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Aging and the perception of 3-D shape from dynamic patterns of binocular disparity

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In two experiments, we investigated the ability of younger and older observers to perceive and discriminate 3-D shape from static and dynamic patterns of binocular disparity. In both experiments, the younger observers' discrimination accuracies were 20% higher than those of the older observers. Despite this quantitative difference, in all other respects the older observers performed similarly to the younger observers. Both age groups were similarly affected by changes in the magnitude of binocular disparity, by reductions in binocular correspondence, and by increases in the speed of stereoscopic motion. In addition, observers in both age groups exhibited an advantage in performance for dynamic stereograms when the patterns of binocular disparity contained significant amounts of correspondence "noise." The process of aging does affect stereopsis, but the effects are quantitative rather than qualitative.

Researchers have investigated how human observers perceive depth and 3-D object shape from binocular disparity for more than 150 years (see, e.g., Helmholtz, 1867/1925; Ogle, 1950, 1958; Wheatstone, 1838). Computer-generated random-dot stereograms have been used since the 1960s to study stereopsis (the perception of depth and 3-D shape from binocular disparity; see, e.g., Julesz, 1960, 1964, 1971). The methodological advantage of using random-dot stereograms lies in the fact that the depicted depths and 3-D shapes are defined only by binocular disparity (i.e., no monocular sources of information about 3-D shape are contained within such stereograms). Because the stereograms are generated by computers, it is possible to create dynamic patterns of binocular disparity that change over time. One can also manipulate perceptually important variables, such as the type and magnitude of noise (see, e.g., Speranza, Moraglia, & Schneider, 1995).

Given the many advantages of random-dot stereograms, it is surprising that they have not typically been used by researchers interested in aging and stereopsis (see, e.g., Bell, Wolf, & Bernholz, 1972; Haegerstrom-Portnoy, Schneck, & Brabyn, 1999; Hofstetter & Bertsch, 1976; Jani, 1966; Wright & Wormald, 1992). Most of the researchers who have evaluated aging and stereopsis have focused solely on determining whether and how stereoacuity changes with increasing age (see, e.g., Greene & Madden, 1987; Haegerstrom-Portnoy et al., 1999; Wright & Wormald, 1992; Yekta, Pickwell, & Jenkins, 1989). Although it is important to determine the smallest depth difference that any given observer can detect, it is also important to note that in everyday life, human observers primarily use stereopsis to perceive the 3-D shape of environmental objects. The perception of 3-D object shape requires the detection and utilization of binocular disparities that are much larger than those involved in studies of stereoacuity. Few researchers to date have used random-dot stereograms to examine how older adults perceive depth and 3-D object shape from suprathreshold binocular disparities (for an exception, see Norman, Dawson, & Butler, 2000).

In past research using conventional static random-dot stereograms, Norman et al. (2000, Experiment 1) found that for any given amount of binocular disparity, older ob-

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servers (mean age was 74.7 years) perceived less depth than younger observers (mean age was 22.3 years). On average, the older observers perceived 21.6% less depth. Otherwise, their performance was qualitatively similar to that of the younger observers. In a second experiment, after the older observers were given more binocular disparity (to compensate for the quantitative difference found in the previous experiment), they were able to discriminate differences in 3-D surface shape at performance levels that were essentially identical to those of the younger observers. In addition, both age groups were similarly affected by disruptions of binocular correspondence and reductions in surface point density. The results of these experiments would appear to indicate that older observers perceive stereoscopically defined surfaces in a manner that is qualitatively similar to that of much younger observers.

The purpose of the present set of experiments was to extend previous research by requiring observers to discriminate 3-D shape from dynamic patterns of binocular disparity that change over time. Past research on aging and the perception of 3-D shape from motion (Norman, Clayton, Shular, & Thompson, 2004; Norman et al., 2000) has shown that older observers cannot reliably discriminate 3-D surface shape when the stimuli are dynamic and the surface points survive for only two successive views (see also the related results of Andersen & Atchley, 1995, Experiment 3). Does this age-related inability to tolerate dynamic patterns also extend to the perception of 3-D shape from binocular disparity? The purpose of Experiment 1 was to answer this question by requiring younger and older observers to judge the 3-D shape of surfaces defined by both static and dynamic random-dot stereograms. In dynamic random-dot stereograms, the implicit 3-D surfaces persist, although the individual points defining the surfaces appear and disappear over time (Fox, Aslin, Shea, & Dumais, 1980; Julesz, 1971, pp. 183–185; Julesz, Breitmeyer, & Kropfl, 1976). The stimuli in Experiment 2 were even more dynamic than those used in Experiment 1. The purpose of this experiment was to evaluate older observers' ability to discriminate the shape of 3-D surfaces (defined by dynamic random-dot stereograms) that themselves moved over time. In this experiment, there were two different sources of optical change that happened simultaneously: At any given moment, the individual surface points were appearing and disappearing, while the underlying binocular disparity field translated across the observers' field of view. No single surface point ever moved, but the underlying implicit surface did.

