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The effects of age upon the perception of depth and 3-D shape from differential motion and binocular disparity

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Abstract. The ability of younger and older adults to perceive the 3-D shape, depth, and curvature of smooth surfaces defined by differential motion and binocular disparity was evaluated in six experiments. The number of points defining the surfaces and their spatial and temporal correspondences were manipulated. For stereoscopic sinusoidal surfaces, the spatial frequency of the corrugations was also varied. For surfaces defined by motion, the lifetimes of the individual points in the patterns were varied, and comparisons were made between the perception of surfaces defined by points and that of more ecologically valid textured surfaces. In all experiments, the older observers were less sensitive to the depths and curvatures of the surfaces, although the deficits were much larger for motion-defined surfaces. The results demonstrate that older adults can extract depth and shape from optical patterns containing only differential motion or binocular disparity, but these abilities are often manifested at reduced levels of performance.

1 Introduction

The scientific study of the human perception of depth and three-dimensional (3-D) shape from binocular disparity and differential motion has a relatively long history. These optical sources of information about depth and shape have been a primary focus of research by perceptual researchers ever since the pioneering works of Wheatstone (1838) and von Helmholtz (1867/1925), respectively. Differences (ie disparities) between the two eyes' retinal images occur whenever an observer binocularly views a solid 3-D object at a relatively close viewing distance (Howard and Rogers 1995). Similar differences in the velocities of retinal motion also occur whenever there is relative movement between an observer and a nearby 3-D object (Braunstein 1976). In the twentieth century, aging also became an important focus of research thanks to the efforts of important early psychologists, such as G Stanley Hall (1922). It is therefore surprising that, until very recently, there has been little scientific investigation of how the process of aging affects the perception of 3-D structure and shape. The purpose of the present investigation was to determine whether deficits related to the perception of depth and shape are common among the elderly and, if so, to estimate the size of the reductions in these abilities.

The studies that have been performed to assess the stereoscopic abilities of the elderly have primarily been limited to investigations of stereoacuity—very few other tasks have been employed (for a notable exception, see Speranza et al 1995). Even then, the experimental findings have been mixed. In a number of studies large differences in stereoacuity have been found across age groups (Jani 1966; Bell et al 1972; Wright and Wormald 1992), while other studies have not found evidence of significant differences (Tiffin 1952; Hofstetter and Bertsch 1976; Greene and Madden 1987; Yekta et al 1989). Perhaps even more surprising is the fact that most of these experiments (eg Jani 1966; Bell et al 1972; Hofstetter and Bertsch 1976; Wright and Wormald 1992, etc) did not use random-dot stereograms, despite the fact that they were developed by Bela Julesz in the late 1950s and early 1960s (eg Julesz 1960, 1964). The use of random-dot stereograms is methodologically important, since they are the only type of stimulus that does not contain monocular sources of information about depth and 3-D shape (Julesz 1971). If random-dot stereograms are not used, one cannot be completely sure that whatever performance is observed is due to the detection and utilization of binocular information per se, such as binocular retinal disparity.

Compared to the moderate number of studies that have focused upon stereoacuity and aging, there has been very little research on whether or how the process of aging affects the perception of 3-D object structure from patterns of optical motion. This is especially surprising, since many experiments have been performed over the last 50 years that have extensively investigated how human observers perceive the 3-D structure of environmental objects and scenes from the differential retinal motion that occurs when observers and objects move relative to each other (Wallach and O'Connell 1953; Green 1961; Braunstein 1962; Braunstein and Andersen 1984; Todd et al 1988; Norman and Lappin 1992; Norman and Todd 1995). In 1995, Andersen and Atchley published the results of a study in which the ability of younger and older adults to detect smoothly curved sinusoidal surfaces defined by motion was examined. They varied a number of important parameters, such as the density of surface points, the spatial frequency of the sinusoidal corrugations, etc. In an additional experiment, Andersen and Atchley required the observers to detect the presence of the sinusoidal surfaces when they were embedded in a random volume of 3-D 'noise', and the signal/noise ratio was varied over time. The results of these experiments showed that the detectability of the surfaces increased as the density of the points was increased, increased as the signal/noise ratio of the stimulus patterns was increased, and decreased as the frequency of the sinusoidal corrugations was increased. In both experiments, the older observers (mean age was approximately 72 years) exhibited less sensitivity at detecting the presence of the sinusoidal surfaces than the younger observers (mean age was approximately 21 years)—in most conditions, the d' values for the older observers were between one-half and one-third of those obtained for the younger observers.

From the research that has been conducted upon perception among the elderly to date, it is not possible to draw many conclusions about their ability to perceive or recognize the 3-D shape of objects. For example, while there have been a number of studies of stereopsis in older adults, none of them has measured how much of a depth interval is perceived when older observers view a stereoscopic pattern containing binocular disparity. Even if they perceive depth from such patterns, we do not know if the magnitude of their perceived depth is in accordance with that expected from the geometry of stereopsis (Cormack and Fox 1985). An analogous question exists for the perception of 3-D surfaces defined by differential motion. When older observers view a motion-defined surface, do the perceived depths or curvatures of the surface agree with the specified or simulated values? In other words, how precise is their knowledge of an object's actual surface structure? There are similar uncertainties about the discrimination and recognition of 3-D shape. For example, can the elderly recognize the shape of environmental objects in a manner that is similar to that of younger adults? Or is their performance qualitatively different? At the present time, the answers to such questions are unknown. The purpose of the current experiments is to resolve some of the outstanding ambiguities about the 3-D perceptual capabilities of older adults by examining their ability to perceive, discriminate, and recognize 3-D objects defined by binocular disparity (experiments 1 and 2) and differential motion (experiments 3–6).

2 Experiment 1

The overall purpose of the first two experiments was to investigate the stereoscopic abilities of older observers, and determine whether there are any significant qualitative or quantitative differences between the abilities of younger and older observers to perceive depth and shape from binocular disparity. It has been suggested for both theoretical and empirical reasons that there may be a distinction in how human observers perceive depth and shape (Koenderink 1990; Tittle et al 1998). Therefore, the purpose of the first experiment was to evaluate the perception of depth interval magnitude for surfaces defined by binocular disparity, while the purpose of the second experiment was to evaluate the perception of stereoscopic surface shape.

2.1 *Method*

2.1.1 *Observers.* Seven younger adults (mean = 22.3 years of age, $\sigma = 1.7$ years, including the third author AKB) and six older adults (mean = 74.7 years of age, $\sigma = 5.8$ years) participated in the experiment. All of the observers had their visual acuity assessed at a 1 m viewing distance (which was the same distance as the stimulus displays that were presented during the experimental trials) with the Landolt C (Riggs 1965). The average acuity was 1.0 min^{-1} for the younger observers and 0.83 min^{-1} for the older observers (1.0 min^{-1} is equivalent to 20/20 vision measured at 20 feet; 0.67 min^{-1} is equivalent to 20/30 vision). If the individual subjects wore glasses/bifocals, they used the correction that gave the best acuity at the 1 m testing distance. Prior to the beginning of the actual experiment, all observers were tested whether they possessed stereopsis or not by requiring them to identify the shape of an object defined only by the binocular disparity in a random-dot stereogram (a 'plus' sign or ✚, standing out in depth from a textured background surface with a disparity of 20.2 min of arc). All of the observers, both younger and older, were able to correctly identify the shape of this 'hovering' surface, thus demonstrating the presence of stereopsis.

2.1.2 *Apparatus.* The random-dot stereograms containing binocular disparity were generated by an Apple PowerMacintosh 8600/300 computer and displayed on a 21-inch Mitsubishi 91TXM monitor (1024 × 768 pixel screen resolution). The stereograms were presented to the observers with CrystalEyes-2 liquid crystal display (LCD) shuttered glasses (StereoGraphics Inc). The left and right stereoscopic images were alternately presented on the computer monitor at a rate of 150 Hz. The LCD glasses operated in sync with the monitor, filtering the images so that the left stereoscopic half-image was seen only by the left eye, while the right half-image was seen only by the right eye. Each eye's view, then, was updated at a temporal rate of 75 Hz. The computer was also used to record the observers' responses during the experiment.

2.1.3 *Stimulus displays.* Random-dot stereograms depicting sinusoidally shaped surfaces modulated in depth (horizontal peaks and troughs) were shown to the observers (for an example, see figure 1) in a dimly-lit room under photopic conditions. The stereograms

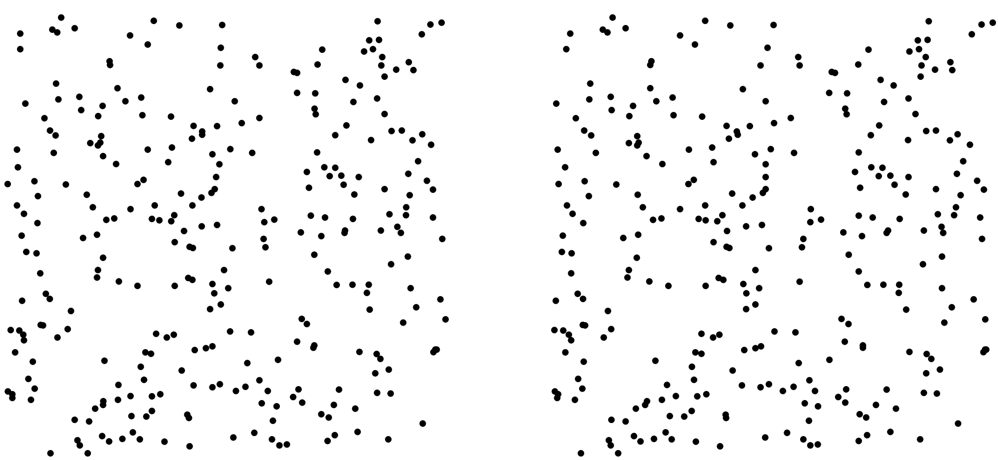


Figure 1. A random-dot stereogram depicting a sinusoidal surface with horizontally oriented peaks and troughs like those used in experiment 1. This 3-D surface is visible if the left and right half-images are simultaneously presented to an observer's left and right eyes, respectively.

contained three levels of zero-peak image disparity (±0.15, ±0.40, and ±0.65 cm which corresponded to approximate maximal retinal disparities of 5.2, 14.3, and 24.4 min of arc, respectively; the average interpupillary distance of the observers was 6.0 cm). The stereograms were viewed at a distance of 100 cm—the size of the stereograms in terms of visual angle was 17.06 deg wide × 12.55 deg tall. The sinusoidal surfaces had two spatial frequencies (0.25 and 0.75 cycle deg^{-1}), as well as two densities of texture elements on the surface (3000 and 15 000 points, resulting in densities of 14 and 70 points deg^{-2}, respectively). The points were positioned with sub-pixel accuracy by anti-aliasing software techniques. This procedure allowed for more accurate control of the disparity of each point, which defined its position on the surface in depth.

