure 7 shows a relative frequency plot for observers between 15 and 29 years of age. For comparison purposes, the dashed function replots the fitted function from Figure 6. Because there is a linear correlation between age and stereo threshold (see below), the mean and standard deviation of the younger age group (mean = 37.74, standard deviation = 21.88) is slightly less than for the larger, more inclusive 15-59 year old age group (mean = 42.81, standard deviation = 24.03). The difference in mean and standard deviation between the younger age group and the more inclusive 15-59 year old age group accounts for the somewhat more leptokurtic shape of the younger age group function and its slight shift to the left. The plot for the younger age group appears about as positively skewed as that evidenced for the entire 15-59 year old age group (in Figure 6) with a prominent tail representing higher stereoacuity values.

A logarithmic transformation was used to “normalize” the data illustrated in Figure 6. This transformation seemed appropriate since it has long been used (e.g., see Fechner,

Figure 7. Relative frequency of values which fall within a 10 arcsec window (i.e., between 10-19, 20-29, 30-39, etc.) as a function of the stereoacuity threshold value (in arcsec) for observers age 15-29 (closed circles). The dotted line represents a normal distribution fit to the mode of similarly plotted data for observers between 15 and 59 years of age.


Normalized Data, Ages 15-29
● ages 15-29, rel. freq.
—— ages 15-29, fit function
- - - ages 15-59, fit function
Relative frequency
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
100
120
Stereo threshold (arcsec)

1860) for describing human sensory performance. Accordingly, the logarithm of the optimal stereo threshold value for each observer less than 60 years of age in Population 1 was determined, yielding a mean (1.57 log arcsec) and standard deviation (0.23 log arcsec). The relative frequency distribution indicated in Figure 8 results from the logarithmically transformed data. The indicated smooth function is a Gaussian curve with a mean and standard deviation of 1.53 and 0.24 log arcsec, respectively. (The antilog of the logarithmic mean is approximately 34 arcsec, and is the geometric mean of the non transformed data set). The coefficient of correlation between the plotted data points and the smooth function is 0.866, indicating a reasonably good Gaussian fit.

The log transformation illustrated in Figure 8 was then used to define norms in terms of standard deviation units or "z-scores" which are presented in tabular fashion in Table 3. This lists various z-score values (left column) and their corresponding stereo threshold values in log arcsec (middle column), and in linear arcsec values (right column).

Incorporating the information presented in Figures 7 and Table 3, Table 4 tentatively divides *all* of the observers representing Population 1 into 6 different categories with stereo threshold values consisting of close approximations of the data from Table 3. Stereoacuity thresholds more than 2 standard deviations below the mean (a threshold less than 13 arcsec) were tentatively designated as *unusually acute stereo sensitivity*. Only one observer fell into this category. Observers with stereoacuity thresholds within ±2 standard deviations of the mean, which in a normal distribution should account for about 95% of the population, were designated as *stereo normal*. Except for the unusually acute stereo individual, this range of stereoacuity values (approximately 13-109 arcsec) accounts for all but 2 of the observers in Population 1 less than 60 years of age who could complete testing with 100 ms stereograms.

Figure 8. Relative frequency as a function of the stereoacuity threshold value (in log arcsec) for observers age 15-59. The indicated smooth function is a Gaussian curve with a mean and standard deviation of 1.53 and 0.24 log arcsec, respectively.

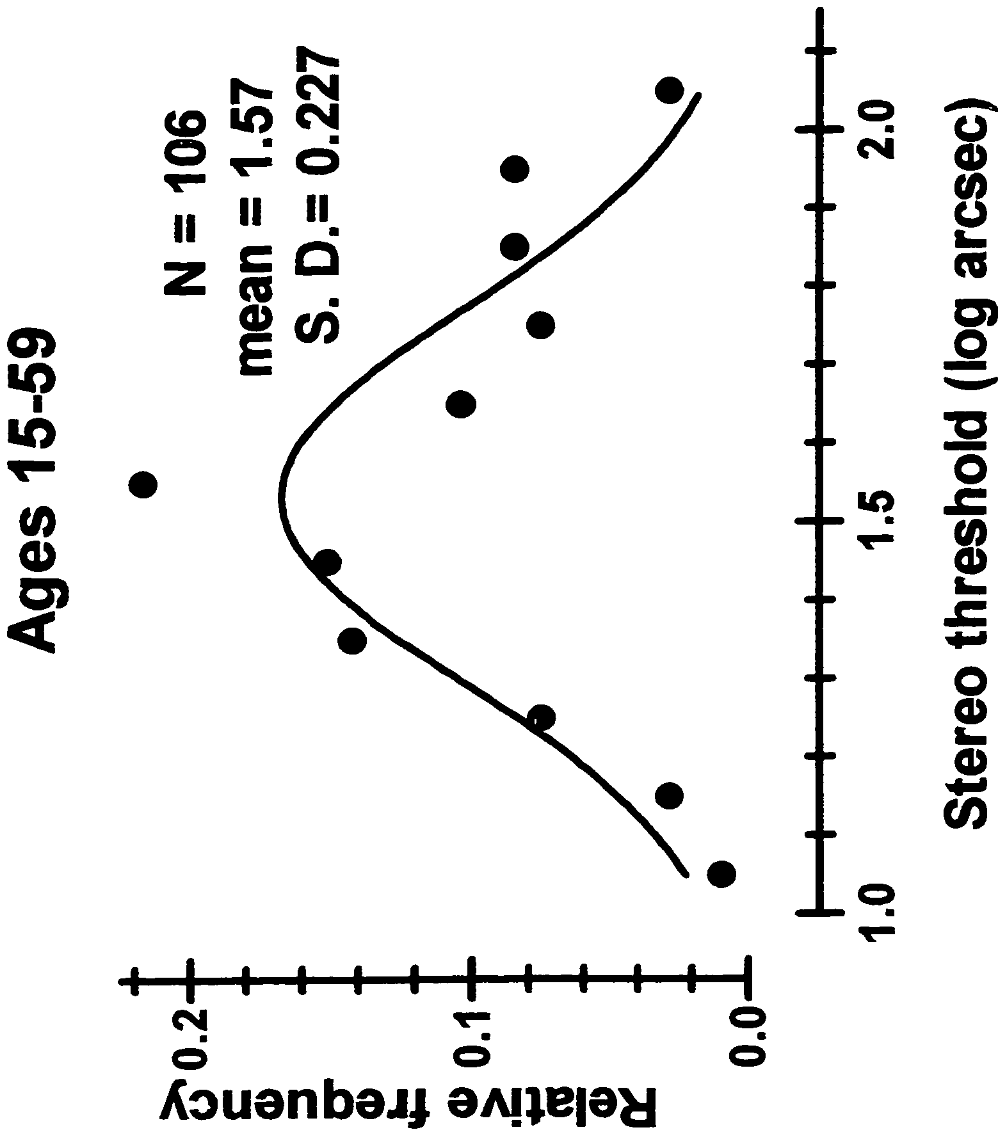

Ages 15-59
N = 106
mean = 1.57
S. D. = 0.227
Relative frequency
0.2
0.1
0.0
1.0
1.5
2.0
Stereo threshold (log arcsec)

Table 3

NORMATIVE TABLE

Log Deviation from Mean in Z scores	Threshold Value (log arcsec)	Threshold Value (arcsec)
-3	0.88866	8
-2	1.11592	13
-1	1.34318	22
0	1.57044	37
1	1.79770	63
2	2.20496	106
3	2.25222	179
4	2.47948	302
5	2.70674	509
6	2.93400	859

Table 4

Designation of Stereoacuity by Threshold in Arcsec

DESIGNATION	RANGE IN TERMS OF STANDARD DEVIATION	RANGE IN ARCSEC
Acutely stereo sensitive	>2 S.D. below the mean	<13
Stereo normal	2 S.D. above/below the mean	13 - 109
Mildly stereo impaired	2-4 S.D. above the mean	110-300
Moderately stereo impaired	>4 S.D. above the mean	301-1000
Markedly stereo impaired	Could detect the "demo" program but could not complete 100 msec testing	
Stereo blind	Could not detect the "demo" program	

Observers with stereoacuity thresholds from 2-4 standard deviations above the mean (approximately 110-300 arcsec) are designated *mildly stereo-impaired.* Observers who could complete the testing procedure with 100 ms duration stimuli but with still higher stereoacuity thresholds are designated *moderately stereo-impaired*: the range of values listed in Table 4 is from approximately 4 standard deviations above the mean (301 arcsec) to a limiting value of 1000 arcsec.

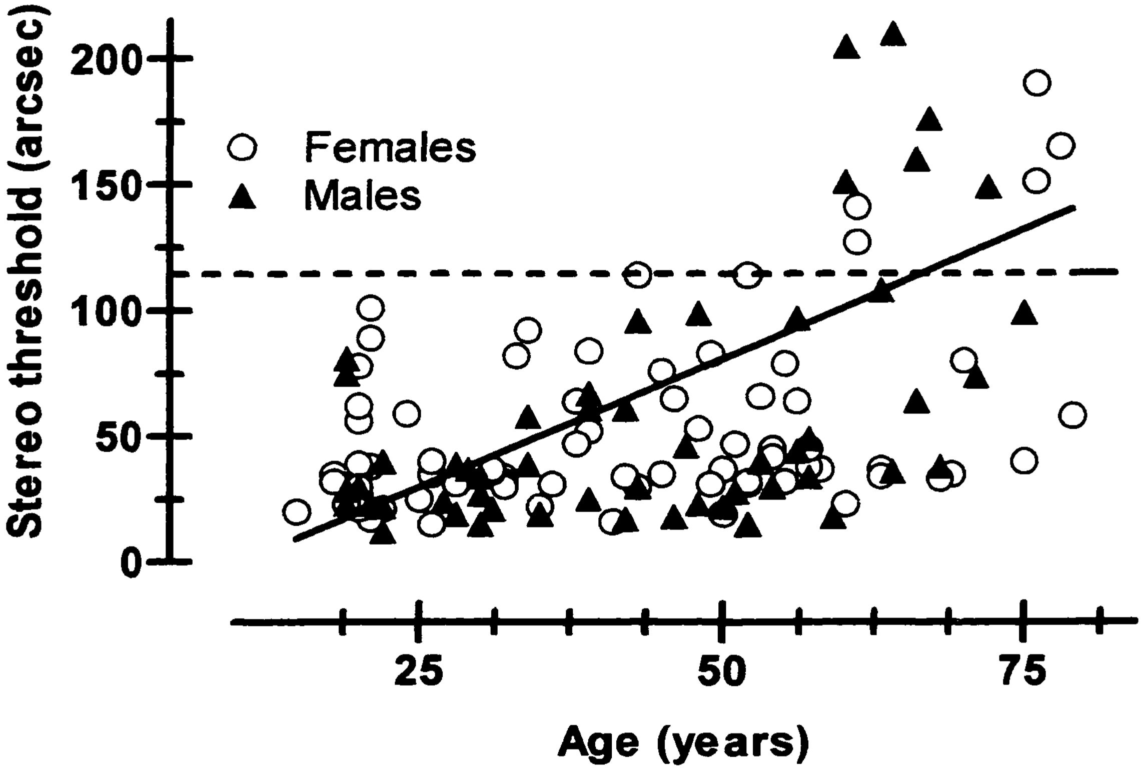
An additional 25 observers were examined who were unable to complete testing with the 100 ms duration stereograms. Of these observers, 22 were able to see depth in random-dot stereograms presented for durations longer than 100 ms. No test was conducted which would determine whether these observers solely used vergence cues, or vergence *and* some residual stereopsis mechanism to detect these longer duration stimuli. Thus, although some of these 22 observers might be stereoblind, it seemed prudent to instead designate all of them as *markedly stereo-impaired.* The designation *stereoblind* was restricted to the 3 observers who failed to discern the "demo" program.

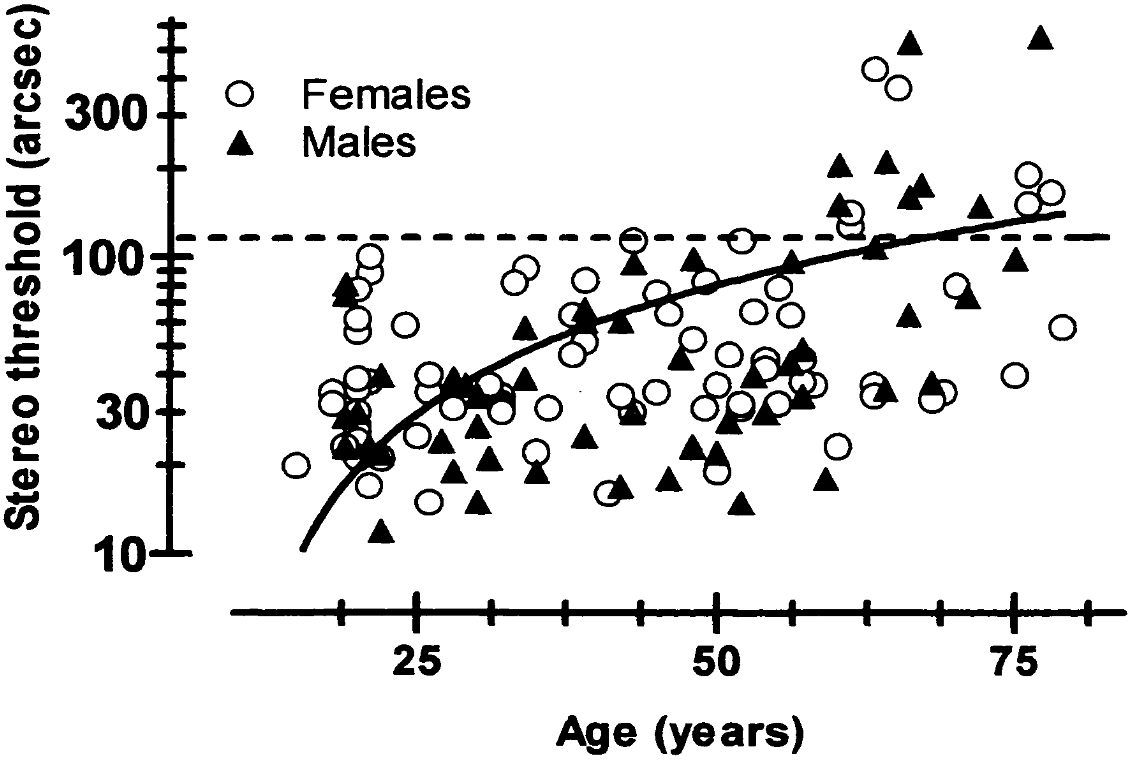
B. Influence of Age on Stereoacuity

1. *Analysis of 100 ms functions*

Figure 9 shows the relationship between the optimal stereoacuity threshold obtained with 100 ms duration stimuli as a function of age. Although the gender of each observer is indicated by symbol shape, the fitted function is the linear regression line fit through all the linear data points. The upper plot, which is restricted to stereoacuity thresholds <250 arcsec, is plotted with a linear ordinate, while the lower plot has a logarithmic ordinate in order to show data from even the least sensitive observer designated as "moderately stereo-impaired." Although there is a great deal of scatter around the regression line, the lowest threshold

Figure 9. Optimal stereoacuity threshold (in arcsec) obtained with 100 ms duration stimuli as a function of age. Gender is indicated by symbol shape. The fitted function is the linear regression line fit through all the data. The horizontal dashed line drawn at the 110 arcsec ordinate position was considered to be a value which delineates "normal" from "stereo impaired" observers based upon normative analysis of data from observers <60 years of age. The upper plot, which is restricted to stereoacuity thresholds <250 arcsec, is plotted with a linear ordinate, while the lower plot has a logarithmic ordinate in order to show data from even the least sensitive observer able to complete testing with 100 ms stimuli.