EXPERIMENT 1

Method

Apparatus. The stereograms were created using a dual-processor Apple Power Macintosh G4 computer (1.42 GHz) and were displayed on a 22-in. Mitsubishi Diamond Plus 200 color monitor. The rendering of the stereograms was accelerated by a Radeon 9000 graphics accelerator (ATI Technologies, Inc.). The observers viewed the stereograms from a distance of 100 cm.

Stimulus displays. The stereoscopic surfaces were presented as anaglyphs (see Julesz, 1971) and were defined by the binocular disparities of 15,000 high-contrast points. In our previous investigation of stereopsis and aging (Norman et al., 2000), the observers viewed the stereograms using CrystalEyes-2 LCD-shuttered glasses (StereoGraphics, Inc.). When using LCD-shuttered glasses, the two eyes' stereoscopic views are not presented simultaneously, but are alternately shown (albeit in quick succession). In the present experiments, we decided to use anaglyphs in order to present the two eyes' stereoscopic views simultaneously. If we also obtain age-related effects in the present study (as we did in Norman et al., 2000), we can be confident that age truly has an effect on older observers' stereoscopic capabilities, and that any reduced performance on the part of older observers is not due to the characteristics of any particular methodology. In the present set of experiments, the surface points presented to one eye were rendered in red, and the points presented to the other eye were rendered in green. Blue was avoided because it has been shown that older observers have difficulty in detecting light of short wavelengths (see, e.g., Sekuler & Sekuler, 2000). The observers wore glasses with red/green filters so that each eye's view contained only the points appropriate for that eye. Before beginning the experiment, all of the observers viewed a series of sample stereograms with the same 3-D surfaces as were used in the experiment (using a peak–trough disparity of 13.8′ of arc). All of the observers, both younger and older, were able to detect the points and their disparity with sufficient precision that they were able to spontaneously and accurately describe the shape of the depicted 3-D surfaces.

Three different surface shapes were simulated in the experiment. Within each of the surface shapes, the magnitude of binocular disparity was modulated as a function of each point's vertical position within the pattern, creating horizontally oriented peaks and troughs. Sinusoidal, square-wave, and ramp (i.e., sawtooth) modulations were used. Each of the three surfaces possessed distinctly different characteristics. The sine-wave surfaces were smoothly curved in depth, whereas the square-wave and ramp surfaces were not. The flat planar surfaces composing the ramp or sawtooth were slanted in depth, whereas the flat planar surfaces composing the square wave were parallel to the frontoparallel plane. These three types of surfaces were similar to those used by Rogers and Graham (1979) in their investigation of motion parallax. The stereograms subtended 20.85º $\times$14.25º of visual angle and were presented within a 1,280 $\times$ 1,024 pixel window. The positions of the surface points in each eye's view were plotted using hardware antialiasing. Because of this subpixel positioning, the modulations of the surfaces in depth were very

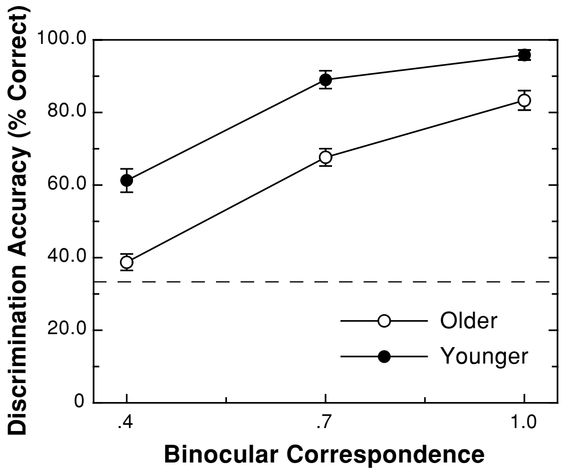

Figure 1. Results of Experiment 1 for the younger and older observers. The observers' discrimination accuracies are plotted as a function of binocular correspondence. Chance discrimination performance is indicated by the dashed line. The error bars indicate ±1 *SE*.

smooth. The stereograms were either static or dynamic. The individual points of the dynamic stereograms were refreshed at either 35 or 70 Hz (i.e., a "new" stereogram with a new, randomly positioned set of points depicting the "same" 3-D surface was presented every 28.6 or 14.3 msec). The spatial frequency of the surfaces was 0.25 cpd visual angle, which is near the peak of the stereoscopic modulation transfer function (see, e.g., Norman, Lappin, & Zucker, 1991; Rogers & Graham, 1982; Schumer & Julesz, 1984).