2.1.4 *Procedure.* The experiment consisted of 12 different conditions (3 levels of zero-peak image disparity × 2 spatial frequencies × 2 texture element densities). Within a single experimental session, the observers made eight adjustments for each condition. Therefore, each observer completed a total of 96 trials (12 conditions × 8 responses). Each experimental session lasted about 45 min, reducing the possibility of fatigue. Each observer's task was to adjust the length of a response bar with the computer mouse until it matched the perceived depth interval between the peak and trough of each sinusoidal surface. All conditions were presented in a random order within a single experimental session.

2.2 *Results and discussion*

The overall results for the younger and older observers are shown in figure 2. For all observers, the average perceived depth interval between the peaks and troughs of the surfaces is plotted as a function of the image disparity. It is evident that the manipulation of disparity produced large changes in the size of the depth intervals perceived by both groups—in particular, the perceived depth intervals increased by substantial amounts as the amount of disparity in the stereograms was increased. One of the older observers, however, performed poorly on this day, despite having good acuity and having passed the stereoscopic shape-identification task involving the + sign described earlier. In this experiment, her judgments of the perceived depth intervals averaged 3.7 cm, with a standard error of 0.13 cm. This performance was perplexing, because she had earlier participated in a pilot experiment with the same task with identical stereograms depicting the same sinusoidal surfaces with the same disparities, densities,

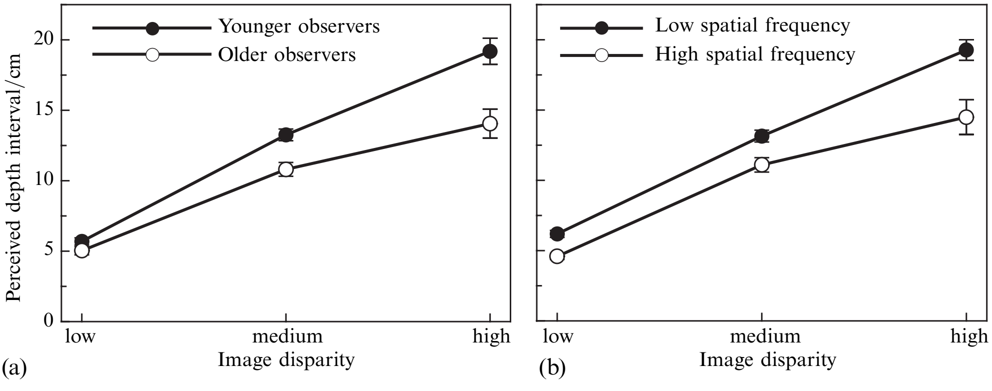


Figure 2. Overall results for experiment 1. (a) The amount of depth perceived by the younger and older observers as a function of image disparity. This panel also illustrates the significant age × disparity interaction (ie depth intervals perceived by the older observers increased at a slightly lower rate relative to those of the younger observers as the magnitude of the image disparity was increased). (b) The results for the low-spatial-frequency and high-spatial-frequency conditions collapsed across age, illustrating the main effect of spatial frequency, as well as the significant spatial frequency × disparity interaction. The error bars in both panels indicate ±1 standard error.

and spatial frequencies. In that pilot experiment with the identical task and stereoscopic stimuli, she performed very well, despite the random order of conditions, and obtained results similar to those of the other older observers. So, for this observer, we have two different sets of judgments, one with essentially the same response on every trial, and one that conclusively indicates that she must possess rather good stereoscopic abilities. The data included in the analysis for this observer were her performance for the day when she could clearly see the stereoscopic surfaces—we were unable to determine the reason for the differences between the two experimental sessions.

The large main effect of disparity evident in figure 2 was confirmed by a four-way split-plot analysis of variance (ANOVA) with age as a between-groups factor and disparity, density, and spatial frequency as within-subjects factors ($F_{2,120} = 276.7$, $p < 0.001$, $\mathrm{MSE} = 5.9$). The results of the ANOVA also revealed significant main effects of age ($F_{1,11} = 7.7$, $p < 0.02$, $\mathrm{MSE} = 40.7$) and spatial frequency ($F_{1,120} = 55.5$, $p < 0.001$, $\mathrm{MSE} = 5.9$), as well as significant two-way interactions of age $\times$ disparity ($F_{2,120} = 12.8$, $p < 0.001$, $\mathrm{MSE} = 5.9$) and disparity $\times$ spatial frequency ($F_{2,120} = 7.6$, $p = 0.001$, $\mathrm{MSE} = 5.9$). No other main effects, two-way interactions, or higher order interactions were significant.

The significant two-way interaction of age $\times$ disparity results from the fact that the older observers' perceived depth-interval magnitudes were somewhat smaller proportionally than those of the younger observers for any given amount of binocular disparity (see figure 2a). Nevertheless, the qualitative pattern of the two groups of observers was essentially identical—as disparity increased, so did the magnitudes of the perceived depth intervals. The main effect of spatial frequency and the disparity $\times$ spatial frequency interaction are illustrated in figure 2b. At all disparities, the perceived depth interval was smaller for the higher spatial frequencies of sinusoidal corrugation. This reduction in perceived depth with increases in spatial frequency occurred for observers in both groups (ie no age $\times$ disparity $\times$ spatial frequency interaction was obtained from the ANOVA).

From the results presented in figure 2, it is clear that the increases in the amount of binocular disparity led to significant changes in the amount of depth that was perceived between the peaks and troughs of the sinusoidal surfaces for all observers in both age groups. However, from the data presented so far, it is unclear whether the magnitudes of the increases in perceived depth were in accordance with what would be expected of the observers in our particular viewing situation. For all observers, an expected depth interval was calculated for each level of binocular disparity, given their individual interpupillary distances according to the equations provided by Cormack and Fox (1985). The ratio or proportion of actual versus expected depth interval for each combination of disparity and spatial frequency is plotted in figure 3 for both age groups. The data in figure 3 were collapsed over high and low density, since the results of the ANOVA revealed no significant effects of density on the observers' judgments. It is evident that, while the older observers, on average, perceived less depth, the pattern of their judgments is essentially identical to that of the younger observers. The differences in performance between the individual older observers cannot be accounted for by differences in their visual acuity. Their acuities and average perceived depths relative to that expected are given in table 1. From an inspection of table 1, it is clear that the observers who performed most accurately (ie proportions of expected depth near 1.0) often had the lowest acuities. This is not necessarily surprising since it has been shown that the stereoscopic perception of depth survives considerable blurring of the retinal images (Julesz 1971).

All of the observers, both young and old, had the most difficulty (ie perceived the least depth relative to that expected) in perceiving the stereoscopic surfaces in the high-disparity/high-spatial-frequency condition. For that condition, the decline in perceived depth for the older observers was very pronounced (see figure 3), in that the

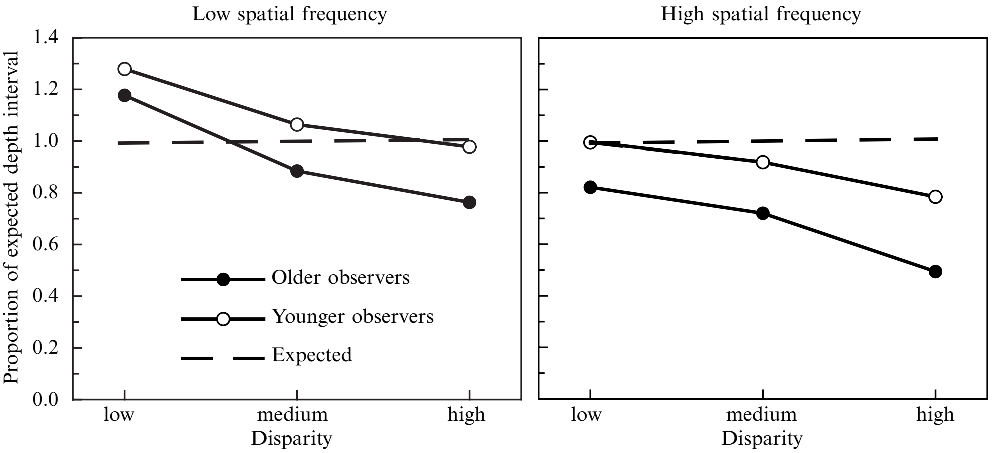


Figure 3. Average results for the younger and older observers: their perceived depth intervals are plotted as proportions of their expected depth intervals. Values greater than 1.0 indicate that the observers perceived a greater depth interval than was expected, while values less than 1.0 indicate that the observers perceived a smaller depth interval than was expected.

Table 1. Relationship between acuity and perceived depth of the older observers in experiment 1.

Observer	Acuity/min $^{-1}$	Average perceived depth (proportion of expected)
2	0.50	1.058
4	0.80	0.780
5	1.00	0.706
6	0.67	0.795
10	1.00	0.745
11	1.00	0.776

perceived depth-interval magnitudes were only half of those expected. In addition, the older observers reported that they were unable to perceive a coherent stereoscopic surface for 25% of the trials for the high-density, high-disparity/high-spatial-frequency condition and for 40% of the trials for the low-density, high-disparity/high-spatial-frequency condition. The results for those conditions plotted in figures 2 and 3 include the judgments for which the observers could perceive the surface, and thus perform the adjustment task. It is important to keep in mind that this high-disparity/high-spatial-frequency condition was the most difficult for the younger observers as well, and that, overall, the performance of the older observers was typically close to that expected (figure 3). Except for the high-disparity/high-spatial-frequency conditions, the older observers perceived at least 75% of their expected depth intervals, demonstrating that their stereoscopic abilities have been largely preserved during the processes of aging. The similarities in the younger and older observers' judgments are especially striking when the stereoscopic surfaces have low spatial frequencies of depth modulation.

