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Stereopsis and aging

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ABSTRACT

Three experiments investigated whether and to what extent increases in age affect the functionality of stereopsis. The observers' ages ranged from 18 to 83 years. The overall goal was to challenge the older stereoscopic visual system by utilizing high magnitudes of binocular disparity, ambiguous binocular disparity [cf., Julesz, B., & Chang, J. (1976). Interaction between pools of binocular disparity detectors tuned to different disparities. *Biological Cybernetics, 22, 107–119]*, and by making binocular matching more difficult. In particular, Experiment 1 evaluated observers' abilities to discriminate ordinal depth differences away from the horopter using standing disparities of 6.5–46 min arc. Experiment 2 assessed observers' abilities to discriminate stereoscopic shape using line-element stereograms. The direction (crossed vs. uncrossed) and magnitude of the binocular disparity (13.7 and 51.5 min arc) were manipulated. Binocular matching was made more difficult by varying the orientations of corresponding line elements across the two eyes' views. The purpose of Experiment 3 was to determine whether the aging stereoscopic system can resolve ambiguous binocular disparities in a manner similar to that of younger observers. The results of all experiments demonstrated that older observers' stereoscopic vision is functionally comparable to that of younger observers in many respects. For example, both age groups exhibited a similar ability to discriminate depth and surface shape. The results also showed, however, that age-related differences in stereopsis do exist, and they become most noticeable when the older stereoscopic system is challenged by multiple simultaneous factors.

We human observers have the remarkable ability to take the subtle differences between the two eye's views (binocular disparities) and use them to perceive depth and 3-D object shape. This process is called stereopsis (see Howard & Rogers, 1995; Julesz, 1971; Tyler, 1991; Wheatstone, 1838). A large proportion of the past research concerning aging and stereopsis has focused upon stereoacuity, determining the smallest depth difference that can be reliably detected using binocular disparity. At the moment there is no clear answer as to whether increases in age have large negative effects upon stereoscopic acuity or whether the effects of age are minor or even nonexistent. Some of the differences between the results of past studies may be due to the large differences in experimental methodology, task, and apparatus. For example, the experiments to date have utilized: (1) the Howard-Dolman apparatus (Brown, Yap, & Fan, 1993), (2) the Frisby stereotest (Haegerstrom-Portnoy, Schneck, & Brabyn, 1999; Wright & Wormald, 1992), (3) the Verhoeff stereopter (Bell, Wolf, & Bernholz, 1972), (4) the Ortho-Rater (Tiffin, 1952), (5) the Diastereo test (Jani, 1966), and (6) various forms of stereograms, such as the TNO test, the RanDot stereogram, and the Titmus stereotest (Garnham & Sloper, 2006; Greene & Madden, 1987; Laframboise, De Guise, & Faubert, 2006; Yekta, Pickwell, & Jenkins, 1989). A description of many of these tests has been provided by Howard and Rogers (1995).

Three of the previously mentioned studies (Bell et al., 1972; Haegerstrom-Portnoy et al., 1999; Wright & Wormald, 1992) found "strong" effects of age upon stereoacuity. Bell et al. did not measure their observers' visual acuities, so one cannot know in hindsight whether the deterioration that they report is a true reduction in stereoacuity per se, or whether their older observers' poorer performance was due to reduced visual abilities in general. The studies of Haegerstrom-Portnoy et al. and Wright and Wormald both used the Frisby stereotest, which incorporates physical depth differences. Haegerstrom-Portnoy et al. concluded from their results (p. 148) that "stereoacuity is quite poor among the elderly". Two additional studies (Garnham & Sloper, 2006; Laframboise et al., 2006) have found what might be considered "moderate" effects of aging upon stereoacuity. Laframboise et al. found that their observers' average stereoacuity thresholds increased with age from 20 s arc (at 10 years) to about 32 s arc at 85 years of age. Garnham and Sloper found that the magnitude of the obtained age differences depended upon which particular stereoscopic test was used. The age effect was largest when the TNO stereotest

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was used, and was reduced for the Titmus stereotest. When they used the Titmus stereotest, 88.2 percent of the 17–29 year-old age group exhibited thresholds of 40 s arc or better. In contrast, 93.3 percent and 85.7 percent of the 50–69 and 70–83 year-old age groups exhibited thresholds of 50 s arc (or better) or 100 s arc (or better), respectively. One can see, then, that according to their data, older adults do possess stereopsis, but increases in age lead to a significant reduction in stereoacuity (i.e., higher thresholds). Garnham and Sloper conclude (p. 94) that "the results for all four stereotests used in this study show that there is some decline in stereoacuity with age and that this affects both near and distance stereoacuity. It seems likely that this reflects a mild decline in the function of cortical disparity detectors with age".

In contrast to the five studies that found moderate-to-strong effects of age upon stereoacuity, four additional studies have found small-to-nonexistent effects of age. In the study by Brown et al. (1993), their observers' stereoacuities increased from about 16 s arc for observers younger than 60 years of age to 27 s arc for observers that were 60 years of age or older. Notice that this is a "small" effect. The older observers, while significantly worse at the task, could still reliably detect small binocular disparities. This small effect of age was driven in large part by the results of two particular observers. If one removes two "outliers" from the 41 total observers in the Brown et al. study, then the previously significant effect of age becomes non-significant ($F(3,35) = 2.7$, $p > .05$). In any event, in the data of Brown et al., there is more variability within any particular age group than there is across age groups. Greene and Madden (1987) measured their observers' visual acuity, stereoacuity, and contrast sensitivity. They concluded (pp. 752–753) that "when the correlations among the measures were taken into account, contrast sensitivity was the only variable that was a significant discriminator of the two age groups". Four of their 24 older observers (16.7 percent) appeared to be stereoblind. This result may be typical—Richards (1970) concluded (p. 384) "that about 20 percent of the population is unable to detect two of the three disparity conditions" (Richards is referring to crossed, uncrossed, and zero disparities). When Greene and Madden excluded these four stereoblind observers from their analysis, there was no significant effect of age upon stereoacuity. Yekta et al. (1989) used the TNO test. They concluded (p. 120) that "no trend for a change in stereopsis with age was found in this study".