Observers. Sixteen observers participated in the experiment. Eight of the observers were 62 years of age or older (mean age was 68.4 years, $SD = 3.6$), whereas another 8 observers were 26 years of age or younger (mean age was 23.3 years, $SD = 2.1$). The older observers were asked (i.e., self-report) about the presence of macular degeneration, glaucoma, cataracts, or other retinal or eye problems. (None were reported.) The observers' visual acuities were assessed at a distance of 100 cm using a Landolt C chart (Riggs, 1965). Both the younger and older observers' mean visual acuity was 1.0 min^{-1} (1.0 min^{-1} is equivalent to 20/20 vision measured at 20 ft). If the observers typically wore corrective lenses (e.g., bifocals), they used the correction that gave them the best visual acuity as they viewed the stereograms. In each age group, half of the observers were male and half were female.

An additional set of 8 younger observers (mean age 21.3 years, $SD = 1.4$, mean acuity = 1.0 min^{-1}) participated in a smaller, control experiment.

Procedure. One of the three surfaces (sine wave, square wave, or ramp) was randomly depicted on every trial. The observers' task was to identify which 3-D surface had been presented; no feedback was provided to the observers regarding the accuracy of their responses. A total of 18 experimental conditions were obtained through the orthogonal combination of three stereogram types (static, slow dynamic, and fast dynamic), three magnitudes of binocular correspondence (.4, .7, and 1.0), and two magnitudes of peak–trough binocular disparity. Noise was introduced into the stereograms by manipulating the amount of binocular correspondence. In the .4 and .7 correspondence conditions, 60% and 30% of the points constituted "noise" (i.e., the positions of those points were uncorrelated across the left and right eyes' half-images) and therefore did not help to perceptually define the surfaces, but rather served to camouflage them. The magnitudes of peak–trough disparity were 1.2′ and 2.1′ of arc for the younger observers (simulating front-to-back depth intervals of 0.6 and 1.0 cm, respectively) and 2.1′ and 3.4′ of arc for the older observers (simulating front-to-back depth intervals of 1.0 and 1.7 cm, respectively). The low and high amounts of binocular disparity were used in separate blocks of trials. Within any given block of trials, each observer judged 135 surface shapes (15 trials for each of the 9 combinations of binocular correspondence and stereogram type at a given magnitude of disparity). Four experimental sessions (two sessions for each of two magnitudes of disparity) were run for each observer. Thus, at the end of the experiment, each observer had judged 540 stereograms (30 trials for each of the 18 experimental conditions).

In the control experiment, the 8 younger observers judged the shape of the stereoscopic surfaces both with and without 0.5 neutral-density filters. Viewing the stereograms through these neutral-density filters served to reduce the brightness of these observers' retinal images by two thirds. This manipulation made their retinal images similar to those of a typical 60-year-old (see Weale, 1963). Thus, if there is an effect of age on stereoscopic shape perception, the inclusion of this control experiment should allow us to determine whether the age effect is related to the reduced retinal illumination that accompanies aging or whether it is due to more central factors. The use of neutral-density filters to simulate the optical effects of aging in younger observers has previously been used by other investigators (see, e.g., Bennett, Sekuler, & Ozin, 1999; Sekuler & Owsley, 1982). In this control experiment, the younger observers participated in two blocks of trials using the neutral-density filters and two blocks of trials without the neutral-density filters. Half of the observers judged the stimuli with the neutral-density filters first; the other half of the observers followed the opposite order of conditions. The internal structure of all four blocks of trials was identical to that used in the main experiment (a peak–trough disparity of 2.1′ of arc was used for these blocks). All of the observers, both in the main and the control experiments, were naive with regard to the purposes of the experiment, were unaware of how the experimental stimuli had been generated, and so forth.