Stereo threshold (arcsec)
200
150
100
50
0
○ Females
▲ Males
25
50
75
Age (years)


Stereo threshold (arcsec)
300
100
30
10
○ Females
▲ Males
25
50
75
Age (years)

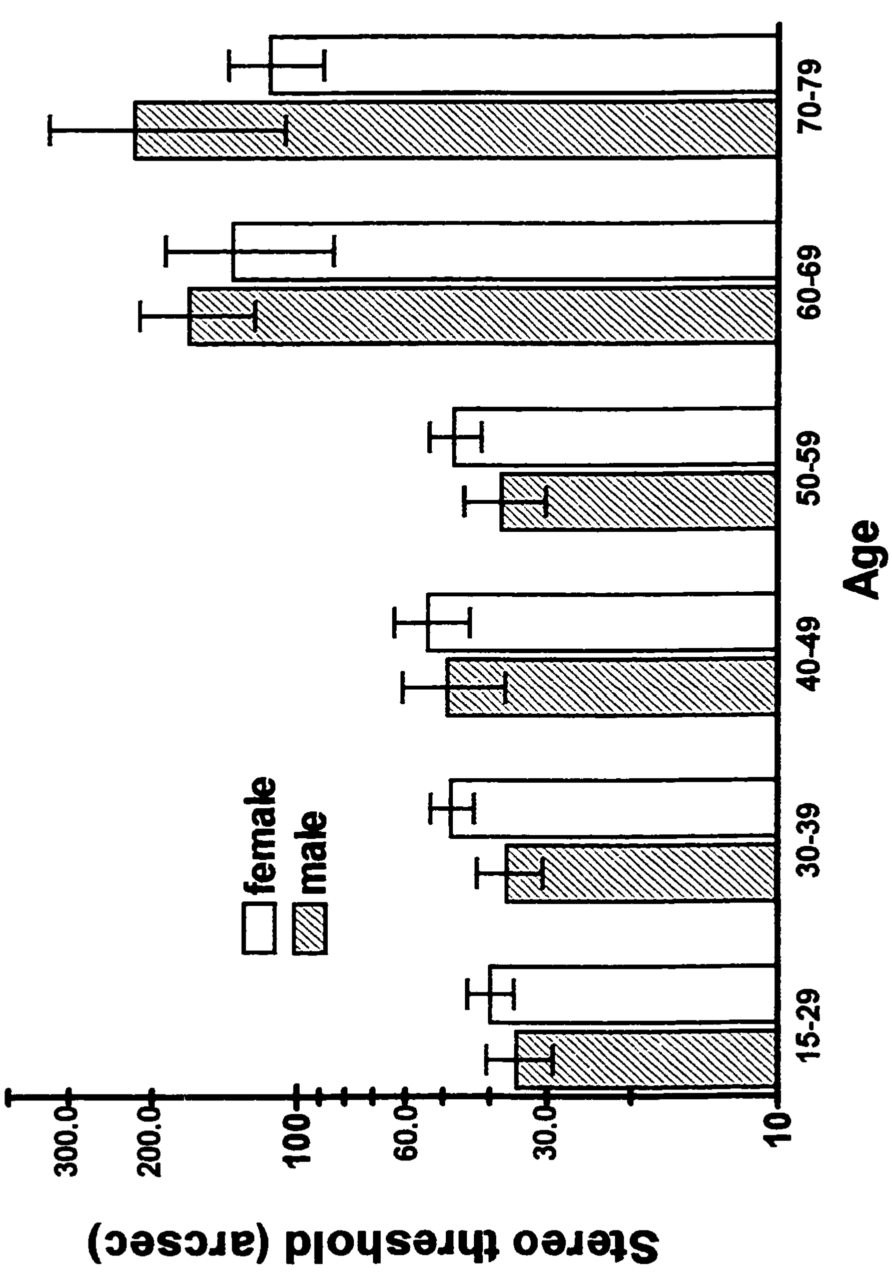
values were obtained with observers less than 30 years of age and the highest threshold values with the observers older than 60 years of age. The overall correlation between age and stereoacuity was statistically significant ($r = +0.44, p < 0.0001$). A test for non linearity of the relationship was not significant ($p = 0.0946$).

The correlation of age and stereoacuity was also calculated separately for male and female observers and in both cases was significant (males: $r = +0.50, p < 0.0001$; females: $r = +0.38, p = 0.0004$). The differences in the coefficients of correlation for male and female observers was examined according to a procedure described by Walker and Lev (1953) and was not significant ($z = 0.795$, i.e., $p = 0.213$).

One other way to analyze these data is to divide observers into the age/decade group that they represent. Figure 10 shows mean stereoacuity threshold (±1 standard error) for both male (cross hatched bars) and female (open bars) observers of six different age groups plotted with a logarithmic ordinate in order to include data from older age groups exhibiting poorer stereoacuity. A two way analysis of variance (ANOVA) conducted with linear mean stereoacuity values grouped by age decade and stratified by gender showed that the influence of age was significant ($F\,[5,123] = 13.58, p < 0.0001$) while gender had no significant effect ($F\,[1,123] = 1.71, p = 0.1929$).

To summarize, the results from observers who completed testing with 100 ms duration stimuli indicate that there was a significant tendency for stereoacuity to decrease with age. The age-related decline in stereoacuity probably partly accounts for the finding in prior studies suggesting that the incidence of stereoanomalies increases with age. To emphasize this point, a horizontal dashed line was drawn at the 110 arcsec ordinate position in Figure 9, which based upon normative analysis of data from observers less than 60 years

Figure 10. Mean stereoacuity thresholds (±1 standard error) for both male (cross hatched bars) and female (open bars) observers of six different age groups.

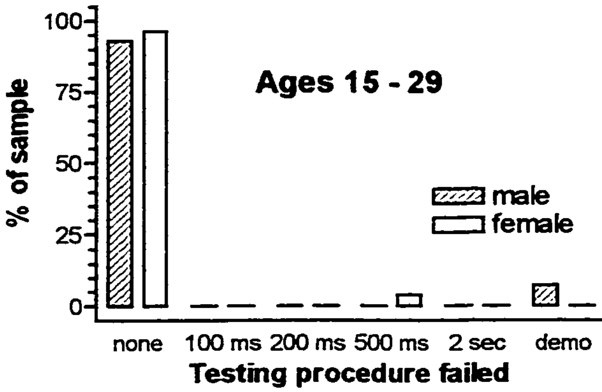

Stereo threshold (arcsec)
300.0
200.0
100
60.0
30.0
10
▭ female
▨ male
15-29
30-39
40-49
50-59
60-69
70-79
Age

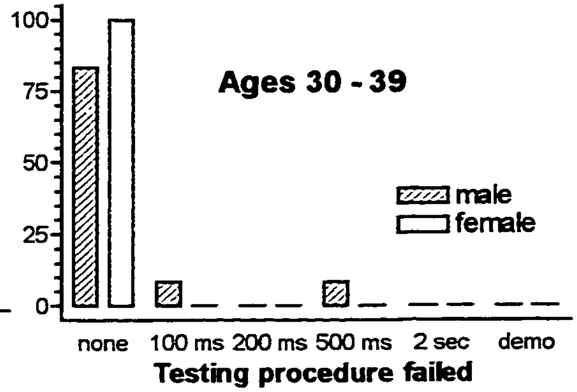
of age (see Figure 8 and Tables 3 and 4 above), was considered to be a value which delineates "stereo normality" from "stereo-impairment." As indicated above, all but two observers less than 60 years of age who completed testing fell into the normal category. In contrast, a large percentage of the 44 observers who were 60 years of age or older (see Figure 9) cannot be included in this category including 25% (11 of 44) who are "mildly stereo-impaired" (thresholds between 110-300 arcsec) and 9% (4 of 44) who are "moderately stereo-impaired"(thresholds between 301 and 1000 arcsec).

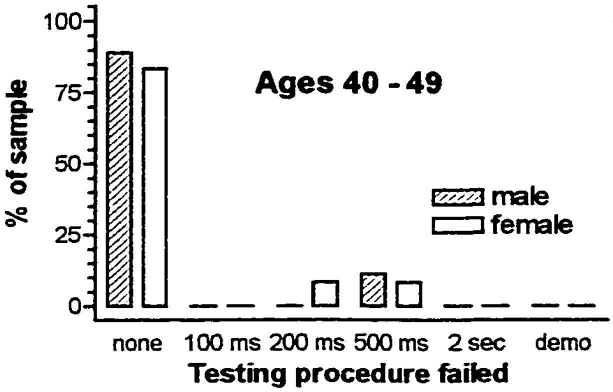
2. *Analysis of Data from all Observers in Population I Including Those Unable to Complete 100 ms Testing*

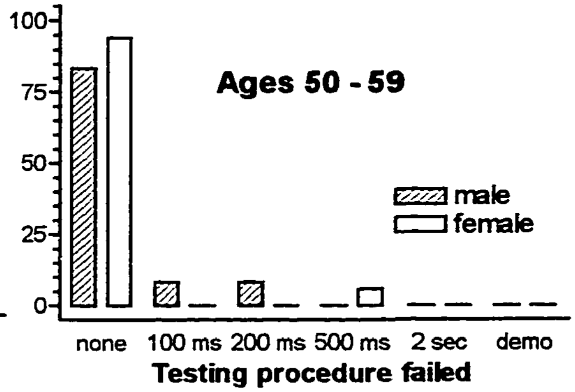
Figure 11 summarizes results from all observers in Population 1 regardless of whether they could complete testing with 100 ms duration stimuli. In Figure 11, the six different sets of coordinates show for the different age brackets, the percentage of male (crossed hatch bars) and female (open bars) observers who failed to complete testing with the demo program, stereograms of 2 sec, 500 ms, 200 ms, or 100ms duration, or who could complete testing with all procedures (the "none" category). The graphs for the four younger age categories show that most observers younger than 60 years of age fall into the "none" category, and most were able to complete testing with the 100 ms duration stimuli. However, with the 60 to 69, and particularly the 70 to 79 year-old age categories, a smaller percentage of observers fell into the "none" category, and a much larger percentage failed to complete testing with either 500 ms or 2 sec stereograms, or with the demo program. To better illustrate the meaning of these data, the six categories of test failures are collapsed into the dichotomous categories, "failing to complete" or "completion" of 100 ms testing. Figure 12 summarizes the percentage of male and female observers "failing to complete" in each of

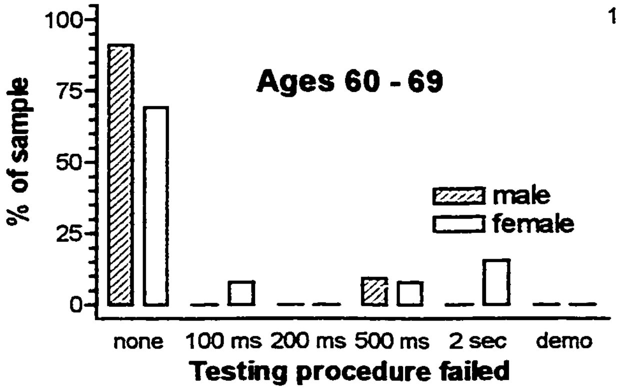
Figure 11. Percentage of male (crossed hatch bars) and female (open bars) observers who failed to complete testing with the demo program, stereograms of 2 sec, 500 ms, 200 ms, or 100ms duration, or who could complete testing with all procedures (the "none" category).