3 Experiment 2

The results of experiment 1 showed that, while there were some quantitative differences between the perceived depth intervals of the older and younger observers, their overall pattern of results was very similar. Except for the high-disparity/high-spatial-frequency conditions, which were difficult for all of the observers, the older observers perceived a substantial proportion of the depth that was expected (typically 75% of expected, or more). However, this high level of performance indicates only that their ability to perceive the magnitude of depth is relatively unimpaired; it does not tell us anything about possible differences in the way in which they perceive the shape of stereoscopic surfaces. The purpose of experiment 2 was to evaluate whether there are any substantive differences in how younger and older observers perceive and discriminate differences in surface shape.

3.1 *Method*

3.1.1 *Observers.* Ten observers participated in the experiment. Half of the observers were adults aged 60 years and older (mean = 72.2 years of age, $\sigma = 6.8$ years), while the other half were 30 years old or younger (mean = 24.6 years of age, $\sigma = 0.9$ years). All of the observers had their visual acuity assessed in the same manner as in experiment 1. The average acuity was 1.0 $\min^{-1}$ for the younger observers and 0.79 $\min^{-1}$ for the older observers.

3.1.2 *Apparatus.* All aspects of the apparatus (computer, monitor, LCD glasses, etc) were the same as those used in experiment 1.

3.1.3 *Stimulus displays.* Random-dot stereograms depicted surfaces similar to those used by Uttal et al (1988). The surfaces were shaped like hemispheres (ie bumps), hyperboloids (ie saddles), and cylinders, both vertical and horizontal (shown as stereograms in figure 4). Another reason that these particular surfaces were chosen is that these are the only generic types of regions that can occur on the surface of a smoothly curved 3-D object, regardless of its overall global shape (Koenderink and van Doorn 1982; Koenderink 1984, 1990). The surfaces were viewed through a circular occluding aperture (diameter = 5.72 deg) so that the observers could not see the outer boundary contour of the surfaces. The stereograms were displayed with one of two texture-element densities (15 or 100 points). The 100-point stereograms were displayed with three amounts of correspondence: 100%, 70%, and 40%. For example, 70% correspondence in a 100-point stereogram would mean that 70 points in one eye's view would have corresponding partners in the other eye's view, while 30 would not (ie those 30 points would be randomly repositioned in the other eye's view). The 15-point stereograms did not contain any reductions in correspondence. Therefore, there were a total of four display types (100-point surfaces with three levels of correspondence and 15-point surfaces with 100% correspondence).

In order to ensure an even, homogeneous distribution of points on the curved surfaces, the points were positioned according to the Antonov–Saleev variant of a two-dimensional Sobol sequence (Press et al 1992). The radius of curvature for all surfaces viewed by the younger observers was 20 cm, while that for the older observers was either 10 cm (four observers) or 5 cm (one observer).

3.1.4 *Procedure.* The experiment consisted of 16 different conditions formed by the combination of four differently curved surfaces (bumps, saddles, vertical cylinders, and horizontal cylinders) and four display types (three correspondence levels for 100-point surfaces and 100% correspondence for 15-point surfaces). The observers' task on each trial was to indicate to the experimenter which of the four surfaces had been presented. The experimenter would then press a key on the computer keyboard to record their choice. The low-density and high-density surfaces were presented in separate blocks of trials. In the first four blocks, the 100-point conditions were shown to the observers while the fifth block contained the 15-point surfaces. Within each of the first four blocks of trials, the observers made 10 judgments per condition. Therefore, there were 120 trials within each of the first four blocks (12 high-density conditions $\times$ 10 judgments). There were 160 trials in the fifth block (4 low-density conditions $\times$ 40 judgments). The observers were expected to complete all five blocks during a single experimental session. Inbetween blocks, they were allowed to take a break if they so desired. The total number

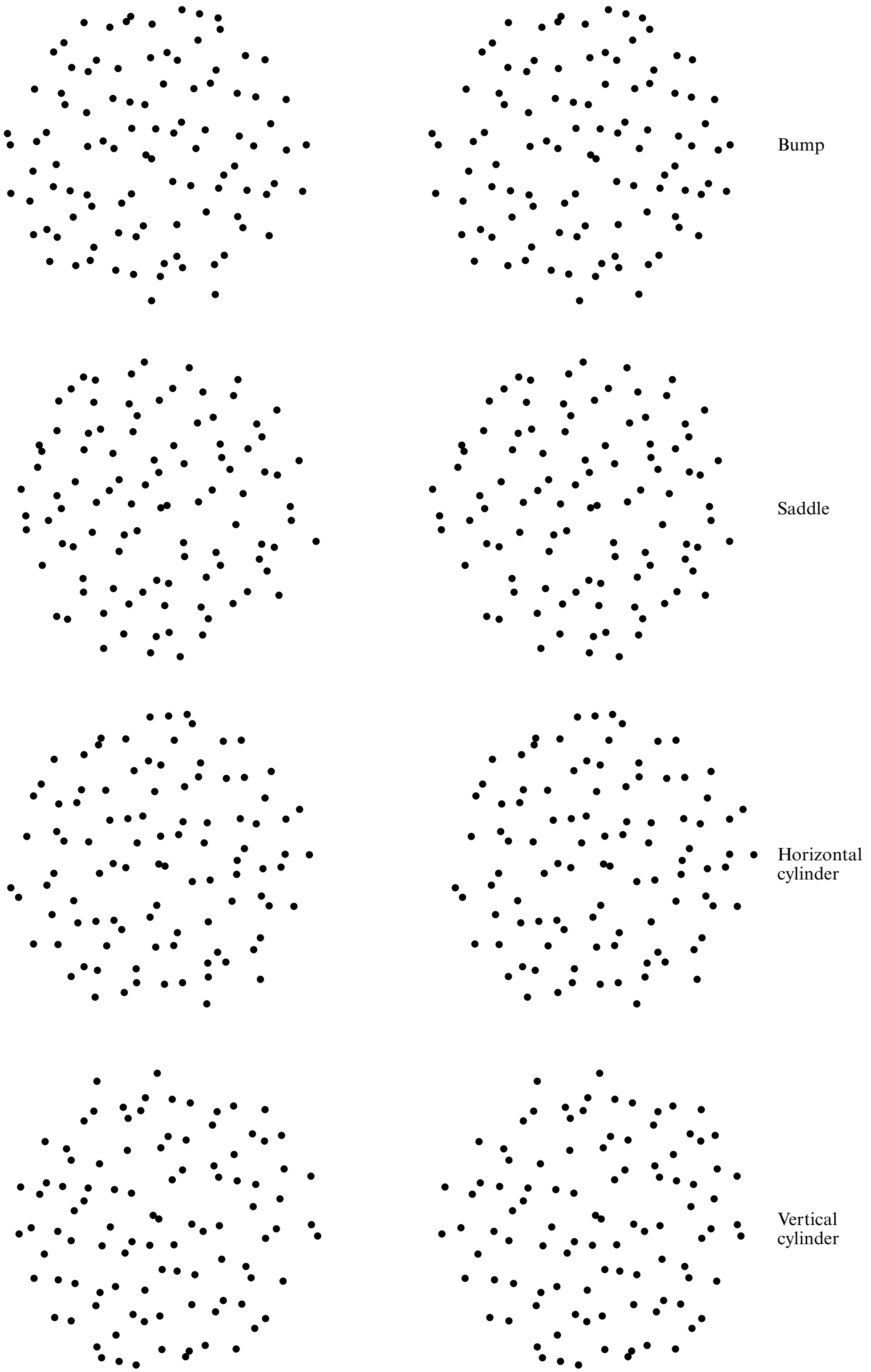


Figure 4. Example stereograms depicting the four differently curved surfaces used in experiment 2.

of trials in a session was 640 (16 total conditions × 40 judgments per condition). Each experimental session usually lasted about 1.5 h. All of the differently curved surfaces (and correspondences for the high-density blocks) were presented in a random order within any given block of trials.

3.2 *Results and discussion*

The results of the manipulation of correspondence for the younger and older observers are shown in figure 5a, and the effect of surface point density is similarly presented in figure 5b. Although the stereoscopic surfaces that were shown to the older age group had more curvature, ie a 10 cm as opposed to a 20 cm radius of curvature, both groups were similarly affected by the changes in point density and correspondence within the four different display types. In particular, performance deteriorated as the correspondence within the stereograms was decreased. As can be seen in figure 5a, the decline in performance was remarkably similar for both younger and older observers. In addition, both age groups were similarly affected by changes in the density of points defining the stereoscopic surfaces (see figure 5b). These effects were verified by two 4 × 4 factorial within-subjects ANOVAs—one for each age group. The ANOVAs for both age groups revealed a significant effect of display type ($F_{3,48} = 84.8$, $p < 0.001$, $\mathrm{MSE} = 91.4$; and $F_{3,36} = 43.7$, $p < 0.001$, $\mathrm{MSE} = 158.3$, for the younger and older groups, respectively). A Scheffé a posteriori analysis revealed that the performance for each of the correspondence conditions was significantly ($p < 0.05$) different from the others. The a posteriori analysis also revealed that the performance for the high-density and low-density conditions was significantly ($p < 0.05$) different for both age groups.