It is clear from this review that there are large differences between the results of the various past studies that have examined aging and stereoacuity. The large difference in outcomes could be due to either differences in methodology or task, or it could be a result of the different populations of older adults whose abilities were being examined. It is instructive to therefore look at the results of a study that examined the stereoscopic abilities of 6400 observers (Tiffin, 1952). Tiffin used a Bausch and Lomb Ortho-Rater in his investigation. In their 1995 book, Howard & Rogers describe some advantages of the Ortho-Rater over the Howard-Dolman apparatus and the Verhoeff stereopter. Tiffin found little to no decrement in stereoacuity with increasing age. He concluded (p. 232) that there was "a slight indication of a drop after the age of fifty-five", but suggested that even this slight drop in performance may be due to an age-related reduction in visual acuity.

In our own past research, we have evaluated the effects of increasing age upon the stereoscopic perception of surface slant and surface shape. Norman, Crabtree, Bartholomew, and Ferrell (in press) found that age did not affect how observers perceive the slant of surfaces defined only by binocular disparity. In contrast, Norman, Dawson, and Butler (2000) and Norman et al. (2006) have shown that aging does lead to significant decreases in observers' ability to perceive the magnitude of front-to-back depth and the 3-D shape of stereoscopic surfaces. They also found, however, that older observers produce the same qualitative patterns of performance as younger observers. For example, Norman, Dawson, and Butler (2000) found that the observers in both age groups perceived more depth with increases in binocular disparity, and that the performance of the younger and older observers was similarly affected by changes in spatial frequency.

One of the most prominent characteristics of stereopsis is that it is robust. Past research has demonstrated that stereopsis persists despite (1) differences in spatial frequency content across the two eyes' views (caused by blurring one retinal image relative to the other, e.g., see Julesz, 1960; Julesz, 1971), (2) each eye's view possessing a different contrast (Legge & Gu, 1989), (3) the magnification of one eye's view relative to the other (Julesz, 1971; Lappin & Craft, 1997), and (4) differences in the orientation of corresponding texture elements across the two eyes' views (Frisby & Julesz, 1975a, 1975b, 1976; Marlowe, 1969; Mitchell & O'Hagan, 1972). The primary purpose of the current set of experiments was to challenge the stereoscopic visual systems of older observers to determine how they are affected by large standing disparities, mismatches in the orientation of corresponding texture elements across stereoscopic half-images, the presence of ambiguous disparities, etc. In particular, Experiment 1 was designed to compare younger and older observers' abilities to discriminate ordinal depth relationships at a variety of standing disparities away from the horopter. Experiment 2 was conducted to determine whether the stereoscopic visual systems of older and younger observers respond similarly to mismatches in the orientations of corresponding texture elements across the left and right eyes' retinal images. The effects of changes in the magnitude and type of binocular disparity (crossed vs. uncrossed) were also evaluated. The purpose of Experiment 3 was to determine whether the stereoscopic visual systems of older observers can resolve ambiguous binocular disparities in the same manner as the stereoscopic visual systems of younger observers.

1. Experiment 1

1.1. Method

1.1.1. Apparatus

The stereograms were created by a dual-processor Apple PowerMacintosh G4 computer, and were displayed on a 22-inch Mitsubishi Diamond Plus 200 color monitor. The resolution of the monitor was 1280 × 1024 pixels. The viewing distance from the observers to the monitor was 100 cm. The room was dimly illuminated by a single 25-watt incandescent light bulb. The stereoscopic views were presented to the observers using CrystalEyes3 LCD-shuttered glasses (StereoGraphics, Inc.).

1.1.2. Stimulus displays

On any given trial, two small red circular spots (luminance was 13.7 cd/m^2, measured with a Minolta LS-110 photometer) were stereoscopically presented for one second against a black background (0.02 cd/m^2). The diameter of each of the spots subtended 17.2 min arc. We chose one second durations, because McKee, Levi, and Bowne (1990) found stereoacuity thresholds to be lowest for stimulus durations of one second. The spots were centered about a fixation cross. Each spot was located 1.15 degrees from the fixation marker; the total angular separation between the two spots was thus 2.3 degrees. The position of the standard spot (in polar coordinates) was randomly determined on each trial, while the test spot was located on the opposite side of the fixation marker (i.e., its orientation in polar coordinates was 180 degrees different from that of the standard). The standard spot was located in front of fixation by either 3, 6, 9, 12, 15, or 18 cm. For an observer with an inter-pupillary distance (ipd) of 6.1 cm (the mean of our observers), these standard depths would correspond to standing disparities of 6.5, 13.4, 20.7, 28.6, 37.0, and 46.0 min arc. The test spot was either closer or farther than the standard by varying amounts; whether the test spot was closer or farther was randomly determined for each trial. Each observer's ipd was measured so that each eye's view could be rendered appropriately.

1.1.3. Procedure

Ordinal depth discrimination thresholds were obtained for each of the six standard depths. On any given trial, the observer was required to identify which spot (either the one towards the right or the one on the left) was closest to them in depth. The observers were required to maintain steady fixation upon the fixation cross. The observers did not know which spots possessed the standard depth or the test depth; they were simply required to indicate which of the two spots was closest to them in depth. No feedback was given regarding the observers' performance. Each observer followed a random order of standard depth conditions.

An adaptive staircase procedure (see Lelkens & Koenderink, 1984; Norman & Todd, 1994) was used to obtain the depth difference thresholds. The initial depth difference (between the standard and test spots) for each observer and standard depth condition was determined by pilot testing. After each correct response, the depth difference was decreased by one step; after each incorrect response, the depth difference was increased by three steps (this procedure converges upon the 75th percentage point of an observer's psychometric function). The initial step size was 0.05 cm, and was halved after the 1st, 3rd, and 7th reversals. For each standard depth condition, data was collected until the tenth reversal. The final estimate of each threshold was obtained by averaging the depth differences for the last eight reversals.

1.1.4. Observers

Twenty observers participated in the experiment. One group of observers consisted of ten older adults (mean age was 73.2 years, SD = 5.6; the range of their ages was 64–83 years). None of these observers reported possessing eye or retinal problems, such as macular degeneration, glaucoma, or cataracts. The other group consisted of ten younger observers (mean age was 20.1 years, SD = 2.2). All of the younger and older observers possessed normal or corrected-to-normal visual acuity: all could resolve details as small as 1.0 min arc. The observers' acuity was measured at one meter with a Landolt C chart (Riggs, 1965). Two of the younger observers were coauthors (A.N.B. and C.L.B.); all of the remaining 18 observers were naïve with regards to the purposes of the experiment, and were unaware of how the experimental stimuli had been generated, etc.