Ages 15 - 29
% of sample
100
75
50
25
0
▨ male
☐ female
none
100 ms
200 ms
500 ms
2 sec
demo
Testing procedure failed


Ages 30 - 39
100
75
50
25
0
▨ male
☐ female
none
100 ms
200 ms
500 ms
2 sec
demo
Testing procedure failed


Ages 40 - 49
% of sample
100
75
50
25
0
▨ male
☐ female
none
100 ms
200 ms
500 ms
2 sec
demo
Testing procedure failed


Ages 50 - 59
100
75
50
25
0
▨ male
☐ female
none
100 ms
200 ms
500 ms
2 sec
demo
Testing procedure failed


Ages 60 - 69
% of sample
100
75
50
25
0
▨ male
☐ female
none
100 ms
200 ms
500 ms
2 sec
demo
Testing procedure failed

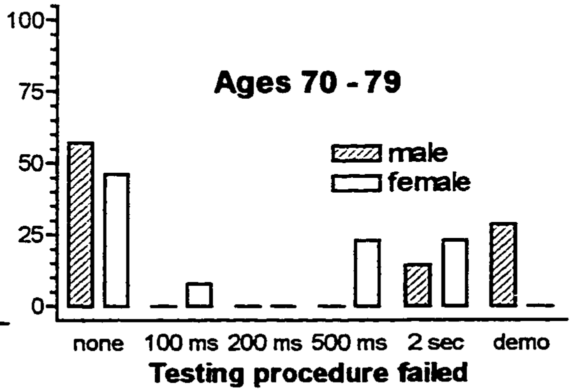
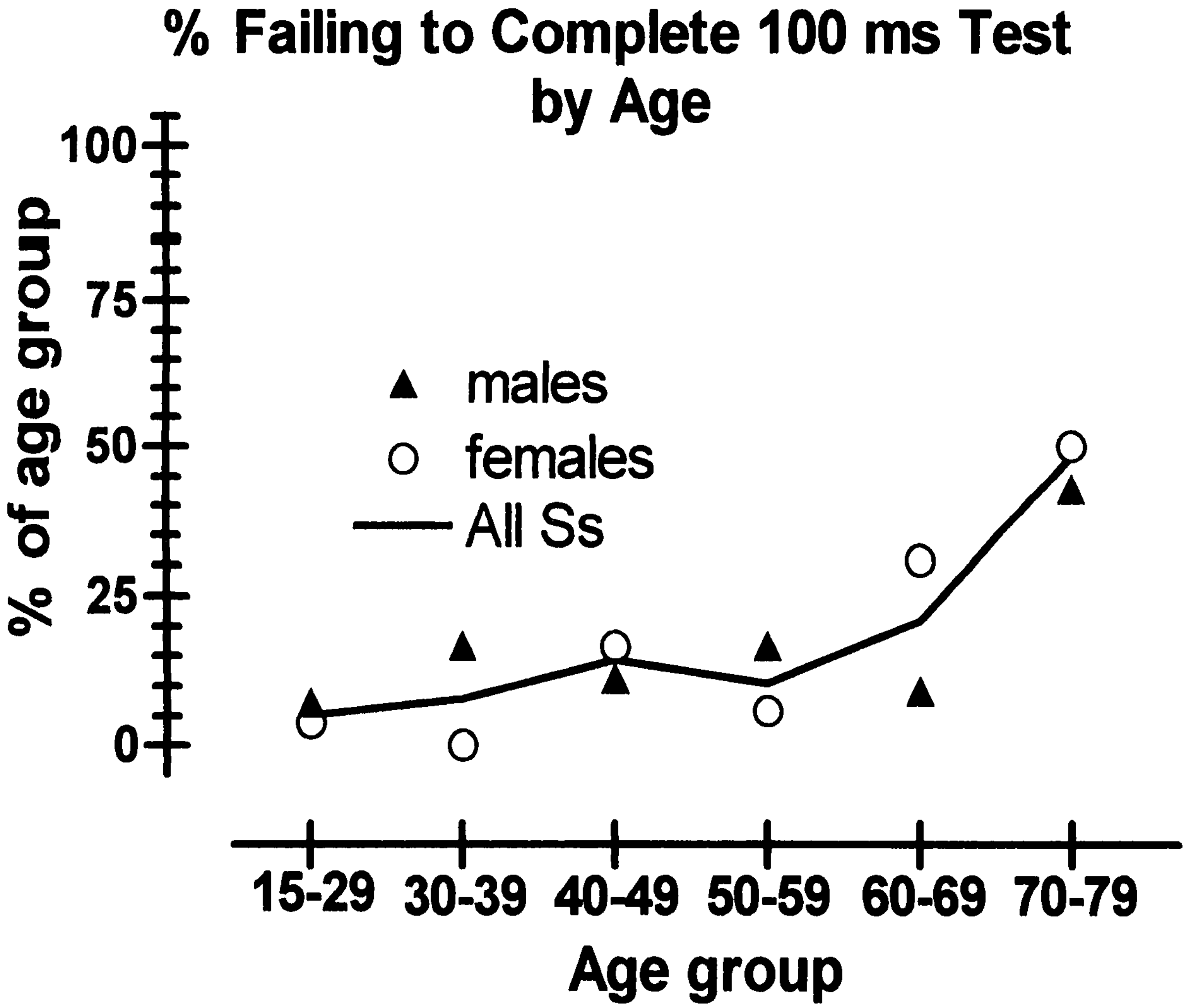

Ages 70 - 79
100
75
50
25
0
▨ male
☐ female
none
100 ms
200 ms
500 ms
2 sec
demo
Testing procedure failed

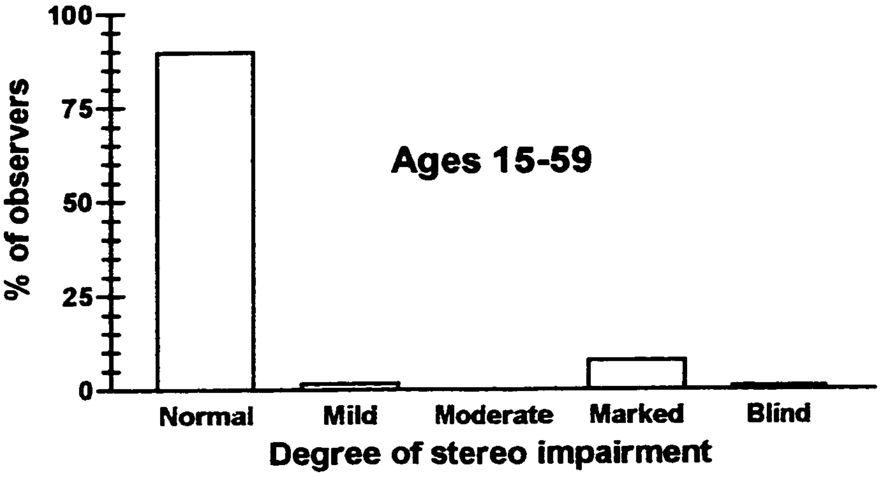
Figure 12. Percentage of male and female observers in each of 6 age categories collapsed into category of "failing to complete" 100 ms testing.

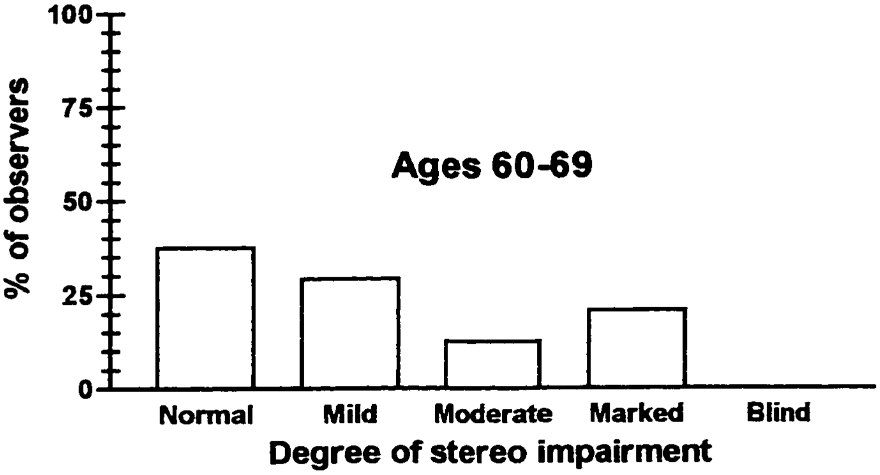

% Failing to Complete 100 ms Test by Age
% of age group
100
75
50
25
0
▲ males
○ females
— All Ss
15-29
30-39
40-49
50-59
60-69
70-79
Age group

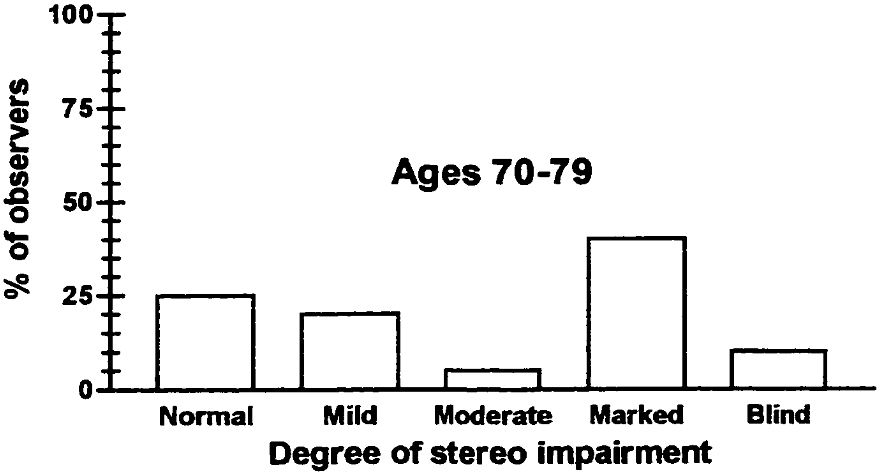
these 6 age categories. This plot shows that the rate of failure to complete testing increases with age. A Spearman rank order correlation shows that this relationship is statistically significant when male and female observers are considered together ($r_s = 0.9429, p = 0.0083$ with a one-tailed test; a one-tailed test was utilized because the failure was assumed a priori to increase with age). Additional statistical analysis verified this conclusion: all observers from Population 1 were stratified into those who could complete the 100 ms duration stimuli testing and those could not. Observers were also separated by age into two groups: those under age 60, and those age 60 and above. To test whether the number of failures increased significantly with age, a Chi-square analysis with Yates correction was performed on the aforementioned data (i.e., failure vs. passing 100 ms stimuli, with age divided into less than 60 and greater than 60 groups) and was significant: $X^2 = 16.20(1), p < 0.0001$. A two by two Chi-square analysis showed that failure rate was not influenced by the gender of the observer (Chi-square analysis with Yates correction stratifying observers by gender; $X^2 = 0.02862, p = 0.8657$). Failure rate was also not significantly influenced by gender when observers 60 years of age or older were stratified into those who perceived depth with 100 ms stimuli and those unable to perceive depth with 100 ms stimuli by gender (Fisher's exact test showed no significant difference, $p = 0.2083$).

The collective meaning of the results summarized in Figures 8-12 can be represented graphically in yet another fashion. The three sets of bar graphs in Figure 13 illustrate the percentage of observers who are either less than 60, between 60 and 69, or between 70 and 79 years of age who fell into each of the five categories for stereoacuity listed in Table 3. Observers 15 to 59 years of age were grouped together because separate bar graphs by decade for these younger observers were highly similar. (For this plot, the single observer

Figures 13. Percentage of observers who are under 60 (top plot), between 60 and 69 (middle plot), or between 70 and 79 years of age (bottom plot) who fell into each of the five categories for stereoacuity. (For this plot, the single observer designated as "acutely stereo sensitive" is grouped with "stereo normals").


100
75
50
25
0
% of observers
Ages 15-59
Normal
Mild
Moderate
Marked
Blind
Degree of stereo impairment


100
75
50
25
0
% of observers
Ages 60-69
Normal
Mild
Moderate
Marked
Blind
Degree of stereo impairment


100
75
50
25
0
% of observers
Ages 70-79
Normal
Mild
Moderate
Marked
Blind
Degree of stereo impairment

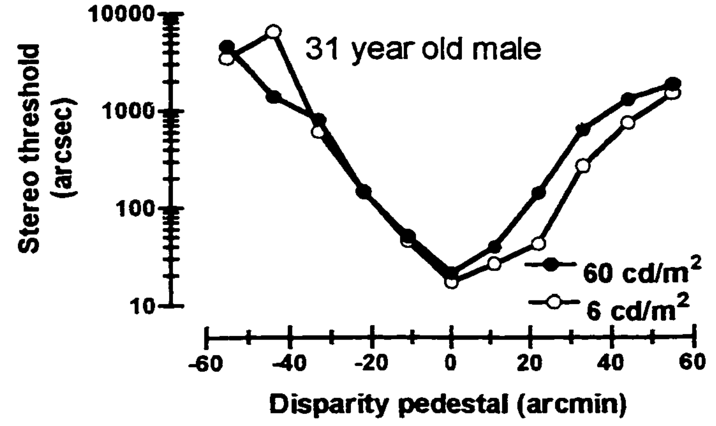
designated as "acutely stereo sensitive" is grouped with "stereo normals"). Almost 90% of the observers less than 60 years of age are classified as "stereo normal." On the other hand, less than 40% of observers between the ages of 60-69 and less than 30% of observers 70-79 can be classified as stereo normal. Further inspection of Figure 13 reveals not only an increase in stereo-impairment with age, but also an increase in the severity of stereo-impairment. Thus, less than 11% of the observers between ages 15-59 are classified as anything other than "stereo normal." For ages 60-69, approximately 29% are mildly impaired, about 13% moderately impaired, and 21% severely impaired. For ages 70-79, the incidence of "mild" and "moderate" impairment decreases, but the incidence of marked impairment increases to approximately 40%. An additional 10% of the observers age 70-79 are stereoblind.