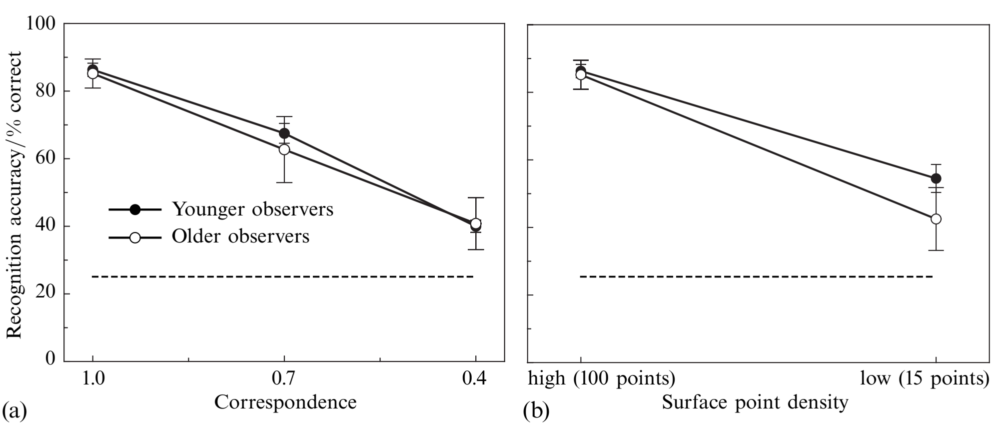


Figure 5. Overall results of the younger and older observers in experiment 2: Recognition accuracy plotted (a) as a function of the correspondence of the stereograms, and (b) as a function of surface point density. The error bars indicate ±1 standard error. The width of the error bars is greater for the older observers and smaller for the younger observers. Chance recognition performance is indicated by the dashed line.

The results for an additional older observer (age = 77 years) were not included in the ANOVA since she needed more curvature than the other older observers (5 cm radius of curvature) in order to perform the shape-discrimination task at above chance levels. In addition, the results for this observer are based upon 20 trials per condition. The overall pattern of results for this observer is similar to those of the other observers, but her performance was less accurate. For example, her performance was highest (58.8% correct) for the 100-point surfaces with perfect correspondence and it deteriorated with decreases in correspondence (50% and 32.5% correct for the 0.7 and 0.4 correspondences, respectively). Her performance, like those of the other observers, was affected by reductions in the number of points defining the surfaces (58.8% and 42.5%

correct for the 100-point and 15-point surfaces, respectively). All of this observer's discrimination performances were above chance levels, except for that of the 100-point surfaces with 0.4 correspondence ($\chi_3^2 = 6.8$, $p > 0.05$).

The results of the ANOVA revealed that there was a significant main effect of surface shape ($F_{3,48} = 19.8$, $p < 0.001$, $\mathrm{MSE} = 91.4$; and $F_{3,36} = 9.2$, $p < 0.001$, $\mathrm{MSE} = 158.3$, for younger and older adults, respectively) as well as significant observer $\times$ surface shape interactions for both groups ($F_{12,48} = 5.7$, $p < 0.001$, $\mathrm{MSE} = 91.4$; and $F_{9,36} = 3.7$, $p = 0.002$, $\mathrm{MSE} = 158.3$, for younger and older adults, respectively). In general, recognition performance was worst for the vertical cylinders. The most recognizable surface for half of the observers was the bump, but for the other half of the observers it was the horizontal cylinder—this difference is responsible for the significant observer $\times$ shape interactions.

Signal detection theory analyses (Elliott 1964; Green and Swets 1966) were also performed to determine which pairs of surfaces for a given condition were highly discriminable (ie less confusable) and which pairs of surfaces were less discriminable (ie more confusable). The results for this analysis are shown in figure 6 for both the younger and older observers for the 100-point surfaces with 1.0 correspondence. Out of the six possible pairs of surfaces, the bump–saddle and saddle–horizontal-cylinder pairs were the most discriminable. The fact that the bump and saddle surfaces are easily discriminable is not surprising given Koenderink's (1990) analysis of smoothly curved objects in terms of bumps and saddles. Essentially all observers in both age groups showed this pattern.

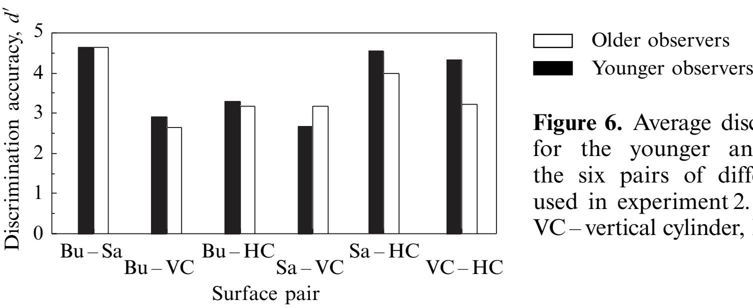


Figure 6. Average discrimination performance for the younger and older observers for the six pairs of differently curved surfaces used in experiment 2. Bu – bump, Sa – saddle, VC – vertical cylinder, HC – horizontal cylinder.

The findings of this experiment suggest that older adults can perceive the shape of stereoscopically defined surfaces at a performance level similar to that of younger adults if the surfaces have more depth and curvature. The manipulation of correspondence and the number of points defining the surfaces affects the elderly in the same way that it affects the younger adults. In particular, as correspondence and point density are reduced, the perception of surface shape becomes more difficult for both age groups. It is important to note that the older observers can discriminate differences in stereoscopic shape at reduced levels of correspondence.

Observers in both groups showed individual differences in recognizing surface shape. Despite some individual differences, however, the vertical cylinders were typically the most difficult surfaces to recognize overall. This is consistent with Norman and Lappin's (1992; also see Norman and Todd 1995; Bradshaw and Rogers 1999) finding that the curvatures of vertical cylinders were the most difficult to detect. As was expected, bumps and saddles were the easiest for the observers to discriminate regardless of age, supporting Koenderink's (1990) idea that these qualitatively distinct regions are important for the perception of shape. In summary, the results of this experiment demonstrate that older adults' perception of shape is not functionally different from that of younger adults. The results do show that older observers are less sensitive to stereoscopic depth and curvature, but their pattern of results is essentially identical to that of younger adults.

4 Experiment 3

The results of the first two experiments on the detection and utilization of binocular disparity have shown that older adults have a substantial amount of stereopsis that is still functional. They do, however, tend to perceive less depth than younger observers for any given amount of disparity. The overall purpose of the remaining experiments (3 – 6) was to extend this investigation to the perception of depth and shape from patterns of optical motion. Andersen and Atchley (1995) have previously examined how older observers detect the presence of smoothly curved 3-D surfaces that are defined by motion and embedded in noise. They found evidence of significant differences between younger and older observers' abilities to perform surface-detection tasks. Nevertheless, all of the older observers in their study were able to perceive depth differences from the moving patterns, particularly at the higher point densities. Although older observers can apparently perceive 3-D surfaces from optical patterns containing differential motion, the amount of depth or curvature they perceive from such patterns is not yet clear. The specific purpose of experiment 3, therefore, was to extend the investigations begun by Andersen and Atchley by requiring observers to make quantitative judgments about the curvatures (ie changes in depth) of smoothly curved surfaces defined by motion.

4.1 *Method*

4.1.1 *Observers.* Ten observers participated in the experiment. Half of the observers were adults aged 60 years and older (mean = 72.4 years of age, $\sigma = 5.5$ years), while the other half were 40 years old or younger (mean = 25.6 years of age, $\sigma = 6.5$ years, including the first and third authors JFN and AKB). All of the observers had their visual acuity assessed in the same manner as in experiments 1 and 2. The average acuity was 1.0 min^{-1} for the younger observers and 0.71 min^{-1} for the older observers.

4.1.2 *Apparatus.* The apparatus used in this experiment was the same as that employed in experiments 1 and 2, with the exception of the LCD glasses, which were no longer needed (no binocular disparity in the present experiment).

4.1.3 *Stimulus displays.* The stimulus displays consisted of either 19 or 91 points arranged into a perturbed hexagonal lattice, like those used by Norman and Lappin (1992). This procedure ensured that all surface regions were sampled in an approximately uniform manner. A stereogram of the 91-point surface is presented in figure 7. When the points moved, the velocities of the points simulated the movement of a surface that was curved in 3-D like a hemisphere (henceforth referred to as a 'sphere'). The apparent-motion sequences consisted of 15 distinct views. These views were refreshed at a rate of 25 Hz.

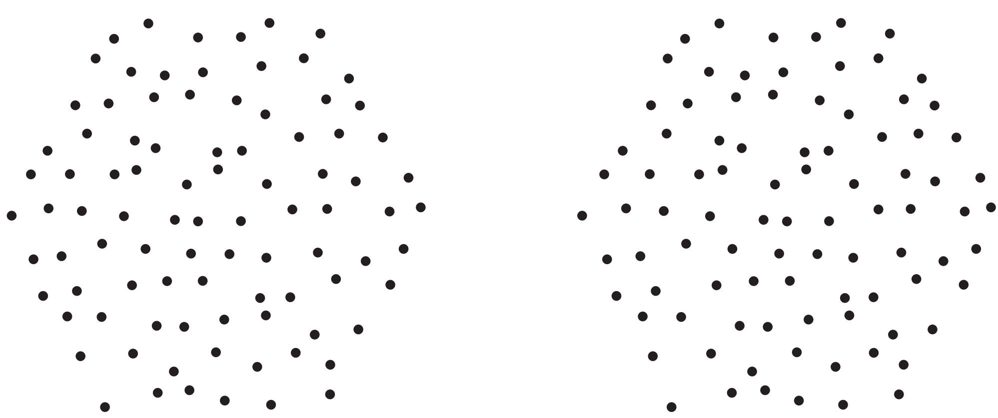


Figure 7. A random-dot stereogram depicting the hemispherical surfaces used in experiment 3. The points defining the surfaces were positioned according to a perturbed hexagonal lattice.

The spherical surfaces rotated 5.0° around a Cartesian vertical axis at every frame transition. These apparent-motion sequences were viewed at a 100 cm viewing distance. The size of the stimulus patterns was approximately 6.9 deg wide × 5.9 deg tall.