The older observers were recruited from local church and civic groups. No selection criteria were used in recruiting the older participants other than the need for good visual acuity. The only practical requirement was that they be able to drive to our laboratory. Our older observers thus represent adults who are still relatively healthy and lead active lives. Our experimental results are not necessarily representative of less active older adults who live in nursing homes or other assisted-care facilities.

1.2. Results and discussion

The observers' results are shown in Fig. 1, and they are very similar to those obtained for experienced observers by McKee et al. (1990). In both cases (results of McKee et al. and the current results with naïve observers), the depth difference (or disparity) needed to perform the task increased as a function of the magnitude of the standing disparity. The results of a two-way analysis of variance (one between-group factor: age, and one within-group factor: standing disparity) showed that the increase in thresholds with increasing standing disparity was significant ($F(5,90) = 35.0$, $p < .0001$, $\eta^2 = .66$). There was no significant main effect of age ($F(1,18) = 0.28$, $p = .6$, $\eta^2 = .015$), and the age × standing disparity interaction was also not significant ($F(5,90) = 0.67$, $p = .65$, $\eta^2 = .036$). In other words, the increases in thresholds that accompany increasing standing disparities were similar in magnitude for both younger and older observers.

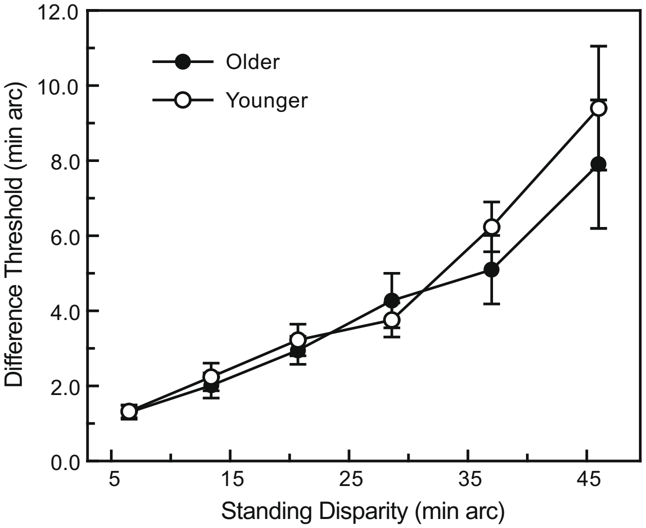

Fig. 1. Results of Experiment 1. The younger and older observers' ordinal depth discrimination thresholds are plotted as a function of the standing disparity. The ordinate plots the depth difference thresholds in terms of disparity (min arc). The error bars indicate ±1 standard error.

In our experiment, we required observers to make ordinal depth judgments at a variety of standing disparities from 6.5 to 46 min-arc. In one sense, our task was similar to a typical stereoacuity task. It was different from a conventional stereoacuity task, however, in that the standard and test spots were offset from the horopter. Nevertheless, our finding of no significant age difference resembles the earlier results of Greene and Madden (1987), Yekta et al. (1989), and Tiffin (1952).

2. Experiment 2

The results of Experiment 1 show that when it comes to judging ordinal depth relationships between stereoscopic locations offset from the horopter, older observers can perform as well as younger observers. Does this similarity in performance also occur when the stereoscopic visual system is challenged in other ways? Consider binocular matching. In order to estimate the magnitude of depth differences and/or an object's 3-D shape, one must first identify corresponding elements in the two eyes' views. Binocular matching is difficult if corresponding texture elements possess different orientations. The purpose of Experiment 2 was to evaluate how the stereoscopic systems of younger and older observers respond when orientation differences between corresponding line segments are introduced into random-line stereograms. The effects of this manipulation upon younger observers are well known from the past stereoscopic literature (Frisby & Julesz, 1975a, 1975b, 1976; Marlowe, 1969; Mitchell & O'Hagan, 1972). In particular, for younger observers stereopsis can tolerate orientation differences of 40–90 degrees between corresponding line segments, depending upon the line length. Will this manipulation have similar effects upon older observers? The purpose of Experiment 2 was to answer this question.

2.1. Method

2.1.1. Apparatus

The apparatus was the same as that used in Experiment 1.

2.1.2. Stimulus displays

The stereograms were composed of 1000 purple line segments presented against a black background (the luminances of the lines and background were 16.1 and 0.02 cd/m^2, respectively). Each line segment was 2 pixels wide, while its length subtended 25.8 min arc. The orientations of the line segments in the left eye's view were chosen randomly. The corresponding line segments in the right eye's view were rotated randomly either clockwise or counterclockwise by amounts that were specific to each experimental condition (30, 39, 48, and 57 degree orientation differences between corresponding line segments in the left and right eye views). On any given trial, a central square or triangle was depicted with either crossed or uncrossed disparity. The disparate squares and triangles possessed equal areas of 100 cm^2. On every trial, the squares and triangles were randomly oriented in the fronto-parallel plane and were presented for one second. Two magnitudes of disparity were used: 13.7 and 51.5 min arc. The stereograms were once again viewed by the observers from a distance of 100 cm; the stereograms subtended 11.4 × 11.4 degrees visual angle. Two sample stereograms are presented in Figs. 2 and 3.

2.1.3. Procedure

There were a total of 16 experimental conditions formed by the orthogonal combination of two disparity magnitudes (13.7 and 51.5 min arc), 2 disparity directions (crossed and uncrossed disparity), and 4 orientation differences between corresponding line segments (30, 39, 48, and 57 degrees). Each observer followed a different, randomly determined order of conditions. Within any particular block of trials devoted to a single condition, the observers performed 60 judgments: their task was to identify the disparate shape presented on each trial (square vs. triangle). No feedback was given regarding the observers' performance. At the end of the experiment, a total of 960 judgments had been performed by each of the observers.

2.1.4. Observers

Twenty observers participated in the experiment. One group of observers consisted of ten older adults (mean age was 71.3 years, SD = 6.0; the range of their ages was 61–82 years). None of these observers reported possessing eye or retinal problems, such as macular degeneration, glaucoma, or cataracts. The other group consisted of ten younger observers (mean age was 21.0 years, SD = 4.0). All of the younger and older observers possessed normal or corrected-to-normal visual acuity. The observers' acuity was once again measured at one meter with a Landolt C chart. One of the younger observers was a coauthor (A.E.C.); all of the remaining 19 observers were naïve with regard to the purposes of the experiment, and were unaware of how the experimental stimuli had been generated.