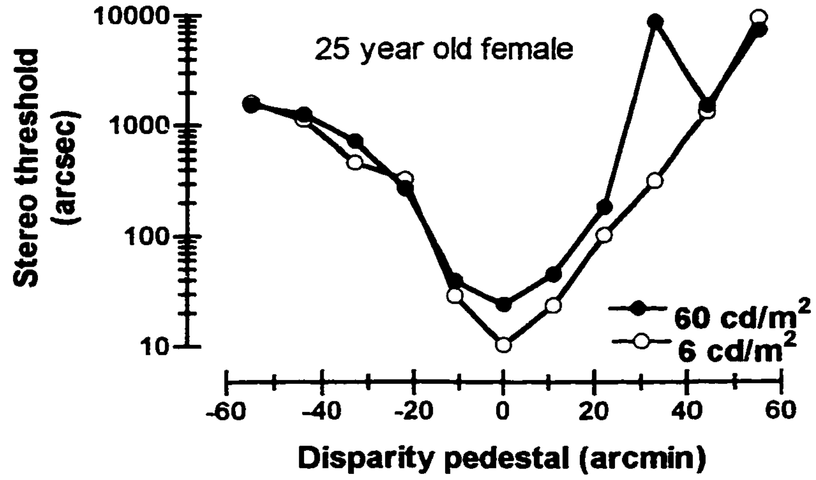
3. *Neither Education, Senile Meiosis, or Differential Practice Effects Contribute to the Influence of Age on Stereoacuity*

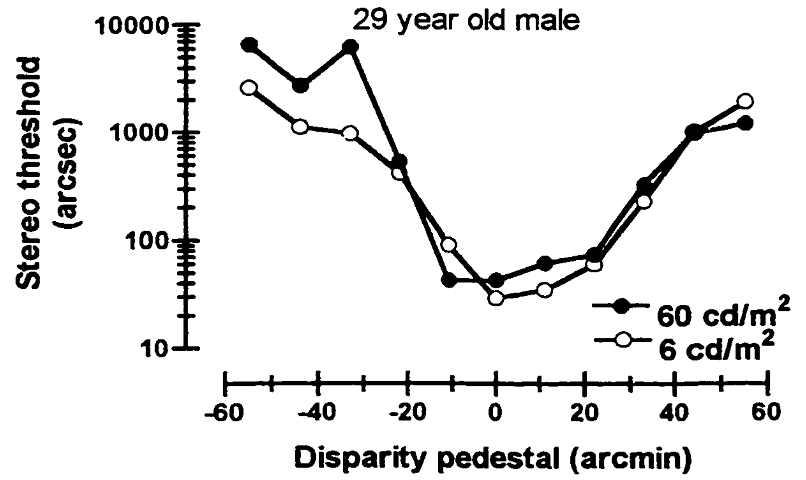
Three factors might conceivably cause the older observers to exhibit poorer stereoacuity than the younger observers. First, some of the older observers had less education than the younger observers and perhaps were less able to comply with the demands of testing. However, for the 25 observers unable to complete testing with the 100 ms duration stimuli, the relationship between education (as indicated by years of schooling) and performance (i.e., optimal stereo threshold with 100 ms stereograms or exposure duration of stereogram perceived) was negligible (Spearman $r_s = 0.0201$, $p = 0.9237$ with a two-tailed test).

A second factor that might account for the decreased stereoacuity in older observers might be the decrease in pupil size with age (senile meiosis). Figure 14 shows results from 3 younger observers (ages 25, 29, and 31) who were tested with the mean stimulus luminance

Figure 14. Mean stereo threshold (in arcsec) as a function of pedestal disparity (in arcmin) with the typical stimulus luminance value (through stereoscopic glasses = 3.0 cd/m^2), and with stimulus luminance reduced by 75% to (through stereoscopic glasses = 0.75 cd/m^2) for three observers. Negative pedestal values indicate uncrossed retinal disparity while positive or unsigned values indicate crossed retinal disparity


31 year old male
Stereo threshold (arcsec)
10000
1000
100
10
-60
-40
-20
0
20
40
60
Disparity pedestal (arcmin)
60 cd/m²
6 cd/m²


25 year old female
Stereo threshold (arcsec)
10000
1000
100
10
-60
-40
-20
0
20
40
60
Disparity pedestal (arcmin)
60 cd/m²
6 cd/m²


29 year old male
Stereo threshold (arcsec)
10000
1000
100
10
-60
-40
-20
0
20
40
60
Disparity pedestal (arcmin)
60 cd/m²
6 cd/m²

value used throughout the remainder of this thesis (through stereoscopic glasses = 3.0 cd/m^2) and with mean stimulus luminance reduced by 75% (through stereoscopic glasses = 0.75 cd/m^2). This reduction in stimulus luminance would produce a change in retinal illuminance nearing 1 log unit, an amount much greater than any estimate of the change in pupillary area associated with senile meiosis. Figure 14 shows that results under both luminance conditions are about the same ruling out the "retinal illuminance" explanation for age-related change in stereoacuity.

It is well known that practice with stereoscopic tasks can subsequently improve stereoacuity (Sowden, Davies, Rose, & Kaye, 1996). Thus, it is possible that younger observers may have been better able to utilize additional practice trials to produce lower stereo thresholds, while older observers may have eventually produced stereo thresholds equivalent to younger observers with additional practice. To investigate this possibility, for a randomly sampled subset of the overall population, the lowest stereo threshold obtained with the 200 ms duration stimuli was divided by the lowest stereo threshold obtained with 100 ms duration stimuli (regardless of the disparity pedestal at which this occurred). The reasoning behind this analysis is as follows: if the effects of practice were still operating by the time an observer was presented with 100 ms duration stimuli, their threshold would then be expected to be lower with the 100 ms duration trials than that obtained with 200 ms duration trials, despite the greater difficulty in the former task owing to the elimination of vergence cues to depth. If however, the effects of practice had reached an asymptote, then similar or poorer performance would be expected with the more difficult 100 ms stimuli. The mean values by age decade were 0.731 for observers 70 to 79, 0.718 for observers 60 to 69, 0.59 for observers 50 to 59, 1.27 for observers 40 to 49, 0.945 for observers 30 to 39, and

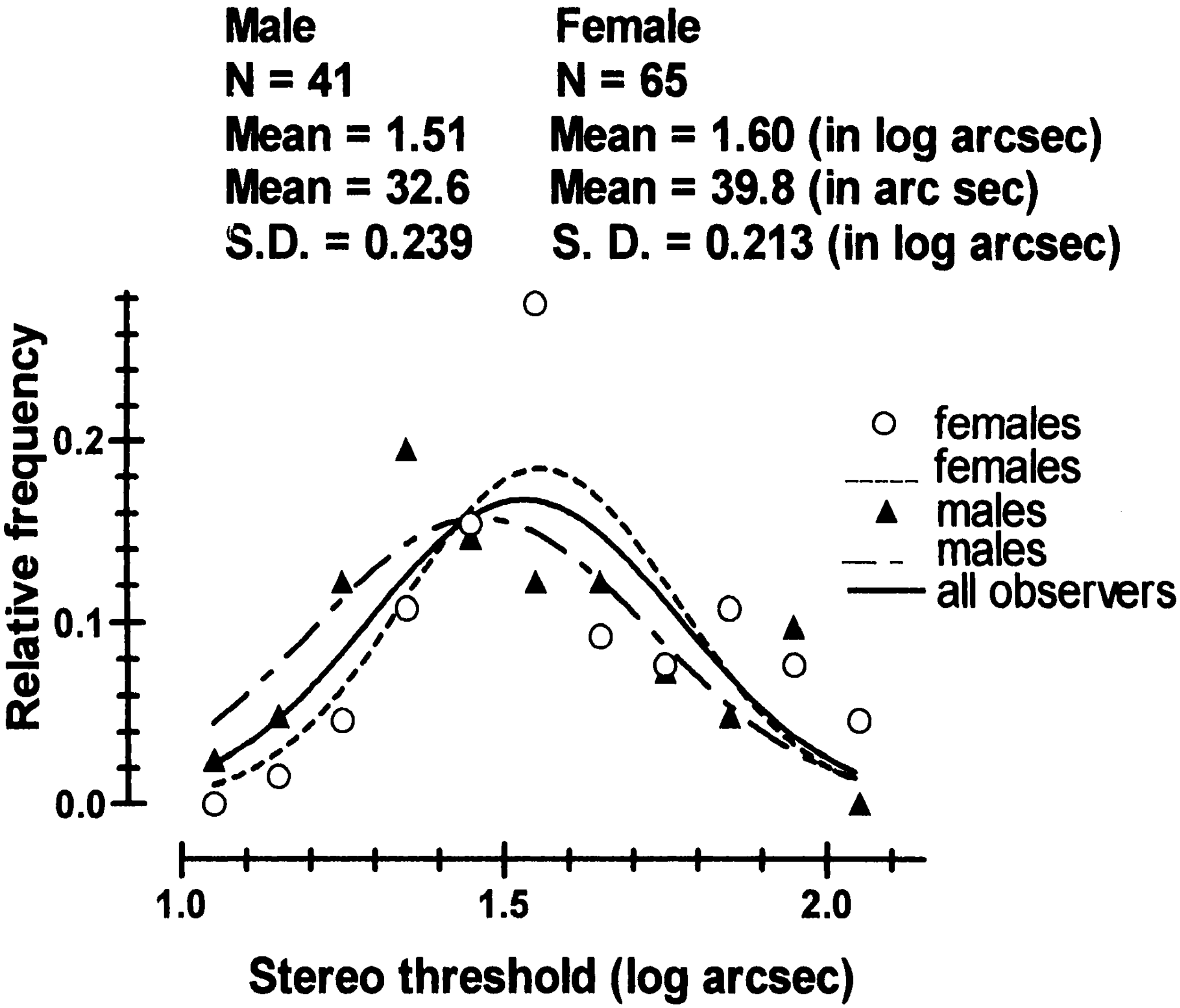
1.19 for observers 15 to 29. The correlation of practice with age was not significant: (r = -0.70, p = 0.05). Thus, any practice effects were random and not age-related.

C. Influence of Gender on Stereoacuity

As a first step in investigating the possible influence of gender on stereoacuity, Figure 15 shows relative frequency as a function of the logarithm of the optimal stereo threshold value obtained with 100 ms duration stereograms with male and female observers represented by separate symbols. The straight line function is a replot of the smooth curve fit to the data for all observers as portrayed in Figure 8. With the exception of perhaps one data point for each gender, the different sets of data and fitted curves correspond with reasonable closeness. As summarized by the numerical values in Figure 15, the data for females indicates a slightly greater mean and smaller standard deviation than corresponding data for males. A two tailed t-test comparing means of the log stereoacuity thresholds for male and female observers between 15 and 59 years of age was not significant (t = 1.849, p = 0.0672); a corresponding t-test comparing *linear* means was not significant (t = 1.396, p = 0.1656). Additionally, t-tests comparing mean stereoacuity for all males and females, including those over the age of 59, were not significant (for linear values t = 0.9953, p = 0.3214; for log values t = 0.1691, p = 0.866). Furthermore, t-tests comparing mean stereoacuity for male and female observers 60 years of age or greater were also non significant (for linear values t = 1.026, p = 0.3139; for log values t = 1.380, p = 0.1789). Finally, as summarized in *Section IIB1* above, the functional relationship between age and the stereoacuity of observers who could complete testing with the 100 ms presentation did not differ significantly between male and female observers.

The possible influence of gender on more severe forms of stereo-impairment was also

Figure 15. Relative frequency as a function of the logarithm of the optimal threshold for males and females. The two sets of symbols and additional fitted curves represent data for each sex separately. The dashed line is a Gaussian curve with a mean of 1.53 log arcsec and a standard deviation of 0.24 log arcsec.


Male
N = 41
Mean = 1.51
Mean = 32.6
S.D. = 0.239
Female
N = 65
Mean = 1.60 (in log arcsec)
Mean = 39.8 (in arc sec)
S. D. = 0.213 (in log arcsec)
Relative frequency
0.0
0.1
0.2
○ females
----- females
▲ males
— - males
—— all observers
1.0
1.5
2.0
Stereo threshold (log arcsec)

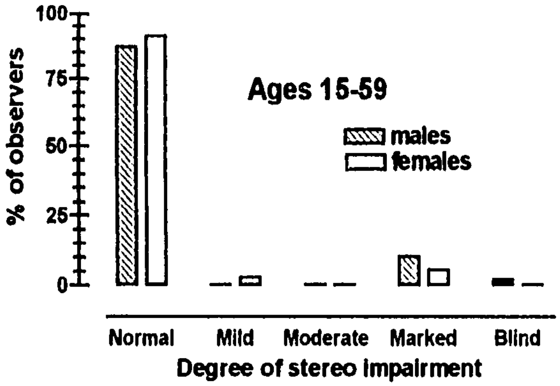
considered. As indicated in *section IIB2* above, the incidence of failure to complete testing with 100 ms stereograms did not relate to gender. Figure 16 stratifies gender differences for more severe types of stereo-impairment. The percentage of male and female observers who were either less than 60, between 60 and 69, between 70 and 79 years of age, or of all ages who fell into each of the five categories for stereoacuity listed in Table 3 is illustrated. (As was the case for Figure 13, the single observer designated as "acutely stereo sensitive" is grouped with "stereo normals.") Probably the most meaningful comparison shows that the incidence of stereo normality which did not depend upon gender. The illustrations suggest that there might be gender differences in the incidence for the other four categories. For example, all (N=3) of the designated *stereoblind* observers are males, but the incidence of *marked stereo-impairment* was much greater for females than males in the older two age groups. However, these observations more likely reflect the small number of observers involved and the semi-quantitative nature of the categories *moderately stereo-impaired, markedly stereo-impaired,* and *stereoblind* rather than meaningful gender differences.

To summarize, the data indicate that it is unlikely that there are any meaningful gender differences in optimal stereoacuity.

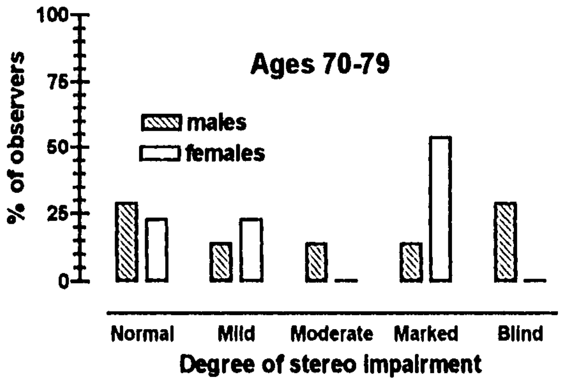
PART III: INCIDENCE OF FIXATION DISPARITY

Figure 17 illustrates the incidence of different types of fixation disparities in *Population 2* as measured by the pedestal disparity resulting in maximal stereo sensitivity for each observer. The upper plot shows relative frequency as a function of fixation disparity with a logarithmic ordinate to better present lower frequencies. Approximately 50% of the population of observers was most sensitive with no (zero) pedestal disparity and about 40% more were maximally sensitive to both crossed and uncrossed disparity values of 11 arcmin.

Figure 16. Percentage of male and female observers under 60, between 60 and 69, between 70 and 79 years of age, or observers of all ages who fell into each of the five categories for stereoacuity listed in Table 3. (The single observer designated as "acutely stereo sensitive" is grouped with "stereo normals").