4.1.4 *Procedure.* A two-alternative temporal forced-choice procedure was used in conjunction with an adaptive staircase method [PEST—parameter estimation by sequential testing (Taylor and Creelman 1967)]. On every trial, the observers viewed two apparent-motion sequences (the 15 views cycled forwards and backwards three times) depicting two differently curved spherical surfaces. The observers' task was to indicate which of the two surfaces was more curved, the first or the second. One of the two alternatives, the 'standard' surface, always had a radius of curvature of 8.0 cm, while the other, the 'test' surface, was less curved (less curved surfaces have a larger radius of curvature). At the beginning of a block of trials, the test surface had a radius of curvature of 12.0 cm. With the use of the adaptive PEST procedure, this difference in curvature was reduced until the observers' thresholds for curvature discrimination (ie estimates of the 75% point of the observers' psychometric functions) were reached. At this point, the block of trials was discontinued. Curvature discrimination thresholds were obtained for the two different densities (91 versus 19 points) of surface points for both the younger and older observers.

4.2 *Results and discussion*

The results are shown in figure 8 for the younger and older observers who were able to perform the task. The observers' thresholds for curvature discrimination are plotted as Weber fractions, ie as the just-noticeable difference in curvature between the standard and test surfaces divided by the curvature of the standard surface (Weber 1834/1978, page 105; also see Norman and Todd 1996, 1998). There were large differences in performance between the two age groups for both the high and low surface densities. The younger observers' thresholds were about half of those for the older observers, indicating that they were more sensitive and could reliably detect smaller differences in curvature. The individual Weber fractions for the older observers for the high-density surfaces are shown in table 2, along with the observers' acuities. It is clear that there is no systematic relationship between the older observers' acuities and their discrimination performance ($r = -0.049$ for the four older observers' results shown in table 2 who could perform the task). This finding resembles those of other researchers who have found no effects of acuity for tasks requiring the detection of 3-D structure from moving patterns (eg Andersen and Atchley 1995).

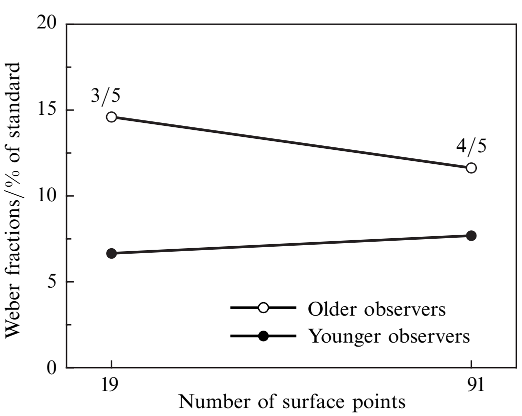


Figure 8. Average discrimination thresholds for the younger and older observers in experiment 3, plotted as Weber fractions. Thresholds could not be determined for one of the five older observers in the high surface-point density condition and for two of the five older observers in the low surface-point density condition.

Table 2. Acuities and Weber fractions for high-density surfaces for the older observers in experiment 3.

Observer	Acuity/min^{-1}	Weber fraction/ % of standard
4	0.50	7.50
5	0.57	–
7	1.00	9.40
9	0.80	10.86
10	0.67	18.74

The results shown in figure 8 were analyzed with a 2×2 split-plot ANOVA with age and surface point density as between-subjects and within-subjects factors, respectively. The ANOVA revealed a significant effect of age ($F_{1,6} = 6.1$, $p < 0.05$, $\text{MSE} = 22.7$), but no main effect of density or interaction between age and density. This analysis revealed that there were significant quantitative differences between the abilities of younger and older observers to discriminate differences in surface curvature, but there were important qualitative differences as well. For example, one of the older observer's thresholds could not be determined by the PEST adaptive procedure for either the low-density or high-density surfaces. Most of the time, PEST rapidly converged on the observers' thresholds within approximately 100 trials; however, this observer (observer 5, age = 75) performed the task in the high-density condition for over 400 trials without us being able to determine his threshold, and the attempt was abandoned. Likewise, he could not perform the task in the low-density condition. An additional older observer could perform the task for high surface point densities, but not for low surface point densities. Therefore, the results shown in figure 8 for the older observers are based upon the responses of four observers in the high-density condition and of three observers in the low-density condition.

In contrast to the results of experiments 1 and 2, which showed that older observers' stereoscopic abilities have been largely preserved, the results of experiment 3 would seem to indicate that there are large differences between younger and older adults' abilities to discriminate differences in the curvatures of 3-D surfaces defined by motion. This difference was especially striking when the surfaces were defined by small numbers of points (ie low surface point densities), since we could not obtain thresholds for 40% of our older observers in that condition.

5 Experiment 4

The previous experiment revealed that older observers have difficulty in perceiving small differences in the curvatures of surfaces defined by motion. The primary purpose of the current experiment was to evaluate whether older observers have similar difficulties in the perception of surface shape. A secondary purpose was to examine the effects of limiting the lifetimes of the points defining the surfaces. In the past, a large body of research has indicated that, at least for younger observers, only 2 successive views of moving points are sufficient for the successful recovery of 3-D shape (Lappin et al 1980; Doner et al 1984; Todd et al 1988; Todd and Bressan 1990; Todd and Norman 1991; Norman and Lappin 1992). In addition, for longer apparent-motion sequences (ie more than 2 views), the ability to perceive the 3-D structure and shape of objects persists when the lifetimes of the individual points defining the object surfaces are limited to only 2 consecutive views (Todd 1985; Dosher et al 1989; Norman 1991). In such a display, any given surface point 'lives' for 2 successive views, then is randomly moved to a new surface location where it then 'lives' for another 2 successive views, etc. This limitation in surface-point lifetime creates a disruption in 'correspondence' over time, since points in one view do not necessarily appear in a 'corresponding' surface location in the next temporal view. Such disruptions in temporal correspondence occur frequently in nature whenever observers view 3-D objects moving behind nearer occluding objects (trees, shrubs, other solid objects, animals, etc). The previous research has shown that human observers' 3-D perceptions are ordinarily robust to disruptions in correspondence over views; the current experiment will evaluate whether older observers' ability to perceive 3-D shape from motion also persists when the point lifetimes are limited to 2 successive views.

5.1 *Method*

5.1.1 *Observers.* The observers were the same as those who had participated in experiment 3.

5.1.2 *Apparatus.* All details of the apparatus were identical to those used in experiment 3.

5.1.3 *Stimulus displays.* The stimulus displays were differently curved surfaces identical to those used previously in experiment 2 (ie bump, saddle, horizontal cylinder, vertical cylinder). The apparent-motion sequences were composed of 15 distinct views, identical to those used in experiment 3, except that the individual views in this experiment were refreshed at a rate of 20 Hz. Once again, the 3-D surfaces rotated 5.0° around a Cartesian vertical axis at every frame transition. The points were randomly positioned on the surfaces and were viewed through a circular occluding aperture identical to that used in experiment 2 (diameter = 5.72 deg) which prevented the observers from seeing the outer boundary contour of the surfaces.

There were two basic types of stimulus displays. In one, the points used to define the surfaces had unlimited lifetimes and survived across all 15 views of the apparent-motion sequences. In the other, each point moved with the appropriate velocity to define the shape of the surface, but survived for only 2 successive views. After surviving for 2 views, these points were randomly repositioned within the circular aperture, and then they moved with the appropriate velocity at the next frame transition. At any given moment in time, approximately 100 points were visible within the aperture window.

The radius of curvature for the surfaces defined by points with a 15-view lifetime was 40 cm for the younger observers and was either 15 cm (one observer) or 10 cm (four observers) for the older observers. The radius of curvature for the surfaces defined by points with a 2-view lifetime was 10 cm for both younger and older observers.

5.1.4 *Procedure.* The experiment consisted of eight different conditions formed by the combination of four differently curved surfaces (bumps, saddles, vertical cylinders, and horizontal cylinders) and two surface-point lifetimes (2 and 15 views). The observers' task on each trial was the same as that used in experiment 2, to indicate to the experimenter which of the four differently shaped surfaces had been presented. The surfaces with 2-view and 15-view point lifetimes were presented in separate blocks of trials. Within each block of trials, the observers made 40 judgments per condition. Therefore, there were 160 trials in each block. The total number of trials in an experimental session was 320 (8 total conditions × 40 judgments per condition). All of the surfaces were presented in a random order within any given block of trials.

5.2 *Results and discussion*

The results for both the younger and older adults are shown in figures 9 and 10 for the 15-view and 2-view point-lifetime conditions, respectively. As can be clearly seen from an inspection of figure 9, four of the five older adults (including one older observer who could not reliably perform the curvature discrimination task used in experiment 3) could discriminate between the differently shaped surfaces at a much higher than chance level ($\chi_3^2 = 455.2$, $p < 0.001$; chance performance would be 25% correct). One observer (observer 9, age = 77 years) failed to discriminate at a level better than chance ($\chi_3^2 = 5.7$, $p > 0.05$).

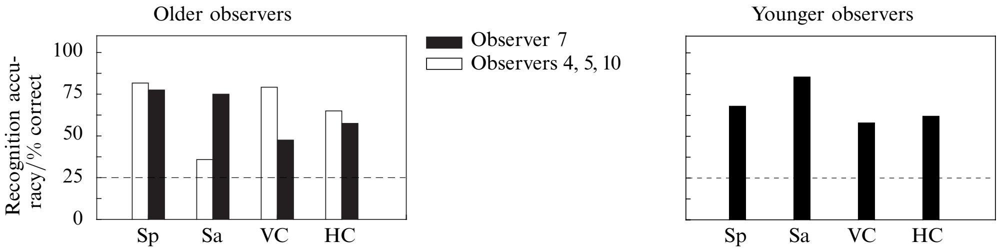


Figure 9. Recognition accuracies for the 15-view point-lifetime condition for the younger and older observers in experiment 4. Separate results are shown for older observer 7 and observers 4, 5, and 10, because they judged surfaces with different radii of curvature (15 cm radius for observer 7; and 10 cm radius for observers 4, 5, and 10). Chance recognition performance is indicated by the dashed line. Sp – sphere, Sa – saddle, VC – vertical cylinder, HC – horizontal cylinder.