Results and Discussion

The results are shown in Figures 1–4. Figures 1–3 illustrate the significant effects obtained with a disparity of 2.1′ of arc (the disparity that was common to both the younger and older observers). Figure 1 plots the observers' performance as a function of binocular correspondence for both age groups. Overall, the younger observers' recognition accuracies were about 20% higher than those of the older observers (i.e., the average overall performance was 82.0% correct for the younger observers and 63.2% correct for the older observers). There was a large effect of reducing the binocular correspondence (i.e., adding correspondence "noise" to the stereograms) for both age groups. These effects were verified by the results of a three-way ANOVA, with one between-subjects factor (age) and two within-subjects factors (binocular correspondence and stereogram type: static, dynamic slow, dynamic fast). There were significant main effects of age [$F(1,14) = 16.5$, $MS_e = 773.0$, $p = .0012$] and binocular correspondence [$F(2,28) = 225.6$, $MS_e = 88.5$, $p < .0001$]. These factors together accounted for 71.7% of the total variance in the observers' judgments (age accounted for 17.3% of the variance, whereas binocular correspon-

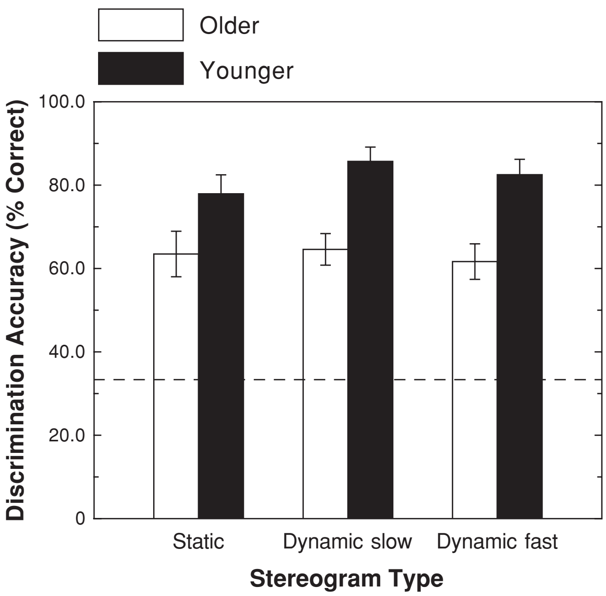

Figure 2. Results of Experiment 1. The younger and older observers' discrimination accuracies are plotted as a function of the type of stereogram (static, dynamic slow, and dynamic fast). Chance discrimination performance is indicated by the dashed line. The error bars indicate ±1 *SE*.