Ages 15-59
▨ males
☐ females
% of observers
100
75
50
25
0
Normal
Mild
Moderate
Marked
Blind
Degree of stereo impairment


Ages 60-69
▨ males
☐ females
% of observers
100
75
50
25
0
Normal
Mild
Moderate
Marked
Blind
Degree of stereo impairment


Ages 70-79
▨ males
☐ females
% of observers
100
75
50
25
0
Normal
Mild
Moderate
Marked
Blind
Degree of stereo impairment

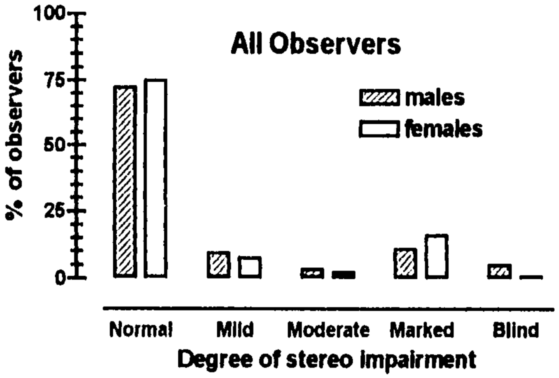
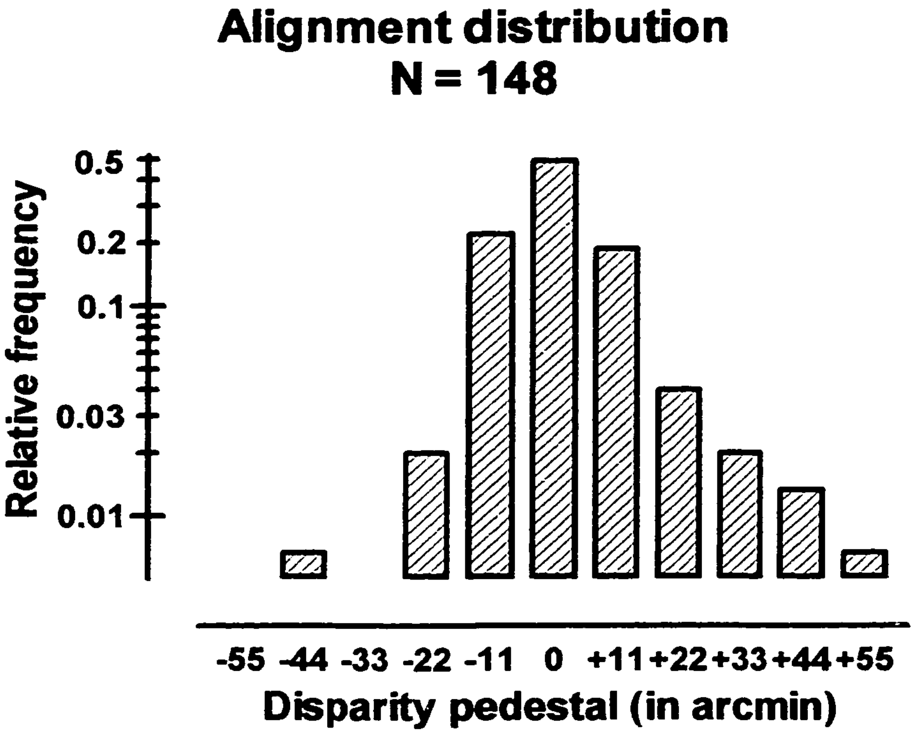
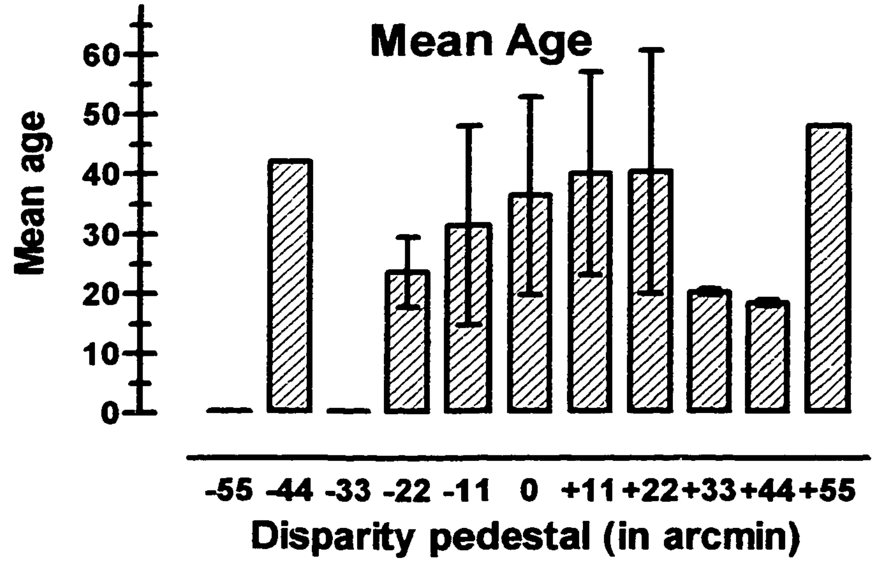

All Observers
▨ males
☐ females
% of observers
100
75
50
25
0
Normal
Mild
Moderate
Marked
Blind
Degree of stereo impairment

Figure 17. The upper most plot shows relative frequency as a function of fixation disparity with a logarithmic ordinate. The middle plot displays the mean age (±1 standard error) for the observers maximally sensitive to each disparity threshold. For all three plots negative pedestal values indicate uncrossed retinal disparity while positive or unsigned values indicate crossed retinal disparity.


Alignment distribution
N = 148
Relative frequency
0.5
0.2
0.1
0.03
0.01
-55 -44 -33 -22 -11 0 +11 +22 +33 +44 +55
Disparity pedestal (in arcmin)

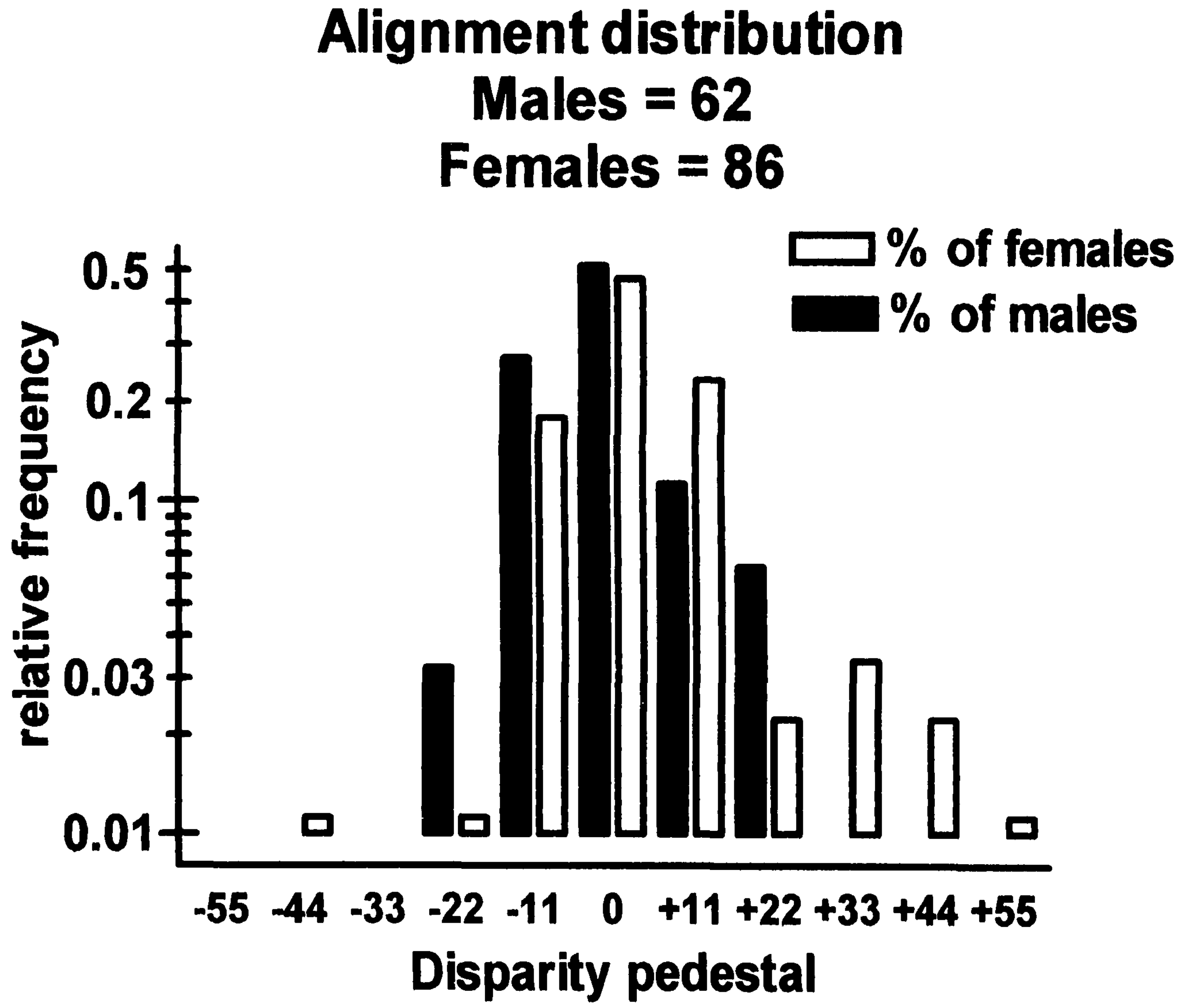

Mean Age
Mean age
60
50
40
30
20
10
0
-55 -44 -33 -22 -11 0 +11 +22 +33 +44 +55
Disparity pedestal (in arcmin)

In other words, approximately 90% of the observers were maximally sensitive to disparities of 11 arcmin or less. Notice that the incidence of still larger fixation disparities is more common for crossed (positive abscissa values) than for uncrossed pedestal values. It should be noted that the data from observers with large (>11 arc minute) disparity values were quite reliable as indicated by standard error values no larger than the standard errors for observers with no fixation disparity. In addition, fixation disparity was not only evident in the 100 ms stereogram data (summarized in Appendix C) but was also evident in the 200 ms stereogram data for the same observers (data not presented).

To determine whether fixation disparities related in any obvious way to age, the bottom set of coordinates in Figure 17 displays the mean age (±1 standard error) for the observers maximally sensitive to each disparity threshold. There is no obvious relationship between the age of the observers and the alignment, and an ANOVA comparing mean age at each pedestal of optimal stereoacuity indicated no significant effect ($F\,[4,4] = 1.89, p = 0.28$).

Figure 18 illustrates the alignment distribution for both male and female observers. These data show that approximately 50% of both male and female observers were maximally sensitive to 100 ms duration stereograms with no disparity pedestal. However, these data also show marked gender differences in the type and severity of the fixation disparity thresholds obtained. First, while more males seemed to be "misaligned" to uncrossed disparity values, more females were "misaligned" to crossed disparity values. As analyzed by a 2 x 2 Chi-square analysis utilizing a Yates correction factor, this difference was statistically significant ($X^2 = 4.662$, $p = 0.0308$.) Second, no male was "misaligned" to pedestal disparities greater than 22 arcmin while approximately 8% of female observers exhibited optimal stereoacuity thresholds with pedestals greater than 22 arcmin from the plane

Figure 18. Relative frequency as a function of fixation disparity with a logarithmic ordinate for male and female observers. Negative pedestal values indicate uncrossed retinal disparity while positive or unsigned values indicate crossed retinal disparity.


Alignment distribution
Males = 62
Females = 86
% of females
% of males
relative frequency
0.5
0.2
0.1
0.03
0.01
-55
-44
-33
-22
-11
0
+11
+22
+33
+44
+55
Disparity pedestal

of fixation. As analyzed by a Fisher's exact test (Chi-square could not be used due to the low expected frequency values), this difference was also statistically significant ($p = 0.0413$). Third, for female observers, the incidence of disparity values >22 arcmin was much greater for crossed (N= 6) than uncrossed (N=1) pedestal values.

Chapter 4

Discussion

Variation in Optimal Stereoacuity in the General Population

The present study established norms for stereopsis using the data from 116 observers under 60 years of age. Of the 116 observers less than 60, 106 could complete testing with 100 ms stereograms. The distribution of optimal stereo threshold values plotted logarithmically described a normal distribution with a mean of 1.57 log arcsec and a standard deviation of 0.227 log arcsec: in terms of linear units, this corresponds to the geometric mean value of 37 arcsec. A geometric mean of 37 arcsec is consistent with previous studies of stereoacuity in which random-dot stereograms have been used as test stimuli (Wood & Tomlinson, 1976; Harwerth & Rawlings, 1977; Greene & Madden, 1987). On a logarithmic scale, 103 observers had threshold values within ±2 standard deviations of this mean (13-109 linear arcsec), a range subsequently defined as *stereo normal*. In addition, one individual was unusually sensitive while 2 more observers had values slightly greater than this range (110-114 arcsec).

The resulting geometric mean is much larger than the typical "average value" (usually a median or arithmetic mean) for stereoacuity reported in the literature, where values as low as 2 arcsec have been recorded (e.g., Howard, 1919). However, it corresponds to values obtained with tests which better eliminated non-stereoscopic cues for depth. For example, Greene and Madden (1987) found a mean threshold of approximately 34 arcsec using the Randot Stereo Test, and Heron, Dholakia, Collins, & McLaughlan (1985) reported a mean of 28.1 arcsec when using the Randot Stereo Test and 36.6 arcsec when using the Titmus

Stereo Test. In addition, most previous studies only describe the mean (or median) and range of stereo thresholds; none fully came to grips with problems of establishing norms. The present study uniquely establishes norms for stereo sensitivity based upon the statistical analysis of data from the 106 observers who could complete testing with 100 ms duration stereograms and semi quantitative observations from the 10 observers who could not.

Incidence of Stereo Deficiencies

Of the 116 observers studied under age 60, 10 (8%) could not complete testing with 100 ms duration stereograms: 9 of these who were able to detect stereograms of longer duration were designated "markedly stereo impaired," while 1 could not detect any stereogram and was designated "stereoblind." This approximate 1% figure for stereoblindness is comparable to less well specified figures including an "informal" report of 2% within the general population by Julesz (1971) and a value of 3% reported by Newhouse and Uttal (1982). The present 8% figure for "stereo impairment" is considerably lower than the 30% value reported by Richards (1970; see also Hering & Bechtoldt, 1981). The figure reported in the present study is likely more valid because it relies upon the accuracy of six categories of stereo sensitivity: four of these are statistically defined in terms of the norms summarized above; while only semi-quantitative, the designations "markedly stereo-impaired" or "stereoblind" are nevertheless operationally defined. Any disagreement between the present results and previous data is based in part upon the relatively small number of observers measured in this and previous studies (i.e., it is impossible to establish one exact value of between 1 and 3% without studying thousands of observers), the lack of strict operational definitions used in previous studies, and/or the "pass/fail" testing criteria used by previous investigators.