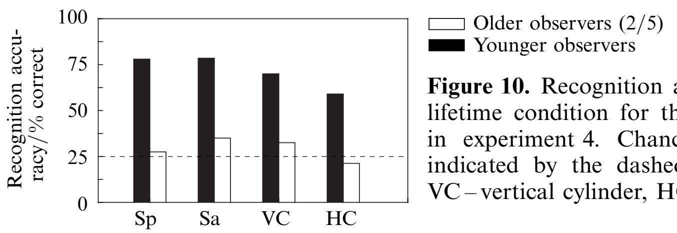


Figure 10. Recognition accuracies for the 2-view point-lifetime condition for the younger and older observers in experiment 4. Chance recognition performance is indicated by the dashed line. Sp – sphere, Sa – saddle, VC – vertical cylinder, HC – horizontal cylinder.

The main difference between the younger and older observers in the 15-view point-lifetime condition was in terms of their overall sensitivity to curvature (also shown by the results of experiment 3). The older observers, with one exception, could discriminate surface shape from motion well above chance if they were provided with more curvature (ie a smaller radius of curvature). The younger observers could perform accurately with a radius of curvature of 40 cm ($\chi_3^2 = 1149.3$, $p < 0.001$), but the older observers needed much more curvature, with radii of 10 or 15 cm. The only other interesting difference in figure 9 concerns the saddle. It was the easiest surface for the younger observers to recognize, but it was generally the most difficult for the older observers.

Perhaps the largest difference between the younger and older observers occurred when the curved surfaces were defined by the motions of points with 2-view lifetimes. These results are shown in figure 10. The younger adults could easily perform the discrimination task if they were given more curvature ($\chi_3^2 = 1080.7$, $p < 0.001$; radius of curvature of 10 cm) than in the 15-view lifetime condition. But, the discrimination task in this condition was impossible for *all* of the older observers to perform. Most of the older observers reported that they only saw 'blinking points' in this condition, and they were unable to perceive these displays as rotations of a solid object in depth. Two of the older observers (observers 4 and 10) attempted to discriminate between the different surface shapes, but they were unable to perform the task at a better than chance level ($\chi_3^2 = 5.65$, $p > 0.05$).

One interesting outcome of this and the previous experiment (experiment 3) concerns the performance of observer 9. In experiment 3, this observer could reliably discriminate differences in the magnitude of surface curvature for the high-density conditions (Weber fraction of 10.9% of the standard curvature). However, she was unable to perform the shape-discrimination task used in the present experiment. This implies that, at least for some observers, in the perception of 3-D structure from patterns of optical motion there is a dissociation between the overall perception of the amount of surface depth and/or curvature and the perception of 3-D shape per se. Selective deficits can apparently occur in the perception of shape that cannot be predicted from a knowledge of an observer's ability to perceive depth. This pattern, if confirmed in other observers, would tend to support Koenderink's (1990) suggestion that shape and depth may be represented differently within the human visual system.

6 Experiment 5

The results of the previous experiment showed that older observers have extreme difficulty in performing discriminations between differently shaped 3-D surfaces when there is a significant lack of correspondence between adjacent views in an apparent-motion sequence. All of the older observers found it impossible to perform the discrimination task in the 2-view point-lifetime condition. This was not true of the younger observers, however. The purpose of experiment 5 was to explore this large age-related difference in more detail by quantitatively manipulating the amount of temporal correspondence.

6.1 *Method*

6.1.1 *Observers.* Eleven observers participated in the experiment. Six of the observers were adults aged 60 years and older (mean = 71.8 years of age, $\sigma = 5.2$ years), while the remaining five were 40 years old or younger (mean = 24.8 years of age, $\sigma = 6.9$ years, including the first and third authors, JFN and AKB). All of the observers had their visual acuity assessed in the same manner as in experiments 1 – 4. The average acuity was 1.0 min^{-1} for the younger observers and 0.66 min^{-1} for the older observers.

6.1.2 *Apparatus.* All details of the apparatus were identical to those used in experiments 3 and 4.

6.1.3 *Stimulus displays.* The stimulus displays and apparent-motion sequences were identical to those used previously in experiment 4 with the following exception. Instead of disrupting temporal correspondence by limiting the lifetimes of individual points to two consecutive views, in this experiment the amount of correspondence between views was manipulated directly as the proportion of points that 'survived' from one view to the next. In particular, discrimination performance was evaluated for stimulus displays with a correspondence of 1.0 (ie all surface points survived until the next view), and partial correspondences of 0.8 and 0.6. In these conditions, 80% and 60% of the points survived until the next view, while the remainder received new randomly chosen positions on the surface. In all other respects, the stimulus displays were identical to those used in experiment 4.

The radius of curvature for the surfaces was 40 cm for the younger observers and was either 15 cm (one observer) or 10 cm (five observers) for the older observers.

6.1.4 *Procedure.* The experiment consisted of 12 different conditions formed by the combination of four differently curved surfaces (bumps, saddles, vertical cylinders, and horizontal cylinders) and three amounts of temporal correspondence (1.0, 0.8, and 0.6). The observers' task on each trial was the same as that used in experiments 2 and 4, to indicate to the experimenter which of the four differently shaped surfaces had been presented. The surfaces with different correspondences were presented in separate blocks of trials. Within each block of trials, the observers made 40 judgments per surface shape. Therefore, there were 160 trials in each block. The total number of trials in an experimental session was 480 (12 total conditions $\times$ 40 judgments per condition). All of the surfaces were presented in a random order within any given block of trials.

6.2 *Results and discussion*

The results are shown in figures 11a and 11b for the younger and older observers, respectively. Three different patterns are evident in these results. One older observer (observer 11) performed above chance ($\chi^2_3 = 56.2$, $p < 0.001$) with a correspondence of 1.0, but could not tolerate any degradation in correspondence. Another older observer (observer 10), on the other hand, was completely unaffected by the manipulation of

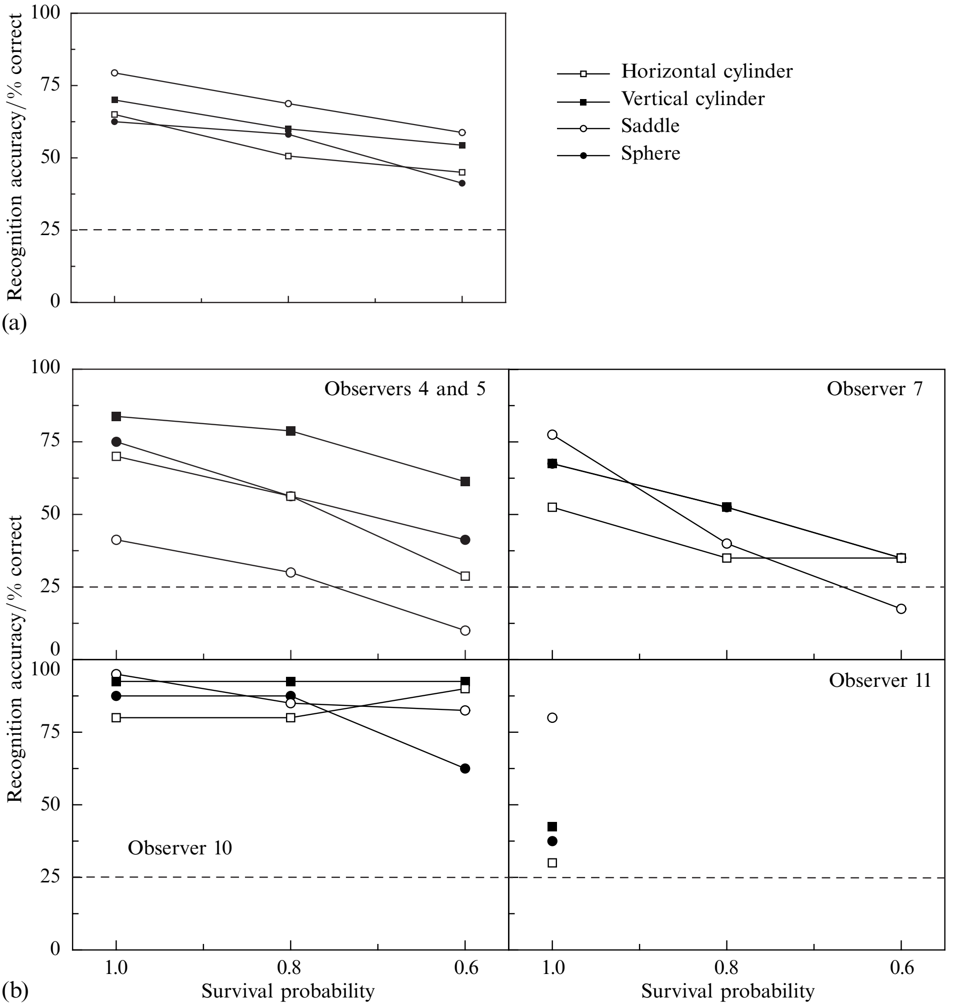


Figure 11. Recognition accuracies for (a) the younger and (b) the older observers in experiment 5. Recognition performance is plotted as functions of point survival probability and surface shape. The results for observer 7 are plotted separately, since she judged surfaces with less curvature. The results for observers 4 and 5, observer 10, and observer 11 are plotted separately owing to their qualitatively different responses to decreases in point survival probability. Chance recognition performance is indicated by the dashed lines.

correspondence. Most of the older observers (observers 4, 5, and 7) were affected by the reductions in correspondence, as were the younger observers. The main difference, once again, was in terms of their overall sensitivity to curvature. For reasonable levels of performance, the older observers needed more curvature (radius of curvature of 10 or 15 cm), while the younger observers needed less (radius of curvature of 40 cm). Despite the similarities in the overall pattern (ie a linear decrease in performance with reductions in correspondence), the older observers appeared to be more affected. For example, most of the older observers were near chance performance levels for a correspondence of 0.6, while as a group the younger observers were still performing above chance at a 40% to 60% level of accuracy. One additional older observer (observer 9) was unable to perform the shape-discrimination task, even for a correspondence of 1.0.