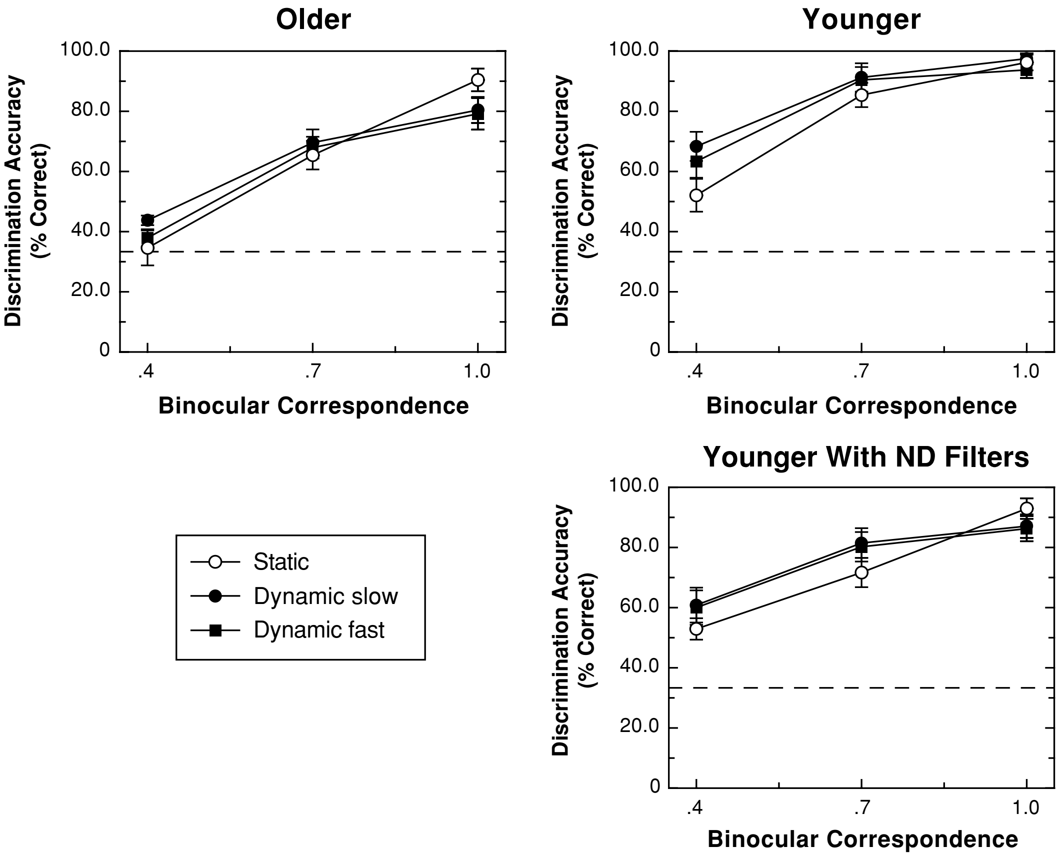

Figure 3. Results of Experiment 1. The significant stereogram type (static, dynamic slow, and dynamic fast) × binocular correspondence interaction is plotted for the older and younger observers, as well as for the younger observers who judged the stereoscopic stimuli using 0.5 neutral-density (ND) filters. Chance discrimination performance is indicated by the dashed lines. The error bars indicate ±1 *SE*.

dence accounted for 54.4%). In addition, there was a very small but significant age × correspondence interaction [$F(2,28) = 4.1$, $MS_e = 88.5$, $p = .028$]; this interaction accounted for only about 1% of the total variance in the observers' judgments. The age × correspondence interaction was most likely due to a ceiling effect on the part of the younger observers when they judged stereoscopic surfaces with 100% binocular correspondence. In this condition (see Figure 1), the younger observers' performance was essentially perfect, and further improvement in performance was therefore impossible.

Figures 2 and 3 illustrate the effects involving stereogram type (static, dynamic slow, dynamic fast). The main effect of stereogram type was significant [$F(2,28) = 5.2$, $MS_e = 47.8$, $p = .012$], but the effect of stereogram type itself depended on age and binocular correspondence. It is readily apparent from an inspection of Figure 2 that there were no significant differences in performance for the older observers across the different stereogram types. The younger observers, however, performed slightly better when they judged dynamic random-dot stereograms, thus leading to a significant age × stereogram type interaction [$F(2,28) = 3.6$, $MS_e = 47.8$, $p = .042$]. Once again, it is possible that this age-related interaction was due to a ceiling effect on the part of the younger observers. Notice that in the static stereogram condition shown in the upper left panel of Figure 3, the older observers demonstrate a linear improvement in performance with increasing binocular correspondence. A similar linear improvement for the static condition was also exhibited by the younger observers who judged the stereoscopic surfaces using 0.5 neutral-density filters (lower right panel of Figure 3). This linear trend did not occur for the younger observers whose data are shown in the upper right panel of Figure 3, because of a ceiling effect that occurred for the 100% correspondence condition. If the younger observers' performance for the static, 100% correspondence condition (shown in the upper right panel of Figure 3) had not been restricted by a ceiling effect, their overall static performance (shown in Figure 2) would have been higher. It is thus likely that the age × stereogram type interaction was due to a ceiling effect on the part of the younger observers.

Figure 3 illustrates another interesting phenomenon: a significant stereogram type (static vs. dynamic) × binocular correspondence interaction [$F(4,56) = 6.4$, $MS_e =$

54.9, $p < .001$]. This interaction was similar for both age groups [i.e., the age × stereogram type × binocular correspondence interaction was not significant; $F(4,56) = 0.47$, $p > .05$]. Notice that when significant amounts of correspondence noise were present (30% and 60% of the points constituted noise), both the younger and older observers performed best when they viewed dynamic stereograms. When no noise was present, however (when correspondence equaled 1.0), the superiority of the dynamic stereograms disappeared; in this case, performance was either the same for static and dynamic stereograms (younger observers) or performance was higher for the static stereograms (older observers, younger observers with 0.5 neutral-density filters). As far as we are aware, the demonstrated superiority of dynamic stereograms in noisy circumstances is a novel finding that has not been reported in the literature on stereopsis. One possible explanation may be that the stereoscopic visual system integrates information over time; if that is so, the new "signal" points that appear every 14.3 or 28.6 msec would allow for a better and higher resolution sampling of the stereoscopic surface, which would be expected to raise performance. This effective increase in sampling apparently helps raise performance the most in difficult situations in which large amounts of noise are obscuring the 3-D surface. A distinctly different explanation for the advantage of dynamic stereograms involves statistical differences in the properties of the noise within the static and dynamic patterns. In the static stereograms, the particular points that are designated as noise persist, and continue to obscure the 3-D surface as long as the observer views the stereogram. In the dynamic case, however, the points that constitute noise change over time (because a new stereogram is presented at a 35- or 70-Hz rate). Over time, the average positions of the noise points in depth will converge to zero (i.e., the frontoparallel plane). The dynamic and continuously changing noise may thus have less of a disruptive influence than the type of unchanging noise that is present within the static stereograms.