Obviously, the incidence of stereo impairment is much higher if results from older observers are considered.

Influence of Age on Stereopsis

The results of the present study were interpreted to indicate that there are two different types of influences of aging on stereoacuity. Firstly, some factor is responsible for the highly significant linear correlation between stereoacuity and age. As a consequence, many older observers would not fall into the "normal" range for stereopsis established with younger observers. For example, in Figure 9, the least squares regression line crossed the demarcating value between "normal" and "mildly stereo impaired" for observers aged 65. Among observers aged 60-79, 25% are mildly stereo-impaired and an additional 9% are moderately stereoimpaired; for observers less than 60, only 2% were mildly and 0% were moderately stereo-impaired. However, the present study also indicates that the incidence of failure to complete testing with 100 ms duration stereograms increases sharply with age. That is, the incidence of "marked" stereo-impairment or "stereoblindness" is only 9% in observers less than 60, while this incidence increases to 21% in observers ages 60-69 and 50% in observers ages 70-79. These data were interpreted to indicate the importance of a second, age-related cataclysmic factor causing a deterioration in stereoscopic vision.

The nature of these two factors which could contribute to an age-related influence on stereoacuity are unclear but are different from any in the literature pertaining to stereopsis. Typically, age-related visual functions are explained by a single factor. For example, visual acuity has been reported to decline linearly across age ranges (Baltes & Lindenberger, 1997). Haegerstrom-Portnoy, Schneck, & Brabyn (1999) also described one equation which predicts a general deterioration in several visual abilities (including stereopsis) with age. However, this function likely stresses the importance of optical factors within the eye because it predicts age-related changes in visual acuity that could not play a role in the present study. However, age-related deterioration in various visual functions can be related to neural, in addition to ocular factors. The reliance upon a cerebral cue (stereopsis) for depth in the current study reinforces this possibility. Additionally, currently popular theories relate sensory functioning to the whole brain (i.e., the "common cause" hypothesis). Lindengberger and Baltes (1994) provided evidence for such a theory when they found that visual and auditory acuity together accounted for 93% of the age-related variance in intelligence in their sample.

If age-related deterioration in various visual functions can be related to neural, in addition to ocular factors, a two-factor approach is more conceivable. For example, it is well established that both motor coordination and various types of memory decrease markedly with aging in the normal general population, but the majority of individuals do not develop either Parkinson's or Alzheimer's disease. Unfortunately, the specific mechanism behind such a two-factored approach to aging and stereopsis remains unclear.

Some researchers have looked to the magnocellular/parvocellular distinction for possible clues to the age-related deterioration in stereoacuity. However, it is unclear to what extent these theoretical divisions are operative even in non pathological stereopsis. For example, single unit recording in the primate has found evidence for stereopsis in the magnocellular cells in layer 4B of V1, the thick stripes of V2, and V3 and MT (DeYoe & Van Essen, 1988). However, lesions to parvocellular cells in the lateral geniculate nucleus of the primate have been found to impair fine stereoacuity (Schiller, Logothetis, & Charles, 1990). Regardless, a detailed review by Spear (1993) suggests little or no age-related difference in stereopsis specific to either the magnocellular or parvocellular systems. On the other hand, an age-related decrease in functional segregation not specific to either processing system has been found in at least one study investigating the "what" and "where" streams of visual processing. Grady et al. (1992) found rCBF increases mostly in occipitotemporal cortex during face-matching tasks, while during dot-location matching tasks, more activation of superior parietal cortex was found. The aforementioned results were found with both young and old observers. However, statistical analyses revealed more activation of the occipitotemporal cortex during the dot-location task and more activation of the superior parietal cortex during the face-matching task for older observers. Perhaps the findings of Grady et al. (1992) represent a deterioration in functional segregation at an anatomical level comparable to the loss of specificity reported by Schmolesky, Wang, Mingliang, & Leventhal (2000) at a cellular level in primate (see *Introduction*). In light of the fact that most studies have not found a decrease in actual cell number in cortical visual areas with age (e.g., Peters, Nigro, & McNally, 1997; Kim, Pier, & Spear, 1997), the possibility that some loss of neural response selectivity underlies an age-related deterioration in stereopsis should be seriously considered.

As summarized in Table 2, 12 of the 14 studies indicate that stereoacuity decreases with aging. All of these studies had at least one of the following limitations: testing procedures involving non-stereoscopic as well as stereoscopic cues, failure to control for visual acuity, limited sample of different age groups, and ill-defined or pass/fail testing procedures. In spite of their shortcomings, the previous studies are in agreement with the present findings which show that stereopsis as a cue for depth perception deteriorates with aging. That an age-related decline in depth perception has been reported in several studies that have included non-stereoscopic depth cues could mean that some yet unspecified brain area that utilizes many different depth cues is affected in aging. Such a possibility could be indicated by additional studies which separately investigate the ability of different aged observers to make discriminations based upon the individual use of other types of depth cues.

In the present study, observers were excluded from participating if they reported a history of ocular pathology and/or visual acuity assessed separately in each eye was less than 20/30 (6/9). Additionally, differential effects of luminance, practice, and/or education did not affect results. The brief exposure times of the stimuli used in the present study (i.e., 100 ms) did not appear to differentially effect stereoacuity of younger versus older observers. That is, despite brief exposure times, observers were given unlimited time to respond. Even with brief exposure times, it has been reported that what suffers with age on such a tachistoscopic task is not task performance itself, but rather reaction time. For example, Anderson, Craik, & Naveh-Benjamin (1998) demonstrated that when older observers were required to complete a reaction time task concurrent with completion of a memory task, reaction time suffered in older individuals compared to younger while no difference in actual memory performance was noted.

Other possible factors that were not controlled may have affected measurement of stereoacuity. For example, it is conceivable that some observers may have suffered from various degrees of strabismus without awareness of the fact. Strabismus, or squint, is a deficit in convergence of the eyes on the intended fixation point. However, if strabismus first occurs in an older child or adult, stereopsis need not be effected if the condition is corrected. Furthermore, strabismus occurs in approximately 7% of the population (Graham, 1974), whereas the results of the present study indicated an incidence of stereoblindness in only 1% of observers below age 60. Another factor concerns the method of assessing visual acuity.

Although Snellen acuity was assessed at 20 feet, stereoacuity was measured at 1 m. Thus, it is possible that some observers, particularly those of older ages who wore bifocals and trifocals, may have had difficulty properly refracting at the test distance.

Variation in Stereoalignment

Stereoacuity is typically maximal at the plane of fixation and declines with increasing distance from fixation (Krekling, 1974). However, the presence of a fixation disparity results in optimal stereoacuity occurring some distance in front of, or behind the plane of fixation. The present study considered the prevalence of fixation disparities in 122 observers with optimal stereoacuity values within the normal range (less than 110 arcsec): 89% had fixation disparities which were 11 arcmin or smaller. Fixation disparity reportedly does not exceed 30 arcmin (e.g., see Carter, 1964) except with peripheral stimulus presentation and/or lack of a fixation target. In fact, neither of these factors could account for the existence of fixation disparities greater than 22 arcmin in 7 (6%) of the observers in the present study. It is possible that these incidences of extreme fixation disparities correlate with two of the types of stereo-impairment reported by Richards (1971): this report had a tremendous influence on the subsequent binocular vision literature (e.g., Fischer and Poggio, 1979). Richards and later investigators interpreted the incidence of different types of stereo-impairment in terms of the existence of separate types of cerebral mechanisms. However, it should be mentioned that in the present study, fixation disparity was defined as optimal stereoacuity with non-zero disparity pedestals. This differs from more classic definitions which typically measure fixation disparity in two ways. Binocular scleral search coils are used to provide objective values of fixation while the shift in dichoptic nonius line alignment provides subjective measures of fixation disparity.

Although individual phorias (i.e., a latent strabismus evident when both eyes are not given a fusible stimulus) may also affect measurement of fixation disparity, rarely did more than several hundred milliseconds pass before an observer was presented with a salient stimulus, while it takes approximately 20 seconds for an eye to come to rest in its position of phoria (Schor, 1979). Thus, it is unlikely that estimates of fixation disparity were affected by undetected phorias.

Results of the present study found no significant change in the incidence or severity of fixation disparity with age, in contrast to the findings of Yekta, Pickwell, and Jenkins (1989). It is likely that the difference in the operational definition of fixation disparity used by Yekta et al. as opposed to that used in the present study was responsible for the contrasting results.

Gender Differences in Stereopsis

Confirming previous reports (Yap, Brown, & Clarke, 1994; Rubin et al., 1997), the present study found no significant gender differences in optimal stereoacuity. However, two gender differences in the incidence of fixation disparity did occur. First, females were much more likely to exhibit optimal stereoacuity with depth pedestals containing crossed retinal disparity while males were more likely to do so with pedestals containing uncrossed retinal disparity. Second, about 8% of the women while 0% of the men were most sensitive with pedestals greater than 22 arcmin from the plane of fixation. Although these gender differences are striking, there appeared to be no underlying genetic or environmental reason for this difference, which has not been reported previously.

Summary

The present study provides normative data for stereoacuity previously unavailable in the literature. Statistical analyses were used to provide quantitative categories of stereoacuity. Resulting corresponding qualitative descriptors were added. While no influence of gender on stereoacuity was found, a definitive age-related deterioration in stereoacuity did occur. Not only did stereoacuity decline with age, but the incidence and severity of stereo-impairment increased with age. Lastly, the incidence and severity of fixation disparity was studied. Approximately 50% of the observers examined exhibited maximal stereoacuity when viewing stimuli off of the plane of fixation.

Appendix A.

Observer Code	On List B?	Sex	Age	Stereo threshold by disparity pedestal in arcmin (+ = crossed/- = uncrossed) -55	-44	-33	-22	-11	0	+11	+22	+33	+44	+55
08030m77	no	m	77	5647	3308	872	1157	552	6042	1165	3992	2749	8826	5087
08040m75	B	m	75	6033	2262	6425	1953	9045	401	117	99	244	571	5338
08040m72	no	m	72	2029	8631	9167	358	149	1775	1459	5010	4107	6540	5706
04190m71	B	m	71	1391	1221	401	212	74	154	80	148	9423	636	1994
08100m68	B	m	68	6583	5901	3680	107	38	67	273	529	2684	4441	8105
06240m67	no	m	67	6706	3085	2154	843	176	5182	5131	247	2648	6033	1427
08180m66	B	m	66	2863	1605	8991	113	101	64	108	214	1084	1252	1565
062a0m66	no	m	66	1994	2703	2894	529	1491	962	2000	3252	6216	3046	2507
062b0m66	no	m	66	5651	3495	6031	5247	160	3210	1005	5412	5663	1834	5074
09159m64	B	m	64	3047	2203	697	156	36	42	151	333	962	1110	5774
07210m64	no	m	64	3623	6323	2041	3445	210	315	782	365	2752	2501	4038
05138m63	B	m	63	9997	9996	3936	9887	7583	108	248	750	4316	1303	9997
09159m60	no	m	60	5414	6795	8991	9556	3184	1208	2972	205	495	1013	4179
10069m60	no	m	60	2652	4912	1441	556	151	400	7303	4996	2391	3004	1684
05078m59	B	m	59	2480	1335	1293	240	39	18	4110	2252	1890	7158	5830
01070m57	B	m	57	1794	4604	6417	679	142	49	142	304	3795	6995	4430
01140m57	B	m	57	5834	7280	4312	1526	114	77	34	155	309	1026	4081
06240m56	B	m	56	1176	5910	2475	8184	1690	896	97	1266	843	783	3346
04108m56	B	m	56	3562	4087	1418	277	87	44	71	158	4556	1588	2560
06240m54	B	m	54	2100	1648	893	493	154	38	30	102	932	1125	1295
04298m53	B	m	53	3782	1504	627	179	56	40	1881	194	1004	2154	9301
10229m52	B	m	52	7212	2510	5716	563	80	15	36	130	306	1176	1475
10279m51	B	m	51	6204	6603	2173	406	51	28	112	273	646	5582	7185

Appendix A. (con't)

Observer Code	On List B?	Sex	Age	Stereo threshold by disparity pedestal in arcmin (+ = crossed/- = uncrossed) -55	-44	-33	-22	-11	0	+11	+22	+33	+44	+55
12179m50	B	m	50	1508	789	343	86	22	39	51	262	775	1073	1669
02190m48	B	m	48	3306	5870	6630	9556	2716	214	99	9045	6673	5469	4016
04108m48	B	m	48	1469	1555	1404	791	220	45	44	23	107	2435	2454
09159m47	B	m	47	1453	2926	2951	166	85	46	176	511	1332	1751	1705
01280m46	B	m	46	2695	2807	520	239	35	18	38	133	843	1166	2332
02230m43	B	m	43	9010	1663	1161	1576	466	96	752	661	829	2244	3894
10019m43	B	m	43	4176	1022	417	110	30	173	91	155	3173	5535	3735
09229m42	B	m	42	2080	1692	3185	356	134	61	85	198	903	852	8858
06098m42	B	m	42	1813	978	503	117	17	38	81	202	4105	1942	9423
09309m39	B	m	39	1490	1139	1110	111	72	67	82	208	1330	2213	9556
03080m39	B	m	39	2116	1280	3756	4128	96	25	37	2559	2554	2174	5474
01140m39	B	m	39	6980	1418	4127	1673	61	949	2122	8724	954	9422	1523
02110m35	B	m	35	5124	8222	962	857	106	19	104	6944	1159	2375	4391
08259m34	B	m	34	2754	1218	919	261	58	230	70	188	1240	6321	2907
10219m34	B	m	34	6006	8247	1336	296	50	39	72	134	607	1320	7120
05278m31	B	m	31	5374	4493	459	169	36	21	43	85	452	892	1238
05278m30	B	m	30	998	421	232	33	27	58	360	720	1062	3522	2804
04260m30	B	m	30	2573	2820	455	126	45	15	42	141	254	493	1696
10219m30	B	m	30	4319	1208	356	179	36	34	84	460	600	703	1813
04130m29	B	m	29	2239	7133	2749	261	74	37	1908	225	884	2310	2334
02180m28	B	m	28	8922	917	279	227	54	19	48	105	1607	1407	2198
02230m28	B	m	28	3272	1632	5325	3024	163	83	122	39	900	6075	6141
03080m27	B	m	27	5390	1293	1184	259	51	24	27	156	321	974	4038