The results shown in figures 11a and 11b for the younger and older observers were subjected to two 3×4 within-subjects ANOVAs, one for each age group. The ANOVA for the older observers was performed upon the results for the three observers (observers 4, 5, and 10) who participated in the same conditions (ie 10 cm radius of curvature at all three levels of correspondence). There were significant effects of correspondence for both the younger ($F_{2,44} = 14.4$, $p < 0.001$, MSE $= 164.9$) and older ($F_{2,22} = 4.1$, $p < 0.05$, MSE $= 424.0$) observers. There were also significant effects of the particular surface shapes (for the younger observers, $F_{3,44} = 4.3$, $p < 0.01$, MSE $= 164.9$; for the older observers, $F_{3,22} = 4.0$, $p < 0.05$, MSE $= 424.0$). For the younger observers, the most recognizable surface was the saddle, while for the older observers, it was the least discriminable surface. This differential performance regarding the saddle-shaped surfaces accounts for the significant main effects of shape. In neither analysis was there a significant interaction between surface shape and correspondence.

7 Experiment 6

The preceding experiments show that older observers can successfully perceive and discriminate surface shape if they are given more curvature, and if the correspondence is sufficiently high. As a general rule, however, the older observers seem to be much less sensitive to the depth and curvature of surfaces defined by patterns of optical motion than are younger observers. Up to this point, the surfaces have been defined by the motions of a set of disconnected points. It is conceivable that the performance of older adults would improve if they were asked to make judgments about more ecologically valid curved surfaces (Gibson 1950, 1966, 1979). In the real world, different parts of an object are connected together by a textured, continuous surface. The purpose of this final experiment was to evaluate the possibility that the observers' perceptions of surface shape might be more accurate in a more information-rich and ecologically valid visual context.

7.1 *Method*

7.1.1 *Observers.* The observers were the same as those who had participated in experiment 5.

7.1.2 *Apparatus.* All details of the apparatus were identical to those used in experiments 3 – 5.

7.1.3 *Stimulus displays.* The stimulus displays portrayed differently curved surface shapes that were identical to those used previously in experiments 2, 4, and 5 (ie bumps, saddles, horizontal cylinders, and vertical cylinders). The specific optical patterns used in this experiment resembled those used in experiment 3, except that the vertices of the perturbed hexagonal lattice (91 points) were connected by triangular polygons that were texture-mapped with a texture resembling red granite (for example stereograms of such surfaces, see figure 12). Performance for these continuous, textured surfaces was compared to that for surfaces defined by the motions of separated points like those used in experiments 3 – 5. All other stimulus details were the same as those in experiments 4 and 5.

The radius of curvature for the surfaces was 70 cm for the younger observers and was either 20 cm (two observers), 15 cm (two observers), or 10 cm (two observers) for the older observers.

7.1.4 *Procedure.* The experiment consisted of 8 different conditions formed by the combination of four differently curved surfaces (bumps, saddles, vertical cylinders, and horizontal cylinders) and two surface types (points versus texture). The observers' task on each trial was the same as that in experiments 2, 4, and 5, to indicate to the experimenter which of the four differently shaped surfaces had been presented. The different surface types were presented in separate blocks of trials. Within each block of trials, the observers made 40 judgments per surface shape. Therefore, there were 160 trials in each block. The total number of trials in an experimental session was 320 (8 total conditions $\times$ 40 judgments per condition). All of the surfaces were presented in a random order within any given block of trials.

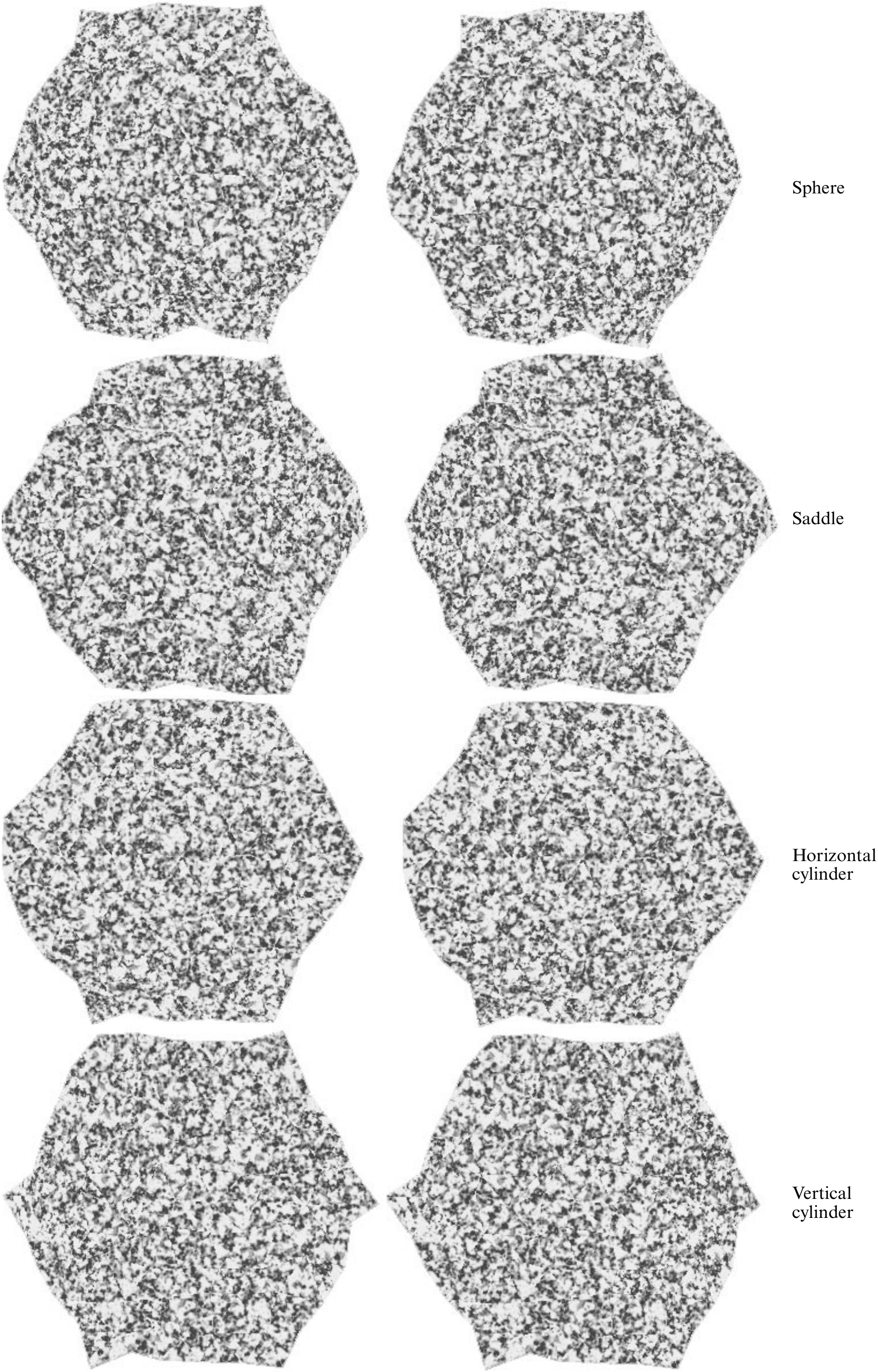
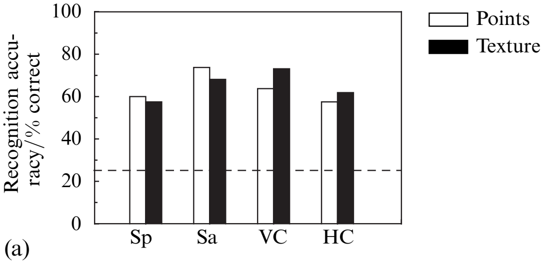


Figure 12. Example stereograms depicting the four differently curved textured surfaces used in experiment 6.

7.2 *Results and discussion*

The results for the younger observers are shown in figure 13a. It is clear that there is no systematic difference between the recognition performances of these observers when they viewed the motions of the two different surface types (isolated points versus continuous texture). The results of a χ^2 analysis also indicated that there was no significant difference in performance ($\chi_3^2 = 3.1$, $p > 0.05$). The analogous results for the older observers are shown in figure 13b. There are no clear differences in performance for the older observers as well. Separate χ^2 analyses were performed for the groups of older observers who viewed the surfaces with the same radii of curvature. For those who discriminated the shape of surfaces with a 20 cm radius of curvature, there was a significant effect of the addition of texture ($\chi_3^2 = 11.0$, $p < 0.02$)—however, for these observers there was an overall decrease in performance with texture as compared with the analogous performance with surfaces defined by the motions of isolated points (mean recognition accuracy for points was 61.3%, while that for textured surfaces was 54.7%). For the older observers who viewed somewhat more curved surfaces (radius of curvature = 15 cm), there was also a significant effect of surface type ($\chi_3^2 = 8.9$, $p < 0.05$), but the nature of the difference was more complicated. In particular, for these observers, performance



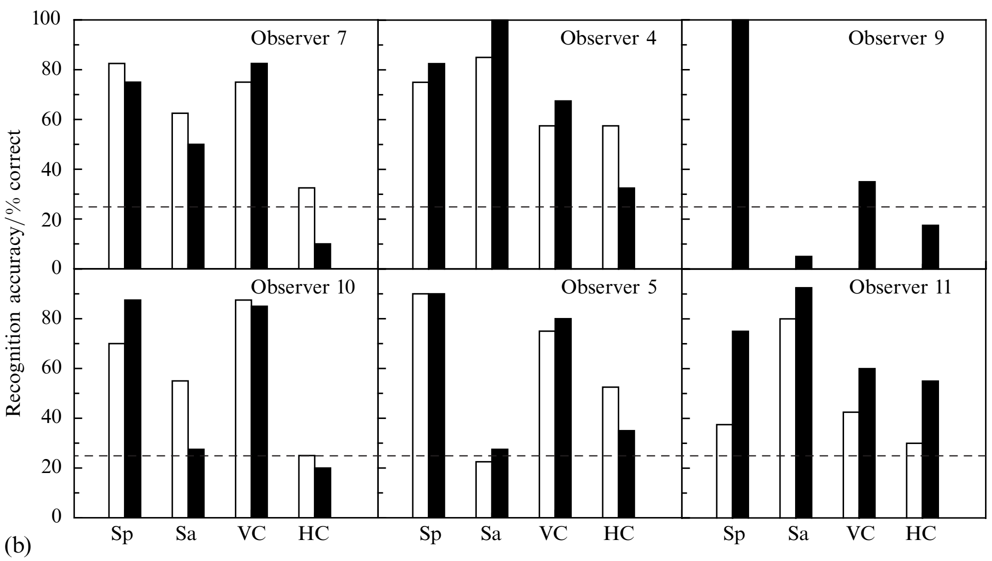


Figure 13. Average recognition performance for (a) the younger and (b) the older observers for the four differently curved surfaces used in experiment 6. Separate results are plotted for surfaces defined by points and those defined by continuous texture. Separate results are shown for the individual older observers. Observers 9 and 11 judged surfaces with a 10 cm radius of curvature; observers 4 and 5 judged surfaces with a 15 cm radius of curvature; observers 7 and 10 judged surfaces with a 20 cm radius of curvature. Chance recognition performance is indicated by the dashed lines. Sp – sphere, Sa – saddle, VC – vertical cylinder, HC – horizontal cylinder.

improved with texture for bumps, saddles, and vertical cylinders, but decreased for horizontal cylinders (the overall mean performance for surfaces defined by points and texture was the same, however—64.4% recognition accuracy).