2.2. Results and discussion

The results are shown in Figs. 4 through 7. The observers' performance is expressed in terms of d', which is a signal detection theory measure of perceptual sensitivity (Green & Swets, 1966; Macmillan & Creelman, 1991). The results of a four-way analysis of variance (1 between-group factor: age, and 3 within-group factors: disparity magnitude, disparity direction, and orientation difference between corresponding line segments) revealed that there was a significant effect of disparity magnitude ($F(1,18) = 27.4$, $p < .0001$, $\eta^2 = .6$), such that the observers' discrimination performance was lower for high disparity magnitudes. This effect of disparity magnitude, however, was limited to the older observers, and the significant interaction of age and disparity magnitude ($F(1,18) = 14.8$, $p = .001$, $\eta^2 = .45$) is clearly evident in the results shown in Fig. 4.

The changes in the amount of orientation difference between corresponding line segments of the stereograms produced large changes in the observers' performance (see Fig. 5; $F(3,54) = 119.4$, $p < .0001$, $\eta^2 = .87$). The observers' performance was very good for an orientation difference of 30 degrees, but deteriorated to near chance levels for an orientation difference of 57 degrees. In addition to a significant 2-way disparity magnitude × orientation difference interaction ($F(3,54) = 15.0$, $p < .0001$, $\eta^2 = .46$), a significant 3-way age × disparity magnitude × orientation difference interaction was also obtained ($F(3, 54) = 3.1$, $p < .04$, $\eta^2 = .15$). The 2-way and 3-way interactions are illustrated in Fig. 6. Notice that changes in the amount of orientation difference had greater effects on performance for low disparity magnitudes and had smaller effects on performance for high disparity magnitudes. This difference accounts for the significant 2-way interaction. The 3-way interaction occurred, because the 2-way interaction was larger for the older observers and smaller for the younger observers: the younger observers' performance was similar across low and high disparity

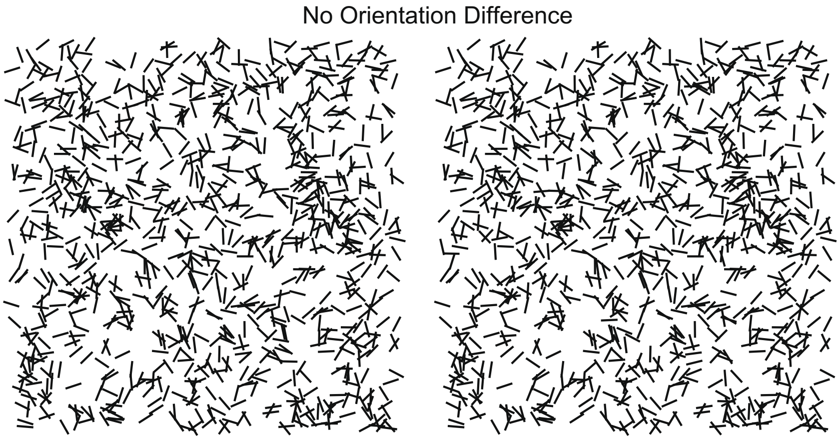

Fig. 2. An example of a line element stereogram similar to those used in Experiment 2. This stereogram depicts a triangle defined by binocular disparity. No orientation differences exist between corresponding line segments across the two eyes' views. This stereogram can be viewed using either crossed or divergent free-fusion (Regan, 2000, p. 345, see Fig. 6.1 and caption). Alternately, this stereogram can be viewed with the assistance of a prism (Julesz, 1965) or a stereoscope (Frisby, 1980, pp. 143–144).

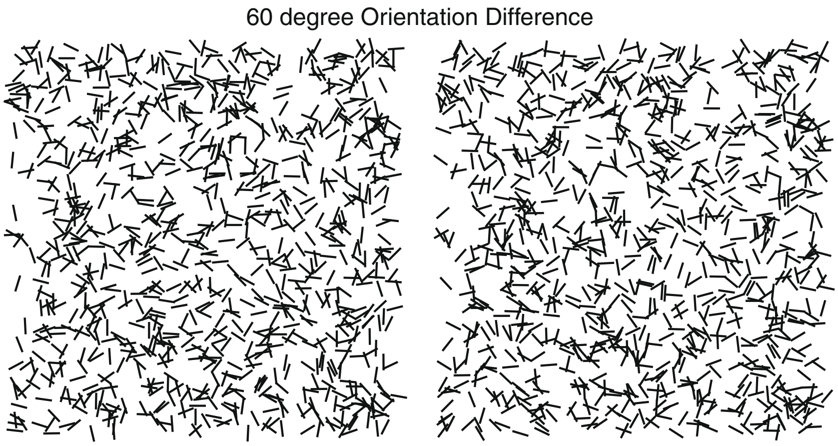

Fig. 3. An example of a line element stereogram with 60 degree orientation differences between corresponding line segments. This stereogram depicts a square defined by binocular disparity.

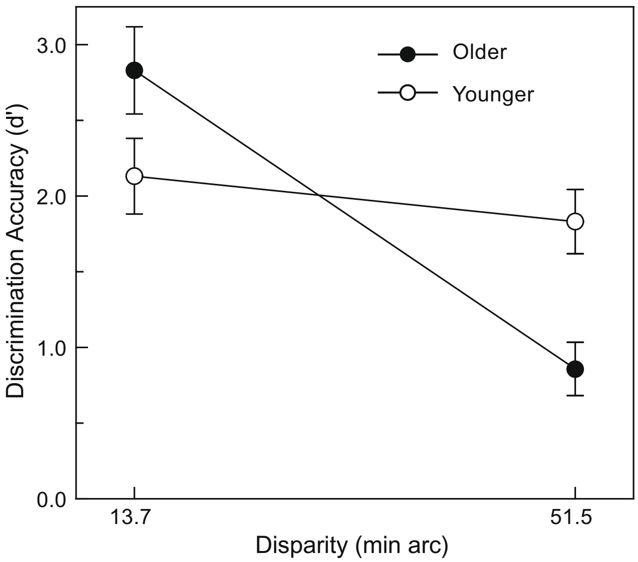

Fig. 4. Results of Experiment 2. The older and younger observers' discrimination accuracies are plotted as a function of the magnitude of binocular disparity. The error bars indicate ±1 standard error. The discrimination accuracies are plotted in terms of d', which is the signal detection theory measure of perceptual sensitivity (e.g., see Macmillan & Creelman, 1991).