Appendix A. (con't)

Observer	On			Stereo threshold by disparity pedestal in arcmin (+ = crossed/- = uncrossed)										
Code	List B?	Sex	Age	-55	-44	-33	-22	-11	0	+11	+22	+33	+44	+55
05318m22	B	m	22	1634	1538	5520	575	1232	22	26	2697	578	6780	5802
02230m22	B	m	22	5348	4208	1341	5257	65	12	248	1831	4120	1490	2692
03068m22	B	m	22	1683	828	508	80	40	88	423	4927	4275	1746	1278
05318m21	B	m	21	6841	1055	320	58	47	23	29	153	6328	2097	1891
04070m20	B	m	20	1792	1043	1082	1469	509	53	37	30	140	622	1156
02160m19	B	m	19	8635	1254	454	218	50	29	44	38	211	398	1457
040a0m19	B	m	19	1004	2605	2375	102	44	23	34	114	612	1150	1345
040b0m19	B	m	19	8862	1251	457	169	75	149	428	1490	1071	7120	2435
03030m19	B	m	19	4936	4897	4514	1999	1605	195	81	115	262	1256	2980
08030f79	B	f	79	8348	5942	1598	677	172	58	196	2779	7684	2289	2824
04190f78	no	f	78	1490	940	2418	356	165	311	941	178	969	1269	1526
08110f76	no	f	76	8990	4542	2863	9556	341	190	549	475	1201	1261	2507
083a0f76	no	f	76	8991	2180	1010	151	189	2683	2560	6097	7493	1359	9287
08310f75	B	f	75	9148	2621	3327	420	92	40	48	206	485	949	1490
08110f70	B	f	70	1823	3555	701	358	80	2565	2036	629	1794	2270	4861
06200f69	B	f	69	4826	5118	4465	661	165	58	35	223	987	2802	9301
07130f68	B	f	68	7638	2548	1559	4916	945	33	42	86	197	3790	5250
08110f65	no	f	65	8934	9423	1070	393	370	413	1466	5624	7169	2593	2561
08110f63	B	f	63	5597	2448	8389	499	145	37	74	224	607	3171	2652
07210f63	no	f	63	6216	8420	1269	574	428	7515	564	5194	1490	7857	4487
01140f63	B	f	63	6883	1113	776	250	49	34	90	491	764	9301	2063
05308f61	no	f	61	8459	9189	7759	1334	7982	127	215	352	7417	1504	2242
04228f61	no	f	61	6893	9033	7645	500	229	141	159	482	1491	1213	1580

Appendix A. (con't)

Observer	On			Stereo threshold by disparity pedestal in arcmin (+ = crossed/- = uncrossed)										
Code	List B?	Sex	Age	-55	-44	-33	-22	-11	0	+11	+22	+33	+44	+55
08030f60	B	f	60	2391	8954	8552	568	145	65	23	100	434	1217	2287
10209f58	B	f	58	9031	4945	1571	928	144	183	37	149	1468	1073	1391
12109f57	B	f	57	6417	4037	1644	2235	270	38	49	328	428	1385	1638
01210f57	B	f	57	2295	6082	8184	1592	217	110	45	125	529	587	3278
01070f56	B	f	56	3102	1831	1409	346	114	82	64	302	996	1508	2124
10209f55	B	f	55	4261	1665	1182	318	120	32	104	431	2114	7521	2515
06018f55	B	f	55	2509	7349	1427	1965	615	99	79	211	394	1138	2435
02160f54	B	f	54	1694	2005	1171	198	132	45	146	263	1130	3443	5851
05268f54	B	f	54	5790	1239	917	297	121	42	74	107	315	890	1617
10229f53	B	f	53	3603	1776	1150	1111	554	415	170	66	70	128	1049
020a0f52	B	f	52	6304	4923	1803	1120	181	46	31	260	754	1154	2330
020b0f52	B	f	52	4318	6862	697	1335	145	32	46	78	981	2088	5362
12039f52	B	f	52	7243	7649	7894	749	454	82	32	129	361	2554	1814
03010f52	no	f	52	2273	1684	8491	1974	2435	114	2118	1261	7493	7381	3809
09249f51	B	f	51	4130	1663	3523	302	116	55	47	657	697	1144	1902
12179f50	B	f	50	2384	3040	442	265	56	37	145	164	619	1414	1823
03010f50	B	f	50	3611	1538	992	502	119	44	19	59	70	330	8049
01280f49	B	f	49	4349	3249	5682	987	399	2732	83	975	8451	1156	1664
01210f49	B	f	49	951	1524	721	168	130	31	2631	281	706	1644	4697
09229f48	B	f	48	3470	4469	7522	6724	5393	1515	3017	166	311	89	53
02040f46	B	f	46	2418	2994	3349	768	138	65	69	825	995	1555	1598
12109f45	B	f	45	9167	6513	4648	318	114	35	132	273	1031	4887	1965
06088f45	B	f	45	6367	3208	5339	266	127	76	137	325	1761	2109	6323

Appendix A. (con't)

Observer Code	On List B?	Sex	Age	Stereo threshold by disparity pedestal in arcmin (+ = crossed/- = uncrossed) -55	-44	-33	-22	-11	0	+11	+22	+33	+44	+55
05158f43	no	f	43	8834	7426	1376	4401	215	127	114	125	423	4252	1779
04028f43	B	f	43	1396	849	251	86	30	36	40	110	461	1383	1955
10279f42	B	f	42	325	34	35	96	462	4663	2443	5361	2956	5541	3121
02230f41	B	f	41	9301	1573	1056	403	87	32	16	40	284	1016	1561
02160f39	B	f	39	9289	5580	6634	6133	6060	84	265	3467	5774	5259	2465
12039f39	B	f	39	1469	1024	831	125	85	52	111	176	5416	2751	801
04098f38	B	f	38	5454	6456	2735	198	100	47	52	456	1730	3076	4214
06038f38	B	f	38	1724	2211	7572	148	65	64	132	1020	1270	2927	8417
07178f36	B	f	36	5186	778	272	84	31	84	408	538	5637	8606	9423
10029f35	B	f	35	824	1180	228	60	22	32	36	240	1165	1245	2571
03010f34	B	f	34	1792	2770	1572	1945	160	92	241	417	199	3152	1965
01070f33	B	f	33	2551	1821	2907	3142	82	1705	3889	544	8325	5541	2492
10069f32	B	f	32	2464	776	137	34	50	341	320	881	1251	2435	4918
09309f32	B	f	32	8020	9422	8826	2314	902	32	2346	1336	3212	2030	6228
03238f32	B	f	32	1982	2700	7063	406	71	31	124	3305	1155	1434	2168
12178f32	B	f	32	2412	2050	607	431	161	30	36	89	219	730	3072
01040f31	B	f	31	8202	4779	2149	413	89	36	145	554	593	2026	8401
06038f31	B	f	31	3335	2105	975	356	70	49	37	89	590	703	2844
04098f28	B	f	28	2273	924	598	156	35	31	33	151	546	1622	1994
05078f26	B	f	26	1780	995	940	201	15	25	25	225	580	936	1983
040a8f26	B	f	26	1971	2119	1096	335	109	38	35	93	1266	2402	1024
040b8f26	B	f	26	2073	2397	1392	768	246	40	44	164	192	952	6443
04068f25	B	f	25	5647	4787	2292	701	121	34	25	108	166	1066	677

Appendix A. (con't)

Observer Code	On List B?	Sex	Age	Stereo threshold by disparity pedestal in arcmin (+ = crossed/- = uncrossed) -55	-44	-33	-22	-11	0	+11	+22	+33	+44	+55
03010f24	B	f	24	4000	3443	544	525	95	59	282	513	940	1576	1242
04238f22	B	f	22	2696	2223	1469	693	85	29	21	8858	437	2882	3010
05228f21	B	f	21	3840	8911	1587	919	188	17	21	39	343	1042	3247
04088f21	B	f	21	1975	6055	5723	2081	800	728	563	64	38	78	474
05088f21	B	f	21	8689	1374	462	413	89	110	305	3010	7429	7983	4039
04308f21	B	f	21	7142	1340	5045	732	101	108	184	285	791	4776	5919
05158f20	B	f	20	2323	9423	1040	206	88	78	210	781	6936	1859	5802
04308f20	B	f	20	3398	1673	604	589	85	36	27	64	199	1039	1434
05138f20	B	f	20	7625	1408	1654	764	364	71	51	36	26	152	622
040a8f20	B	f	20	2307	2465	2264	1266	304	100	36	118	277	4383	2359
05208f20	B	f	20	6252	8414	3553	7249	2007	1671	490	107	56	6905	2761
04088f20	B	f	20	9167	5601	4774	927	383	39	74	224	857	4188	7129
04228f20	B	f	20	4321	1073	981	205	36	24	48	160	540	1347	1663
03030f20	B	f	20	2200	1526	619	163	30	40	94	913	1274	2070	4014
02230f20	B	f	20	9422	2566	3251	3948	2899	62	2130	1091	895	992	1516
040b8f20	B	f	20	1673	2228	769	585	41	30	21	30	160	5239	8602
03030f19	B	f	19	2068	1157	440	65	82	23	27	56	4141	1601	4889
030a0f18	B	f	18	3623	1014	872	78	37	35	150	739	799	9289	7051
030b0f18	B	f	18	4530	2752	1567	1279	114	32	62	733	1172	1618	3339
07098f15	B	f	15	1572	1049	420	34	20	26	66	507	1068	1921	1830

Appendix B.

Trial passed/failed and lowest stereo threshold (by stimulus duration) obtained by observers unable to complete testing with 100 ms stimuli.

Observer code	sex	age	Trial failed	Trial passed	Stimulus duration (ms) 2000	500	200	100
04190m78	m	78	demo	none				
04190m76	m	76	2000	demo				
08250m72	m	72	demo	none				
07280m66	m	66	500	2000	48	675	1155	1965
06088m52	m	52	200	500	173	385		
02110m50	m	50	100	200	288	473	276	1565
02110m46	m	46	500	2000	199	1114		1115
10049m35	m	35	500	2000	16			1336
04050m35	m	35	100	200	138	473	415	1247
02180m29	m	29	demo	none				
04190f77	f	77	500	2000	34			
083b0f76	f	76	2000	demo	502			
04190f74	f	74	500	2000	38			
05268f73	f	73	100	200	35	77	419	856
08240f72	f	72	500	2000	382	735		
041a0f72	f	72	2000	demo				
041b0f72	f	72	2000	demo				
04190f68	f	68	2000	demo				
08250f63	f	63	500	2000	83	1131		
07210f62	f	62	100	200	23		17	2008
04190f60	f	60	2000	demo				
09019f50	f	50	500	2000	251			1098
04298f46	f	46	500	2000	102			2025
02160f42	f	42	200	500	323	327	859	2086
04248f20	f	20	500	2000	144			1239

Appendix C.

Observer Code	On List A?	Sex	Age	Stereo threshold by disparity pedestal in arcmin (+ = crossed/- = uncrossed)											Pedestal of lowest threshold value
				-55	-44	-33	-22	-11	0	+11	+22	+33	+44	+55	
10279f42	A	f	42	325	34	35	96	462	4663	2443	5361	2956	5541	3121	-44
10279f42	A	m	20	3899	6321	3235	49	8184	1301	4081	1127	2363	9289	8357	-22
042b8m19	no	m	19	1242	477	376	53	393	116	857	2133	2186	8184	5131	-22
10069f32	A	f	32	2464	776	137	34	50	341	320	881	1251	2435	4918	-22
040b0m19	A	m	19	8862	1251	457	169	75	149	428	1490	1071	7120	2435	-11
08110f70	A	f	70	1823	3555	701	358	80	2565	2036	629	1794	2270	4861	-11
12179m50	A	m	50	1508	789	343	86	22	39	51	262	775	1073	1669	-11
04190m71	A	m	71	1391	1221	401	212	74	154	80	148	9423	636	1994	-11
052d8f19	no	f	19	6512	6167	5968	176	30	3286	1526	4536	2362	6817	4857	-11
01140m39	A	m	39	6980	1418	4127	1673	61	949	2122	8724	954	9422	1523	-11
07178f36	A	f	36	5186	778	272	84	31	84	408	538	5637	8606	9423	-11
08100m68	A	m	68	6583	5901	3680	107	38	67	273	529	2684	4441	8105	-11
05088m22	no	m	22	2966	2976	2271	592	52	80	63	75	315	1204	6033	-11
03030f20	A	f	20	2200	1526	619	163	30	40	94	913	1274	2070	4014	-11
04308f21	A	f	21	7142	1340	5045	732	101	108	184	285	791	4776	5919	-11
05078f26	A	f	26	1780	995	940	201	15	25	25	225	580	936	1983	-11
05068m25	no	m	25	1701	1406	481	37	13	159	136	5593	1915	7481	7437	-11
06098m42	A	m	42	1813	978	503	117	17	38	81	202	4105	1942	9423	-11
05088f21	A	f	21	8689	1374	462	413	89	110	305	3010	7429	7983	4039	-11
050b8m21	no	m	21	2470	1923	1311	388	89	3603	103	1765	6188	1767	2262	-11
04028f43	A	f	43	1396	849	251	86	30	36	40	110	461	1383	1955	-11
07098f15	A	f	15	1572	1049	420	34	20	26	66	507	1068	1921	1830	-11

Appendix C. (con't)