In contrast to the younger observers and the previously mentioned older observers, for the two remaining older observers (who viewed highly curved surfaces with a radius of curvature of 10 cm) there seemed to be a positive effect of texture. A χ^2 analysis performed for one of these older observers (observer 11) revealed a highly significant difference ($\chi_3^2 = 27.0$, $p < 0.001$) between the performances for the two surface types (mean recognition accuracy for the surfaces defined by points was 47.5%, while that for texture was 70.6%). This systematic improvement for this observer can be seen in figure 13b. For the other older observer who viewed surfaces with a 10 cm radius of curvature (observer 9), the shape-discrimination task was impossible given only the motions of isolated points, but was somewhat possible when the surfaces were defined by continuous texture—her overall recognition accuracy was 39.4% and was significantly different from chance ($\chi_3^2 = 98.9$, $p < 0.001$). It is clear, however, that she was able to detect only the bump surfaces at high levels of accuracy—the detection performance for the other curved surfaces was near or below chance levels (see figure 13b).

8 General discussion

The results of the current experiments demonstrate that older observers in general retain a significant amount of functionality with respect to the perception of depth and shape. In particular, their stereoscopic vision seems to be both qualitatively and quantitatively similar to that of younger observers. The results of experiment 1 showed that the older observers perceived about 80% of the depth that was expected from the disparities of the sinusoidal surfaces (see figure 3). The only surfaces that were particularly difficult for the older observers to perceive were those defined by the specific combination of high disparities and high spatial frequencies; all of the other surfaces were perceived by them to have front-to-back depths that were quantitatively similar to the younger observers. The results of experiment 2 showed that older observers can also discriminate between differently curved surfaces in a manner essentially identical to that of the younger observers if the surfaces are given more curvature (to compensate for the slightly reduced sensitivity found in experiment 1). In particular, the manipulation of stereoscopic correspondence had identical effects upon both the younger and older observers (see figure 5a), as did the reductions in the number of points defining the stereoscopic surfaces (figure 5b). Furthermore, both the younger and older observers found the same pairs of surfaces to be easily discriminable (bump versus saddle, see figure 6), while they found other pairs of surfaces to be less discriminable (bump versus vertical cylinder). This similarity in the ability of the younger and older observers to perceive the depth and shape of surfaces defined by binocular disparity lends additional support to those experiments that have previously found no differences in the performance of stereoscopic tasks as a function of age (Tiffin 1952; Hofstetter and Bertsch 1976; Greene and Madden 1987; Yekta et al 1989; Mittenberg et al 1994).

The results for experiments 3–5 showed that there were significant differences in the way the older and younger observers perceived the depth and shape of 3-D surfaces defined by differential motion. While in some respects the performance of the older adults was similar to that of the younger adults, in other respects it was very different. For example, the results of experiment 3 showed that the older observers were much less sensitive to depth and curvature than the younger observers—their Weber fractions were on average 83% higher. The difference was even larger than this figure implies, since the Weber fractions plotted in figure 8 reflect the performance of only those older observers who could perform the curvature-discrimination task—one of the five observers could not perform the task at the high surface-point densities, and two of the five observers could not perform the task at the low surface-point densities.

The difference in sensitivity to curvature obtained in experiment 3 between the older and younger observers was also manifested in experiments 4–6, which required the observers to perform a shape-discrimination task. In order to discriminate between the various types of curved surfaces at a threshold level, the older observers once again needed more curvature. Furthermore, the results of experiments 4 and 5 indicated that, even at these reduced levels of performance, the older observers needed longer point lifetimes in order to perform the surface-discrimination task. The older observers performed best in experiments 4 and 5 when the points defining the surface survived across all 15 views of the apparent-motion sequences. Performance was impaired when the correspondence across adjacent views was reduced to levels below 1.0, but was still possible for most of the older observers (particularly for a correspondence of 0.8). At the 0.8 correspondence, fully half of the constituent points of a surface survived for 4 views (3 transitions between adjacent pairs of views, 0.8^3), and 10% of the points survived for 11 views (10 transitions between adjacent pairs of views, 0.8^{10}). When the lifetimes of the surface points were reduced to only 2 successive views in experiment 4, the shape-discrimination task became impossible for all of the older observers, but this manipulation had relatively little impact upon the performance of the younger observers. For a surface detection task, Andersen and Atchley (1995) found that the presence of extraneous noise points impaired the performance of older observers. It would appear that the type of noise used in the current experiments 4 and 5 had an impact upon performance that is at least as large as, if not larger than, that used by Andersen and Atchley.

The apparent inability of older observers to adequately perceive and discriminate the shape of surfaces defined by the motions across 2 successive views is puzzling. It has been shown (Todd and Bressan 1990; Koenderink and van Doorn 1991; Todd and Norman 1991) that 2 successive views are mathematically sufficient for the recovery of enough geometrical information to permit the discrimination of the different types of curved surfaces used in the present investigation (experiments 4–6). Indeed, in previous research on younger adult observers, performance for such discriminations is good when the motions are limited to 2 successive views and does not improve significantly with the addition of more views (eg Todd and Norman 1991; Norman and Lappin 1992). This has also been demonstrated with longer apparent-motion sequences where the individual surface points only survive for 2 successive views (Todd 1985; Dosher et al 1989; Norman 1991), and was also evident in the present experiment 4 with the relatively good performance of the younger observers (see figure 10). It is readily apparent, however, that older observers are different in that they cannot make effective use of the information about shape that is contained within moving patterns where the elements survive for only 2 successive views.

The surfaces used in the current set of experiments were defined optically by the binocular disparities and velocities of luminous points. The older observers' performance was relatively good for the stereoscopic tasks, but it was often poor for tasks requiring the discrimination of surfaces defined by differential motion. It is conceivable that the performance of the older observers would improve if they were asked to discriminate between moving surfaces that more closely resemble those in real-world environments. The results of experiment 6, however, showed that there was little difference in the abilities of younger and older observers to discriminate between differently curved 3-D surfaces defined by isolated points versus continuous texture. This suggests that the deficits that were found in the older adults' abilities to perceive 3-D surfaces defined by motion are general, and that they are not limited to the specific characteristics of the stimuli that were used in experiments 3–5.

It is interesting to consider what underlying factors might have led to the complete inability of our older observers to perceive 3-D shape and structure from moving patterns with 2-view point lifetimes (figure 10)—this is the single largest perceptual deficit observed in this study. The finding that all members of one group, but none of another, can perform a particular perceptual task does not occur frequently. When our younger observers view such displays, they routinely report that they perceive coherently rotating 3-D surfaces, despite the fact that some of the individual points defining the surface are disappearing and appearing at every frame transition. Younger observers can apparently 'ignore' the points that spontaneously appear and disappear, and group all of those remaining points that survive across individual frame transitions into a percept of a single, rigidly rotating 3-D surface. This does not happen for the older observers—they consistently report that all they see are 'blinking dots'. They see no 3-D surface of any kind, no rigid rotation of any object, despite the fact that any younger observer can look at the same display and perceive it as the rotation in depth of a solid 3-D object. One possibility for this perceptual failure is that the older observers cannot 'ignore' the noise points that appear/disappear at particular frame transitions, and thus group all of the points together. Thus, the underlying failure may be one involving grouping, based upon such factors as common fate (Wertheimer 1923/1938). Indeed, there is no mathematically possible rigid 3-D solution if one considers the motions of all of the points in this particular type of stimulus display. The process of grouping and determining which points 'belong together' across views is a critical early requirement for the functionally later process of determining shape from those particular element motions. In this light, it is intriguing that the processes underlying grouping have also been implicated as the likely failures in those patients with visual apperceptive agnosias (Farah 1990; also see Gelb and Goldstein 1918/1938). According to Farah (1990, page 38), "the underlying impairment in apperceptive agnosics appears to lie in their grouping processes, in that they have adequate perception of local properties of the visual field ..., but generally cannot perceive higher order shape tokens". It is well known (see Humphreys and Riddoch 1987; Farah 1990) that the usual cause for visual agnosia is brain damage caused by head wounds, strokes, carbon monoxide poisoning, etc. It is thus possible that the failure of our older observers to perceive coherent rotations of a 3-D object from a motion display utilizing 2-view point lifetimes is an early reflection or symptom of minor damage to neural mechanisms involved in basic visual processes, such as grouping similar elements into wholes.

This study has shown that the capabilities of adults with respect to the perception of 3-D shape do not necessarily change as a function of age. We found stereoscopic vision to be largely preserved, but at the same time found evidence of significant deteriorations in older observers' abilities to perceive the structure and shape of curved surfaces defined by motion. It will be important for future research to determine whether these changes (eg possible deficits in grouping and establishing correspondences of moving elements over time) are associated with any impairments in the ability of older adults to perform everyday tasks in ordinary environments. It is possible, however, that no functional impairments accompany the identified reductions in the ability of older observers to perceive 3-D shape from motion—as they become older, the elderly may increasingly rely on other sources of information about shape, such as internal contours, shading, occlusion boundaries, and binocular disparity. More research is definitely needed to distinguish between these important possibilities.

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