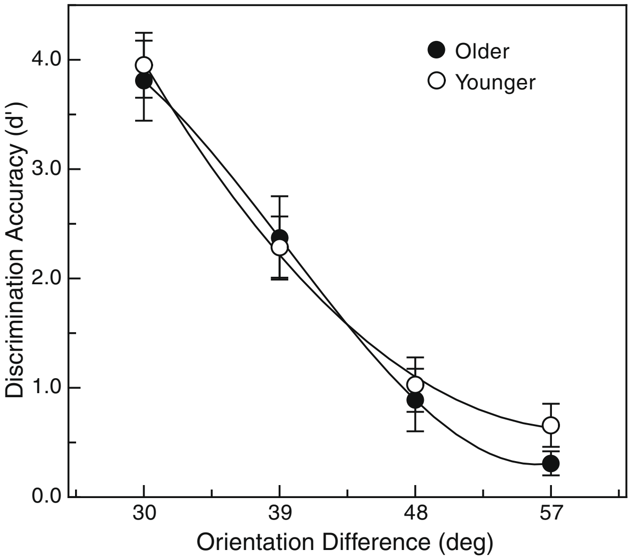

Fig. 5. Results of Experiment 2. The older and younger observers' discrimination accuracies are plotted as a function of the orientation difference between corresponding line segments across the two eyes' views. The error bars indicate ±1 standard error.

magnitudes, while the older observers' performance for high and low disparity magnitudes was quite different.

The direction of disparity also produced changes in the observers' performance. The observers' performance was better when the stereoscopic figures were depicted with crossed disparity and was worse when uncrossed disparities were present ($F(1,18) = 36.1$, $p < .0001$, $\eta^2 = .67$, also see Manning, Finlay, Neill, & Frost, 1987; Mustillo, 1985; Patterson, Moe, & Hewitt, 1992). This main effect of disparity direction can be seen in Fig. 7 – notice that the observers' performance was always higher for crossed disparities. Both the direction of disparity × disparity magnitude ($F(1,18) = 4.5$, $p < .05$, $\eta^2 = .2$) and the direction of disparity × orientation difference ($F(3,54) = 7.8$, $p = .0002$, $\eta^2 = .3$) interactions were significant. These interactions are evident in the results depicted in Fig. 7: the left panel plots the direction of disparity × disparity magnitude interaction, while the right panel illustrates the direction of disparity × orientation difference interaction. The interactions depicted in Fig. 7 show that the effects of disparity magnitude and amount of orientation difference were slightly larger for the crossed disparities.

In this experiment, a strong effect of age was obtained (Fig. 4), such that the older observers' shape discrimination performance was significantly worse than that of the younger observers when the stereograms contained large binocular disparities. There are at least two general reasons why increasing age might be associated with poorer performance on visual tasks. One potential reason involves optical factors: Weale (1963) has shown that the retina of an average 60-year-old receives only one-third of the light that the retina of a 20-year-old would receive under identical viewing conditions. Another possibility is that aging effects are a consequence of neural and neurophysiological deterioration within the cerebral cortex (e.g., Raz et al., 2005; Resnick, Pham, Kraut, Zonderman, & Davatzikos, 2003; Schmolesky, Wang, Pu, & Leventhal, 2000; Smith, Chebrolu, Wekstein, Schmitt, & Markesbery, 2007; Yu, Wang, Li, Zhou, & Leventhal, 2006). In this experiment, the observed age effect cannot be due to optical factors, because in the

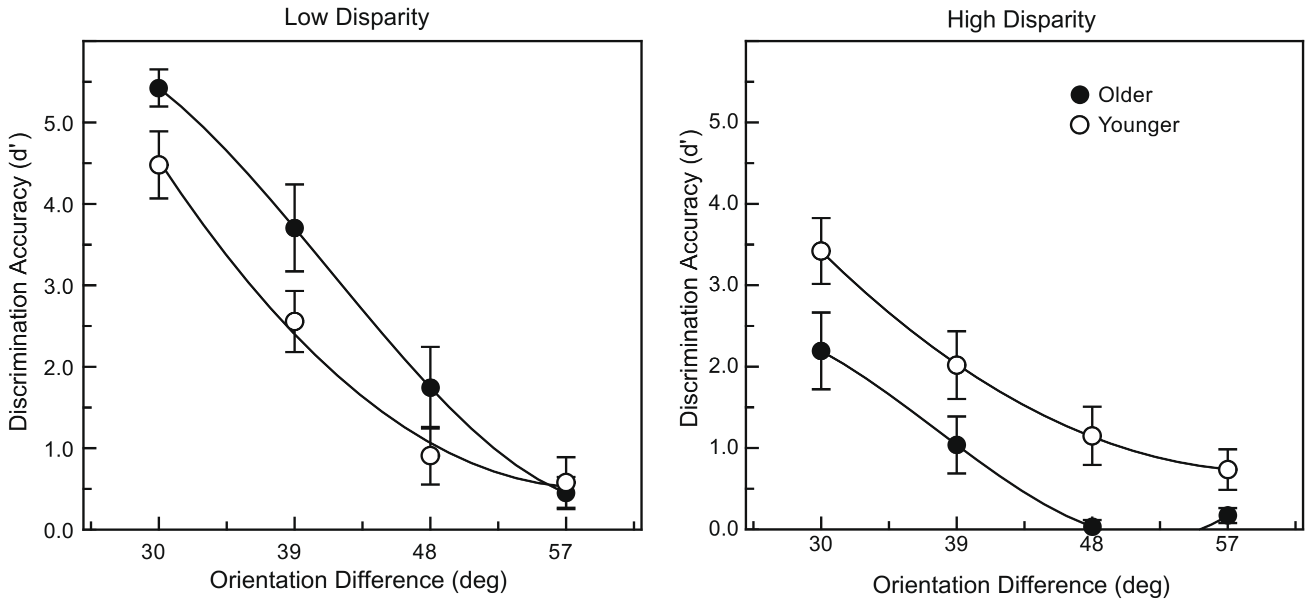

Fig. 6. Results of Experiment 2. The older and younger observers' discrimination accuracies are plotted as functions of the magnitude of binocular disparity and the orientation difference between corresponding line segments across the two eyes' views. The error bars indicate ±1 standard error.