Figure 4 shows the effects of changes in disparity magnitude. As one would expect, increases in disparity led to significant improvements in performance for both the older [$F(1,7) = 54.0$, $MS_e = 108.8$, $p = .0002$] and younger [$F(1,7) = 16.4$, $MS_e = 310.8$, $p = .005$] observers. In this graph, one can readily see the relatively large difference between the performance of the younger and older observers at a disparity of 2.1′ of arc. However, it is important to note that the older observers could perform just about as well as the younger observers, if the amount of disparity was increased to 3.4′ of arc.

The results of the control experiment revealed that there was no significant difference between the performance of the younger observers when they wore the 0.5 neutral-density filters and when they did not [$F(1,7) = 4.0$, $MS_e = 277.9$, $p = .086$]. This control experiment was performed to evaluate whether the effect of age obtained in the main experiment was due to the reduced retinal illuminance that accompanies aging (this occurs because of senile miosis, lens opacification, etc.; see Sekuler & Sekuler, 2000). The neutral-density filters made these younger observers' retinal images the same brightness as those of a 60-year-old adult. The performance of the younger observers with the neutral-density filters was 5.5% less, on average, than that obtained without the neutral-density filters. This 5.5% difference, however, was not statistically significant. Even if this small difference had been significant, it could not have accounted for the effect of age obtained in the main experiment, since there was a much larger difference (almost 20%) in performance between the younger and older observers (see Figure 1). In addition, the results of the control experiment revealed the presence of the same stereogram type (static vs. dynamic) × binocular correspondence interaction that was obtained in the main experiment [$F(4,28) = 7.6$, $MS_e = 50.1$, $p = .0003$] (see lower right panel of Figure 3). This replication would appear to indicate that this effect is indeed genuine: When significant amounts of correspondence noise are present, human observers discriminate 3-D surface shape best when the stereograms are dynamic. This superiority in performance obtained with dynamic stereograms, however, does not exist when noise is absent.

EXPERIMENT 2

In Experiment 1, many of the stereoscopic stimuli were dynamic, in the sense that the individual points defining the 3-D surfaces were changed every 14.3 or 28.6 msec (the monocular half-images of the stereograms looked much like what one would see on the screen of a television tuned to a blank channel). In these stereograms, the individual surface points were refreshed at rapid rates, but the patterns of binocular disparity themselves remained

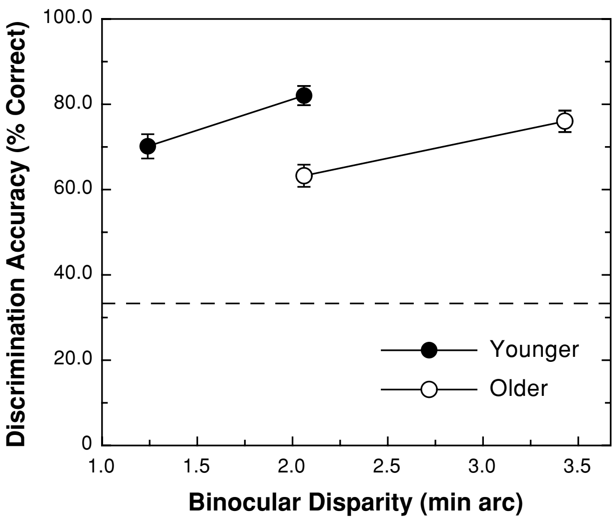

Figure 4. Results of Experiment 1 illustrating the effect of changes in the magnitude of peak–trough binocular disparity. Chance discrimination performance is indicated by the dashed line. The error bars indicate ±1 *SE*.

stationary over time (i.e., the 3-D surfaces remained constant even though the points defining them survived for only short periods of time). In Experiment 2, the dynamic random-dot stereograms were made even more dynamic by putting the patterns of binocular disparity into motion.

Method

Apparatus. The apparatus was identical to that used in Experiment 1.

Stimulus displays. The stimulus displays were identical in almost all aspects to the slow dynamic random-dot stereograms used in Experiment 1. The only difference was that the stereoscopic surfaces moved (translated vertically in either an upward or downward direction) in some of the conditions of the present experiment. The magnitude of peak–trough disparity was 2.1′ of arc for both age groups.