Observer	On			Stereo threshold by disparity pedestal in arcmin (+ = crossed/- = uncrossed)											Pedestal of lowest
Code	List A?	Sex	Age	-55	-44	-33	-22	-11	0	+11	+22	+33	+44	+55	threshold value
01070f33	A	f	33	2551	1821	2907	3142	82	1705	3889	544	8325	5541	2492	-11
08259m34	A	m	34	2754	1218	919	261	58	230	70	188	1240	6321	2907	-11
10029f35	A	f	35	824	1180	228	60	22	32	36	240	1165	1245	2571	-11
04248f18	no	f	18	4437	2480	1818	248	69	83	462	164	895	2014	1441	-11
03068m22	A	m	22	1683	828	508	80	40	88	423	4927	4275	1746	1278	-11
05208m19	no	m	19	2464	1088	553	181	23	940	35	2644	525	1144	1745	-11
05278m30	A	m	30	998	421	232	33	27	58	360	720	1062	3522	2804	-11
05138f19	no	f	19	615	525	205	45	29	47	103	231	572	970	2209	-11
04238f17	no	f	17	2125	1013	256	66	30	52	101	168	7601	1570	3990	-11
05078m19	no	m	19	9088	8053	4855	416	31	44	63	5836	1148	2138	7507	-11
10019m43	A	m	43	4176	1022	417	110	30	173	91	155	3173	5535	3735	-11
042a8f19	no	f	19	1670	2566	1376	366	56	88	126	129	518	6555	9301	-11
04238f18	no	f	18	6065	9167	5352	176	53	66	102	722	3890	2750	2733	-11
04308m20	no	m	20	1813	3286	2498	251	30	3440	2156	1088	1049	5531	2604	-11
09159m64	A	m	64	3047	2203	697	156	36	42	151	333	962	1110	5774	-11
04260m30	A	m	30	2573	2820	455	126	45	15	42	141	254	493	1696	0
02230m22	A	m	22	5348	4208	1341	5257	65	12	248	1831	4120	1490	2692	0
08030f79	A	f	79	8348	5942	1598	677	172	58	196	2779	7684	2289	2824	0
08310f75	A	f	75	9148	2621	3327	420	92	40	48	206	485	949	1490	0
07130f68	A	f	68	7638	2548	1559	4916	945	33	42	86	197	3790	5250	0
08110f63	A	f	63	5597	2448	8389	499	145	37	74	224	607	3171	2652	0
04130m29	A	m	29	2239	7133	2749	261	74	37	1908	225	884	2310	2334	0

Appendix C. (con't)

Observer Code	On List A?	Sex	Age	Stereo threshold by disparity pedestal in arcmin (+ = crossed/- = uncrossed) -55	-44	-33	-22	-11	0	+11	+22	+33	+44	+55	Pedestal of lowest threshold value
040a0m19	A	m	19	1004	2605	2375	102	44	23	34	114	612	1150	1345	0
08180m66	A	m	66	2863	1605	8991	113	101	64	108	214	1084	1252	1565	0
01040f31	A	f	31	8202	4779	2149	413	89	36	145	554	593	2026	8401	0
04108m56	A	m	56	3562	4087	1418	277	87	44	71	158	4556	1588	2560	0
05138m63	A	m	63	9997	9996	3936	9887	7583	108	248	750	4316	1303	9997	0
05268f54	A	f	54	5790	1239	917	297	121	42	74	107	315	890	1617	0
04088f17	no	f	17	4107	1500	568	125	52	16	36	149	411	902	6959	0
042b8f19	no	f	19	7294	5764	902	8166	145	69	161	381	4440	2693	2213	0
02160m19	A	m	19	8635	1254	454	218	50	29	44	38	211	398	1457	0
05078f19	no	f	19	1286	1261	367	86	41	28	56	246	772	2078	1254	0
04228f20	A	f	20	4321	1073	981	205	36	24	48	160	540	1347	1663	0
10279m51	A	m	51	6204	6603	2173	406	51	28	112	273	646	5582	7185	0
03080m39	A	m	39	2116	1280	3756	4128	96	25	37	2559	2554	2174	5474	0
12178f32	A	f	32	2412	2050	607	431	161	30	36	89	219	730	3072	0
09309f32	A	f	32	8020	9422	8826	2314	902	32	2346	1336	3212	2030	6228	0
10209f55	A	f	55	4261	1665	1182	318	120	32	104	431	2114	7521	2515	0
01210f49	A	f	49	951	1524	721	168	130	31	2631	281	706	1644	4697	0
030b0f18	A	f	18	4530	2752	1567	1279	114	32	62	733	1172	1618	3339	0
03238f32	A	f	32	1982	2700	7063	406	71	31	124	3305	1155	1434	2168	0
03030f19	A	f	19	2068	1157	440	65	82	23	27	56	4141	1601	4889	0
05318m21	A	m	21	6841	1055	320	58	47	23	29	153	6328	2097	1891	0
04098f28	A	f	28	2273	924	598	156	35	31	33	151	546	1622	1994	0

Appendix C. (con't)

Observer	On			Stereo threshold by disparity pedestal in arcmin (+ = crossed/- = uncrossed)											Pedestal of lowest
Code	List A?	Sex	Age	-55	-44	-33	-22	-11	0	+11	+22	+33	+44	+55	threshold value
01140f63	A	f	63	6883	1113	776	250	49	34	90	491	764	9301	2063	0
05318m22	A	m	22	1634	1538	5520	575	1232	22	26	2697	578	6780	5802	0
05278m31	A	m	31	5374	4493	459	169	36	21	43	85	452	892	1238	0
05068m17	no	m	17	4605	6466	1381	392	101	34	63	644	868	1022	1800	0
03080m27	A	m	27	5390	1293	1184	259	51	24	27	156	321	974	4038	0
030a0f18	A	f	18	3623	1014	872	78	37	35	150	739	799	9289	7051	0
02110m35	A	m	35	5124	8222	962	857	106	19	104	6944	1159	2375	4391	0
02180m28	A	m	28	8922	917	279	227	54	19	48	105	1607	1407	2198	0
12109f45	A	f	45	9167	6513	4648	318	114	35	132	273	1031	4887	1965	0
01280m46	A	m	46	2695	2807	520	239	35	18	38	133	843	1166	2332	0
020b0f52	A	f	52	4318	6862	697	1335	145	32	46	78	981	2088	5362	0
02040f46	A	f	46	2418	2994	3349	768	138	65	69	825	995	1555	1598	0
05158f19	no	f	19	4964	4272	1235	1188	432	36	121	224	762	8502	6006	0
052a8f19	no	f	19	1154	604	417	173	40	33	44	133	466	4501	1376	0
05078m59	A	m	59	2480	1335	1293	240	39	18	4110	2252	1890	7158	5830	0
05228f21	A	f	21	3840	8911	1587	919	188	17	21	39	343	1042	3247	0
03010f24	A	f	24	4000	3443	544	525	95	59	282	513	940	1576	1242	0
12179f50	A	f	50	2384	3040	442	265	56	37	145	164	619	1414	1823	0
10229m52	A	m	52	7212	2510	5716	563	80	15	36	130	306	1176	1475	0
10219m30	A	m	30	4319	1208	356	179	36	34	84	460	600	703	1813	0
09229m42	A	m	42	2080	1692	3185	356	134	61	85	198	903	852	8858	0
12109f57	A	f	57	6417	4037	1644	2235	270	38	49	328	428	1385	1638	0

Appendix C. (con't)

Observer Code	On List A?	Sex	Age	Stereo threshold by disparity pedestal in arcmin (+ = crossed/- = uncrossed) -55	-44	-33	-22	-11	0	+11	+22	+33	+44	+55	Pedestal of lowest threshold value
02230f20	A	f	20	9422	2566	3251	3948	2899	62	2130	1091	895	992	1516	0
04088f20	A	f	20	9167	5601	4774	927	383	39	74	224	857	4188	7129	0
10219m34	A	m	34	6006	8247	1336	296	50	39	72	134	607	1320	7120	0
050a8m21	no	m	21	2092	7769	3470	4701	136	39	44	122	236	787	1555	0
06038f38	A	f	38	1724	2211	7572	148	65	64	132	1020	1270	2927	8417	0
04298m53	A	m	53	3782	1504	627	179	56	40	1881	194	1004	2154	9301	0
040b8f26	A	f	26	2073	2397	1392	768	246	40	44	164	192	952	6443	0
04098f18	no	f	18	1414	2050	902	238	59	41	50	118	217	1410	1565	0
04308f19	no	f	19	2118	2750	718	318	52	36	186	408	931	6661	3769	0
01070m57	A	m	57	1794	4604	6417	679	142	49	142	304	3795	6995	4430	0
09309m39	A	m	39	1490	1139	1110	111	72	67	82	208	1330	2213	9556	0
05148m18	no	m	18	6815	5285	2217	1376	440	67	335	669	658	1210	2043	0
02160f54	A	f	54	1694	2005	1171	198	132	45	146	263	1130	3443	5851	0
09159m47	A	m	47	1453	2926	2951	166	85	46	176	511	1332	1751	1705	0
05018m19	no	m	19	7974	1466	4571	295	61	46	74	95	706	3028	1335	0
05208m20	no	m	20	7288	3192	5375	8444	297	105	214	296	805	1555	1758	0
04098f38	A	f	38	5454	6456	2735	198	100	47	52	456	1730	3076	4214	0
12039f39	A	f	39	1469	1024	831	125	85	52	111	176	5416	2751	801	0
02230m43	A	m	43	9010	1663	1161	1576	466	96	752	661	829	2244	3894	0
03010f34	A	f	34	1792	2770	1572	1945	160	92	241	417	199	3152	1965	0
06088f45	A	f	45	6367	3208	5339	266	127	76	137	325	1761	2109	6323	0
05158f20	A	f	20	2323	9423	1040	206	88	78	210	781	6936	1859	5802	0

Appendix C. (con't)

Observer Code	On List A?	Sex	Age	Stereo threshold by disparity pedestal in arcmin (+ = crossed/- = uncrossed) -55	-44	-33	-22	-11	0	+11	+22	+33	+44	+55	Pedestal of lowest threshold value
02160f39	A	f	39	9289	5580	6634	6133	6060	84	265	3467	5774	5259	2465	0
06038f31	A	f	31	3335	2105	975	356	70	49	37	89	590	703	2844	11
02190m48	A	m	48	3306	5870	6630	9556	2716	214	99	9045	6673	5469	4016	11
06240m56	A	m	56	1176	5910	2475	8184	1690	896	97	1266	843	783	3346	11
10209f58	A	f	58	9031	4945	1571	928	144	183	37	149	1468	1073	1391	11
02230f41	A	f	41	9301	1573	1056	403	87	32	16	40	284	1016	1561	11
020a0f52	A	f	52	6304	4923	1803	1120	181	46	31	260	754	1154	2330	11
12039f52	A	f	52	7243	7649	7894	749	454	82	32	129	361	2554	1814	11
01280f49	A	f	49	4349	3249	5682	987	399	2732	83	975	8451	1156	1664	11
052b8f19	no	f	19	3465	8991	1472	677	104	38	21	87	2640	1368	5701	11
040b8f20	A	f	20	1673	2228	769	585	41	30	21	30	160	5239	8602	11
04238f22	A	f	22	2696	2223	1469	693	85	29	21	8858	437	2882	3010	11
01210f57	A	f	57	2295	6082	8184	1592	217	110	45	125	529	587	3278	11
042a8m19	no	m	19	4410	2037	1626	660	230	153	65	78	357	554	6412	11
06240m54	A	m	54	2100	1648	893	493	154	38	30	102	932	1125	1295	11
05228m18	no	m	18	3507	2807	2554	6100	782	146	74	92	2330	899	7626	11
09249f51	A	f	51	4130	1663	3523	302	116	55	47	657	697	1144	1902	11
01070f56	A	f	56	3102	1831	1409	346	114	82	64	302	996	1508	2124	11
04068f25	A	f	25	5647	4787	2292	701	121	34	25	108	166	1066	677	11
04308f18	no	f	18	7007	2441	1607	1705	1410	301	60	158	250	615	2478	11
03010f50	A	f	50	3611	1538	992	502	119	44	19	59	70	330	8049	11
03030m19	A	m	19	4936	4897	4514	1999	1605	195	81	115	262	1256	2980	11

Appendix C. (con't)

Observer Code	On List A?	Sex	Age	Stereo threshold by disparity pedestal in arcmin (+ = crossed/- = uncrossed) -55	-44	-33	-22	-11	0	+11	+22	+33	+44	+55	Pedestal of lowest threshold value
04308f20	A	f	20	3398	1673	604	589	85	36	27	64	199	1039	1434	11
040a8f26	A	f	26	1971	2119	1096	335	109	38	35	93	1266	2402	1024	11
08030f60	A	f	60	2391	8954	8552	568	145	65	23	100	434	1217	2287	11
01140m57	A	m	57	5834	7280	4312	1526	114	77	34	155	309	1026	4081	11
06200f69	A	f	69	4826	5118	4465	661	165	58	35	223	987	2802	9301	11
06018f55	A	f	55	2509	7349	1427	1965	615	99	79	211	394	1138	2435	11
040a8f20	A	f	20	2307	2465	2264	1266	304	100	36	118	277	4383	2359	11
05018f18	no	f	18	2984	8357	4214	6067	2106	110	113	74	140	7264	440	22
04070m20	A	m	20	1792	1043	1082	1469	509	53	37	30	140	622	1156	22
04108m48	A	m	48	1469	1555	1404	791	220	45	44	23	107	2435	2454	22
08040m75	A	m	75	6033	2262	6425	1953	9045	401	117	99	244	571	5338	22
10229f53	A	f	53	3603	1776	1150	1111	554	415	170	66	70	128	1049	22
02230m28	A	m	28	3272	1632	5325	3024	163	83	122	39	900	6075	6141	22
05208f20	A	f	20	6252	8414	3553	7249	2007	1671	490	107	56	6905	2761	33
04088f21	A	f	21	1975	6055	5723	2081	800	728	563	64	38	78	474	33
05138f20	A	f	20	7625	1408	1654	764	364	71	51	36	26	152	622	33
052c8f19	no	f	19	3290	2018	3645	1189	9189	9556	1881	5934	144	42	2435	44
05078f18	no	f	18	7259	2106	3605	1195	878	210	134	113	71	35	94	44
09229f48	A	f	48	3470	4469	7522	6724	5393	1515	3017	166	311	89	53	55

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