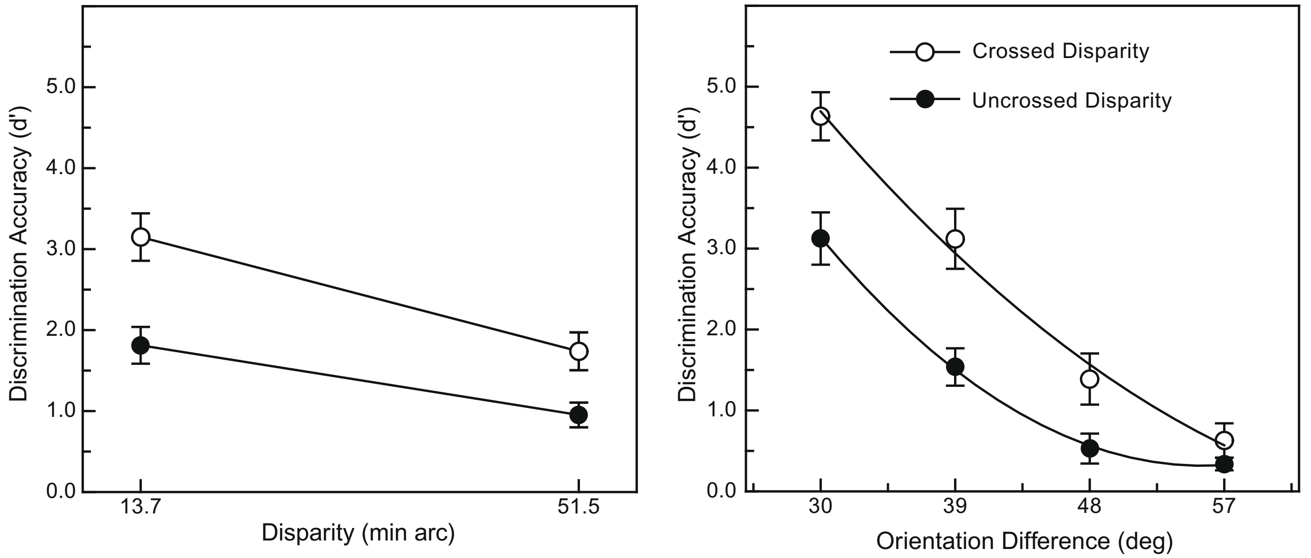

Fig. 7. Results of Experiment 2. The observers' discrimination accuracies are plotted as functions of the direction of binocular disparity (crossed vs. uncrossed), the magnitude of binocular disparity, and the orientation difference between corresponding line segments across the two eyes' views. The error bars indicate ±1 standard error.

low disparity conditions (where the stimuli were otherwise equivalent to those used in the high disparity conditions), the older observers outperformed the younger observers. If optical factors were responsible for the age effect, the older observers should have exhibited reduced performance in both disparity conditions.

3. Experiment 3

In Experiments 1 and 2, the direction of disparity in the stereograms (crossed, uncrossed) was unambiguous. In those experiments, we found that older observers generally perceive depth and shape from disparity in a manner that is similar to that of younger observers (e.g., see Figs. 1 and 5). In the 1960's and 1970's Bela Julesz and colleagues explored how human observers perceive depth in stereograms that possess ambiguous binocular disparities (e.g., Julesz & Chang, 1976; also see Julesz, 1964; Julesz, 1971, and Julesz & Johnson, 1968a, 1968b). The binocular disparities in the Julesz and Chang stereograms were ambiguous in that they simultaneously specified two different 3-dimensional surfaces: one that possessed crossed disparity with respect to the background and one that possessed uncrossed disparity with respect to the background. At any given time, however, the observers only perceived one of these two 3-D configurations, either a central square floating in front of the background or a central square recessed behind the background. Julesz and Chang interpreted this result as indicating that one pool of disparity detectors (e.g., those responsible for detecting crossed disparities) is capable of inhibiting another pool of disparity detectors (e.g., those responsible for detecting uncrossed disparities). Recent physiological research on senescent monkeys (Leventhal, Wang, Pu, Zhou, & Ma, 2003; Schmolesky et al., 2000) has demonstrated that aging leads to deterioration in the functionality of inhibitory synapses within primary visual cortex. Other psychophysical findings with human observers are also consistent with the idea that aging leads to a decrease in inhibition within the visual system (Betts, Taylor, Sekuler, & Bennett, 2005; Norman, Norman, Pattison, Taylor, & Goforth, 2007). If aging does lead to a deterioration in inhibition within primary and/or extrastriate visual cortex, then older observers may not be able to tolerate ambiguous disparities. When presented with two conflicting stereoscopic percepts, older observers may not be able to successfully inhibit one to obtain a clear perception of the other. One purpose of Experiment 3 was to evaluate whether older observers do perceive ambiguous stereograms in a manner that is similar to younger observers.

When Julesz and Chang (1976; also see Julesz, 1971) presented ambiguous stereograms for brief durations (160 ms), they found that most observers had a natural bias to perceive the depth of the central square as being either "in front" or "behind". Julesz (1971) and Julesz and Chang (1976) found that it is possible to reverse an observer's natural bias by presenting a small sample of dots that have an unambiguous disparity in the opposite direction. If the number of unambiguous "bias dots" is sufficient, their presence causes the entire surface to be "pulled" from an observer's naturally preferred state to the opposite sign of depth. Instead of seeing a noisy depth organization (a central square at an observer's preferred depth with a scattering of bias dots at the opposite sign of depth), the observers only see a single depth organization that is the reverse of their natural bias. If we find in the current experiment that older observers can tolerate ambiguous binocular disparities, will they also exhibit the stereoscopic "pulling" that Julesz (1971) and Julesz and Chang (1976) describe? If older observers do exhibit stereoscopic pulling, how many bias dots will be needed to reverse their natural bias? Does aging lead to changes in stereopsis so that it is less flexible and more resistant to change? The purpose of Experiment 3 was to answer such questions.

3.1. Method

3.1.1. Apparatus

The apparatus was the same as that used in Experiments 1 and 2.