Observers. Eight younger (mean age was 21.4 years, $SD = 1.7$) and 8 older observers (mean age was 70.3 years, $SD = 4.5$) participated in the experiment. Five of the younger observers had previously participated in Experiment 1, whereas 6 of the 8 older observers had. All of the younger observers in this experiment viewed the stereograms using the same 0.5 neutral-density filters that were employed in the control experiment of Experiment 1. Therefore, any age effect obtained in the present experiment could not be due to the reduced retinal illumination that accompanies aging, because the brightness of all of the younger observers' retinal images was adjusted to be identical to that of a 60-year-old adult. The younger observers' mean acuity was 1.0 min^{-1}, whereas that for the older observers was slightly less, 0.9 min^{-1} (1.0 min^{-1} is equivalent to 20/20 vision measured at 20 ft; 0.8 min^{-1} is equivalent to 20/25 vision). If the observers typically wore corrective lenses (e.g., bifocals), they used the correction that gave them the best visual acuity to view the stereograms. No observer reported any significant eye disorders, such as macular degeneration or glaucoma. All of the observers were naive with regard to the purposes of the experiment, the nature of the experimental stimuli, and so forth.

Procedure. The observers' task was to discriminate between the same 3-D surfaces as were used in Experiment 1 (i.e., sine wave, square wave, and ramp). There were a total of nine experimental conditions formed by the orthogonal combination of three speeds of vertical surface motion (0º, 2.7º, and 5.4º visual angle/sec) and three binocular correspondences (.7, .85, and 1.0). Each experimental session consisted of 108 trials (12 repetitions × 9 conditions). All observers participated in two experimental sessions; thus, at the end of the experiment, each observer had judged 216 stimuli (24 trials × 9 conditions). Within each session, the order of the three 3-D surfaces and experimental conditions was randomly determined. Whether the surfaces translated upward or downward in the moving conditions was also determined randomly for each trial.

Results and Discussion

The results are shown in Figure 5. As can be seen readily in the graphs, there were significant main effects of age, speed, and binocular correspondence. These effects were verified by a three-way ANOVA with one between-subjects factor [age, $F(1,14) = 6.9$, $MS_e = 2,067.6$, $p < .02$] and two within-subjects factors [speed and binocular correspondence: effect of speed, $F(2,28) = 28.6$, $MS_e = 100.3$, $p < .0001$; effect of binocular correspondence, $F(2,28) = 14.7$, $MS_e = 70.4$, $p < .0001$]. None of the interactions were significant. The quantitative effect of age was almost exactly the same as that obtained in Experiment 1 (the difference in discrimination performance in Experiment 1 was 18.8%, whereas that obtained in the present experiment was 19.9%). The increases in speed and reductions in binocular correspondence negatively affected the observers' discrimination performance, and this decline was exactly the same for the younger and older observers.

GENERAL DISCUSSION

The results of the present experiments have revealed that the stereoscopic visual system of older observers is functionally very much like that of younger observers. There is apparently little or no qualitative difference, only a quantitative one. Manipulations of amounts of binocular correspondence (Figures 1, 3, and 5), magnitudes of binocular disparity (Figure 4), and the speed of stereoscopic motion (Figure 5) affect younger and older observers in a very similar manner. This finding agrees with those of Norman et al. (2000, see Experiments 1 and 2), who also found important similarities in the stereoscopic performance of younger and older observers.

This functional similarity in stereopsis between younger and older observers does not always hold for the perception of 3-D shape from motion. Norman et al. (2004, see their Figure 1) found that older observers, unlike younger observers, cannot perceive or discriminate 3-D shape from motion parallax when the surface points survive for only two consecutive views, or 100 msec (their performance was no better than chance in this condition). The same result was also obtained for the perception of 3-D shape from rotational motion (i.e., the kinetic depth effect; Norman et al., 2000, see their Figure 10). It seems clear that limiting the lifetime of points in a structure-from-motion display has a devastating effect on the ability of older observers to perceive and discriminate 3-D shape. In this context, it was remarkable to find in the present experiments that severely limiting the lifetimes of the stereoscopic points to only 14.3 or 28.6 msec had no adverse effect on the accuracy of the older observers' judgments (see Figure 2). The fact that the same manipulation affects older observers' stereoscopic and shape-from-motion judgments quite differently suggests that the ability to perceive 3-D shape from motion and the ability to perceive 3-D shape from binocular disparity rely on separate mechanisms (these mechanisms, however, do interact; see Nawrot & Blake, 1991; Norman & Todd, 1995). It would appear from a comparison of present and past results that aging has a more deleterious effect on neural mechanisms that extract information about 3-D shape from motion. In contrast, stereopsis appears to possess a more privileged status: Its qualitative aspects are well preserved with age.