3.1.2. Stimulus displays

The stimuli were essentially identical to the ambiguous random-dot stereograms used by Julesz and Chang (1976), with the exception that the density of texture elements was higher. The background of the stereograms was composed of an array of 40,000 (200 × 200) square texture elements. The central stereoscopic square was defined by the disparities of 10,000 texture elements (100 × 100). Each texture element (4 × 4 pixels) had a 50 percent probability of being colored either red or black (the luminances of the red and black texture elements were 14.6 and 0.02 cd/m^2, respectively). The stereograms were viewed by the observers at a distance of 57.3 cm; the stereograms subtended 24 × 24 degrees visual angle.

The central square was presented with a disparity of 13.7 min - arc. Because of how the ambiguous stereograms were constructed (based upon the "wallpaper effect", see Julesz, 1971), it is possible to make stereoscopic matches across the left and right eyes' views that correspond to either crossed or uncrossed disparity. Thus, the disparity of the central square in Fig. 8 is ambiguous in that the square may either appear to float in front of the background or be recessed behind it.

3.1.3. Procedure

Each observer participated in two experimental sessions. Each session was composed of 110 trials (11 experimental conditions × 10 trials/condition/session). Thus, at the end of the experiment, each observer had completed a total of 220 trials. There were five conditions in which either 50, 250, 500, 1000, or 2000 bias dots with unambiguous crossed disparity were randomly placed within the central square region of the stereograms. There were an additional five conditions in which the bias dots (50, 250, 500, 1000, or 2000) possessed unambiguous uncrossed disparity. In one condition, no bias dots were included in the stereograms. Each stereogram was presented for 133 ms to minimize the possibility of significant convergence eye movements (Pobuda & Erkelens, 1993; Rashbass & Westheimer, 1961; Westheimer & Mitchell, 1956). In between trials, the observers maintained steady fixation upon a fixation marker presented in the plane of the computer monitor. After viewing each stereogram, the observer was asked to indicate the location of the central square surface in depth, either "in front" of the background or "behind" the background. The observers were instructed to always report the location in depth of the central square, and to not report the location in depth of any bias dots (if they appeared to have a different location in depth than the central square).

3.1.4. Observers

Twenty-five observers participated in the experiment. Two additional potential observers (one younger male, aged 20 years, and one older male, aged 74 years) were unable to participate because they were stereoblind and did not possess stereopsis (i.e., they were completely unable to perceive depth and 3-D shape in random-dot stereograms). One group of observers consisted of ten older adults (mean age was 70.9 years, SD = 4.1; the range of their ages was 66–80 years). None of these observers reported possessing significant eye or retinal problems, such as macular degeneration, glaucoma, or cataracts. The other group consisted of fifteen younger observers (mean age was 23.0 years, SD = 2.9). The observers' visual acuity was once again measured using the Landolt C, this time at a near viewing distance of 50 cm. The younger observers' average acuity was 1.0 min^{-1}, while that for the older observers was slightly less, 0.87 min^{-1} (1.0 min^{-1} is equivalent to 20/20 vision measured at 20 feet; 0.8 min^{-1} is equivalent to 20/25 vision). One of the younger observers was one of the coauthors (CLW); all of the remaining 24 observers were naïve with regards to the purposes of the experiment, and were unaware of how the experimental stimuli had been generated.

3.2. Results and discussion

Out of the 25 total observers who performed the task, 20 of them (80 percent) demonstrated threshold amounts of pulling. Three of the remaining five observers exhibited some pulling, but their performance never reached threshold levels. Only two observers did not demonstrate stereoscopic pulling. Of the 20 observers who demonstrated significant pulling, 10 were older and 10 were younger. In the statistical analyses to follow, we analyzed the thresholds for the 20 observers who exhibited significant stereoscopic pulling.

Nine of the 20 observers possessed a strong natural bias for perceiving the briefly presented ambiguous central square as "behind". That is, in the condition where no bias dots were included in the stereograms these observers perceived the central square as behind on 75 percent or more of the trials. Two of the observers possessed a similar natural bias to perceive the ambiguous surfaces in front, while the remaining nine observers had no strong bias for either in front or behind. This inter-observer variability in natural bias is consistent with the results of Julesz and

Fig. 8. An example of an ambiguous random-dot stereogram similar to those used in Experiment 3 (this stereogram has 64 rows and columns of texture elements, instead of the 200 rows and columns used to create the experimental stimuli). This stereogram contains no bias dots, and it is thus possible to perceive the central square either floating in front of the background or recessed behind the background. When one depth organization is perceived the opposite sign of depth cannot be perceived and vice-versa.

Chang (1976). In their experiment, two of the observers (BJ & JJC) possessed a strong "behind" bias, while observer RAP exhibited a similar bias for "front".

Representative results for six individual younger and older observers are shown in Fig. 9. In this figure two observers (observers 2 and 15) did not exhibit a strong natural bias in the no bias dots condition, but it was possible to consistently "pull" the central square behind as long as a sufficient number of bias dots were present in the stereograms. Likewise, observers 4, 5, 12, and 16 exhibited a strong natural bias for behind (see their responses for the no bias dot condition), but it was possible to completely reverse their natural bias and "pull" the central stereoscopic surface to the front. For each observer, we fit a logarithmic function to their responses and then used the 75th percentage point on this function to estimate the threshold number of bias dots needed to obtain reliable stereoscopic "pulling". On average, the observers needed 531.8 bias dots (5.3 percent of the texture elements located within the central stereoscopic square) to obtain reliable "pulling". These results are consistent with those of Julesz and Chang (1976), and Julesz (1971), p. 214), who stated that "this natural bias can be overcome by a slight physical bias of 3–10% depending on the subject".

In our experiment we did not find any significant effect of age upon the number of bias dots needed to obtain stereoscopic "pull-

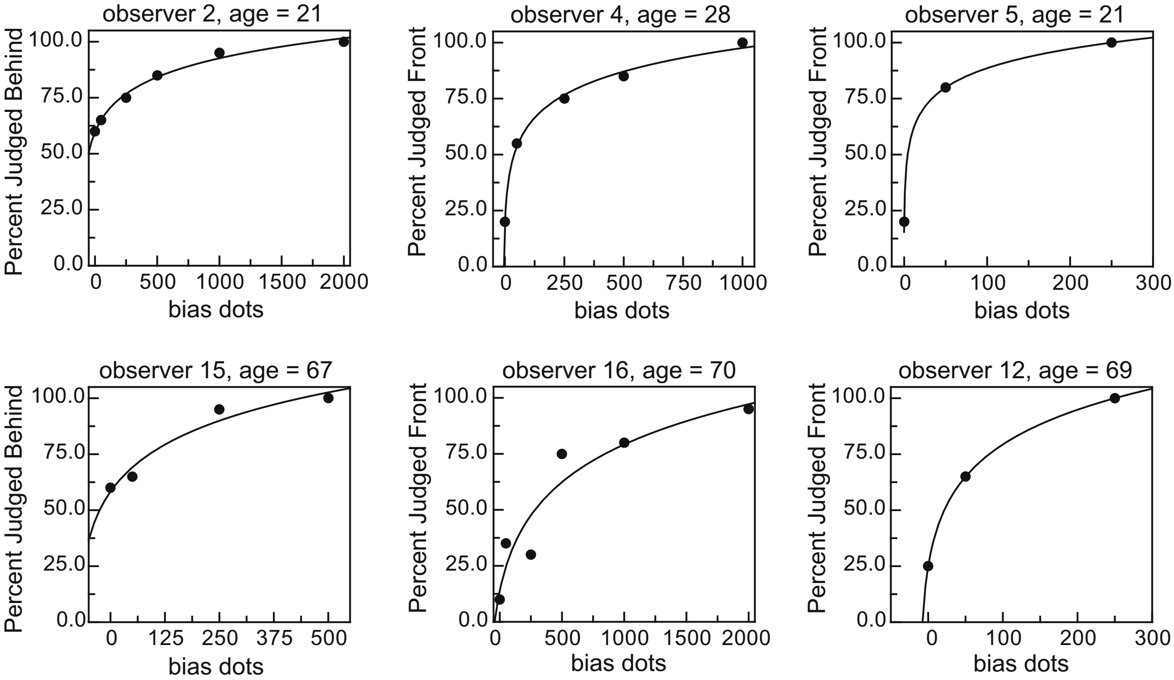

Fig. 9. Representative results for six individual observers (3 younger observers and 3 older observers) illustrating the stereoscopic "pulling" that was obtained in Experiment 3. The best-fitting logarithmic functions are shown along with the observers' data. It is readily apparent that there were individual differences: observer 2, for example needed 2000 bias points for complete stereoscopic pulling (i.e., 100% behind judgments), while observer 4 needed only half of that (1000 bias points) for 100% pulling. In contrast, observer 15 needed 500 bias points, while observers 5 and 12 only required a mere 250 bias points for complete pulling.

ing” ($t(18) = -1.127$, $p = .27$, two-tailed). The younger observers needed an average bias of 4.05 percent, while the older observers needed an average bias of 6.59 percent. It is important to note that the magnitudes of both of these biases fall within the “normal” range of performance (3–10%) indicated by Julesz (1971). We conducted a power analysis to determine how many observers would be needed in each of the age groups to have a 90 percent chance of statistically detecting this difference (6.59 vs. 4.05 percent), given the inter-observer variability in thresholds. Assuming that this difference reflects a true effect of age, the power analysis revealed that 85 observers in each age group (170 total observers) would be needed to have a 90 percent chance of statistically detecting the observed difference. One can see, therefore, that even if this age-related difference is genuine, that it is very small relative to the variability in stereoscopic pulling that occurs across individual observers within any particular age group.

4. General discussion

The results of the current experiments have demonstrated that in many respects, the aging stereoscopic visual system retains a significant amount of functionality and flexibility. Under our experimental conditions, older observers discriminate depth differences in a manner that is similar to younger observers, even at high standing disparities (see Fig. 1). In addition, older observers can effectively discriminate surface shapes defined by the disparity contained in random line stereograms, even when binocular matching is difficult (see Fig. 5). The stereoscopic systems of older observers can also resolve ambiguous binocular disparities; the number of bias dots needed to obtain reliable stereoscopic pulling in Experiment 3 fell into the “normal range” (see Julesz, 1971) for both older and younger observers (see Fig. 9).

It is also important to acknowledge, however, that aging does not completely spare the stereoscopic capabilities of older observers. The results of Experiment 2 clearly demonstrate that older observers cannot perform stereoscopic discriminations of surface shape (d' values near zero) when their stereoscopic system is simultaneously challenged by higher magnitudes of binocular disparity (51.5 min arc) and large orientation differences between corresponding stereogram texture elements (see right panel of Fig. 6). This deterioration is clearly associated with age. Past research has shown, for example, that younger observers can perceive stereoscopic surfaces even when they are presented at large standing disparities. For example, observers in a study by Schumer and Julesz (1984) were able to discriminate between a flat surface presented at a standing disparity of 52 min arc and a sinusoidally-modulated surface possessing peaks and troughs at disparities of 50.3 and 53.7 min arc. Given this historical context, it is clear that our younger observers (in Experiment 2) performed normally, since they were capable of accurately discriminating stereoscopic shape with binocular disparities as large as 51.5 min arc (see Fig. 4).

Taken together, the current results and those of past research demonstrate that many aspects of stereopsis remain functional at least through the age of 83 years. The results of Experiment 1, along with those of Greene and Madden (1987), Yekta et al. (1989), and Tiffin (1952) indicate that older observers can possess stereoacuities comparable to those of younger observers. The results of Norman et al. (2000), Norman et al. (2006) and Laframboise et al. (2006) indicate that older observers can perceive stereoscopic depth despite large reductions in binocular correspondence. Younger and older observers are also similarly affected by changes in the spatial frequency of stereoscopic surfaces (Norman et al., 2000). Despite these similarities, the older stereoscopic system is not immune to the effects of increasing age. The results of Norman et al. (2000) show that for any given amount of binocular disparity, older observers perceive less depth than younger observers; the results of Norman et al. (2000) also reveal that older observers are less sensitive to the curvature of stereoscopic surfaces. Quantitative differences occur between younger and older observers when they discriminate stereoscopic shape (Norman et al., 2006). It seems clear that the neural and neurophysiological changes associated with aging (e.g., Leventhal et al., 2003; Raz et al., 2005; Resnick et al., 2003; Schmolesky et al., 2000; Smith et al., 2007; Yu et al., 2006) lead to deficits in some aspects of stereoscopic functioning, while other aspects are well preserved. We believe that further research is needed to determine whether the age-related differences that do exist in stereopsis have negative consequences for everyday visually guided behavior.

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