Despite the qualitative similarity, the results of our experiments indicate that there is a modest quantitative difference between the stereoscopic capabilities of younger and older observers. Older observers typically have reduced sensitivity to contrast within optical patterns (see, e.g., Elliott, Whitaker, & MacVeigh, 1990; Haegerstrom-Portnoy et al., 1999; Norman, Ross, Hawkes, & Long, 2003). Legge and Gu (1989, see their Figures 5 and 6) showed that decreases in stimulus contrast lead to eleva-

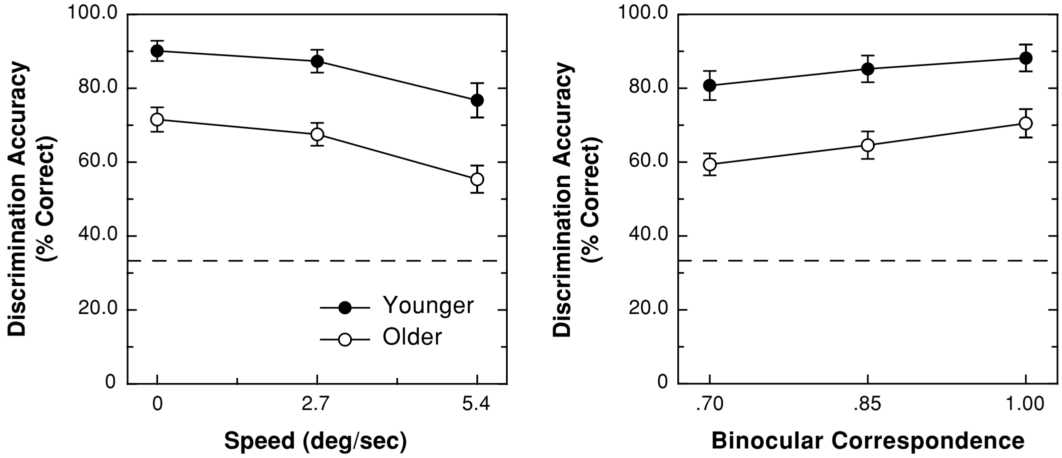

Figure 5. Results of Experiment 2 for the younger and older observers. The observers' discrimination accuracies are plotted as functions of the speed of stereoscopic motion (left panel) and binocular correspondence (right panel). Chance discrimination performance is indicated by the dashed lines. The error bars indicate ±1 *SE*.

tions in stereoscopic detection thresholds (detection of crossed vs. uncrossed disparity). It is thus possible that some of the age-related quantitative deficit in stereoscopic shape discrimination that we observed (see, e.g., Figures 1 and 5) may be due to reductions in the older observers' sensitivity to contrast. It may be important, however, to note that the stereoscopic stimuli used by Legge and Gu (sine-wave luminance gratings whose phase was differentially shifted across the two eyes' views) were quite different from the random-dot stereograms (with high-contrast, bright points arrayed against a black background) employed in the present study. Lit, Finn, and Vicars (1972) and Ogle and Weil (1958) found that changes in the contrast of stereoscopically presented lines had little or no effect on stereoacuity judgments as long as the target lines were sufficiently visible. At the moment, it is thus unclear how much of the age-related deficit that we observed is attributable to older observers' reduced sensitivity to contrast. Future experiments on aging and stereopsis that manipulate contrast will be needed to settle this issue.

The present experiments demonstrated that dynamic random-dot stereograms lead to better performance on shape discrimination than do conventional static random-dot stereograms when significant amounts of correspondence noise are present (see Figure 3). This superiority of dynamic stereograms existed for all three groups of observers in Experiment 1—the younger observers, the older observers, and the younger observers who viewed the stereograms using 0.5 neutral-density filters. Although dynamic random-dot stereograms have been utilized for about 30 years (see, e.g., Fox et al.,1980; Julesz, 1971; Julesz et al.,1976), this finding has not been noticed before (as far as we are aware). This superiority of dynamic stereograms is probably due to either an effective increase in the spatial sampling of the underlying 3-D surfaces or to statistical effects involving the noise itself (i.e., over time, the average depth of the noise points in the dynamic stereograms converges to zero, and such noise may thus have less of a disruptive effect on the observers' discrimination performance than does the unchanging noise present in the static stereograms).

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