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Seeing into Old Age: Vision Function Beyond Acuity

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ABSTRACT: *Purpose.* To provide a comprehensive description of vision function beyond acuity in older individuals. *Methods.* A sample of 900 individuals between the ages of 58 and 102 years (mean age of 75.5) was binocularly tested wearing habitual correction on a battery of psychophysical tests including high and low contrast acuity, low contrast low luminance acuity, disability glare, contrast sensitivity, color vision, stereoacuity, recovery from glare, and attentional visual fields. *Results.* High contrast acuity is reasonably well maintained on average, even into very old ages. Spatial vision measures under conditions of reduced contrast or luminance, or glare reveal significant impairment in a large portion of the aged. Many older individuals also have greatly reduced stereopsis, poor color discrimination, and severely restricted peripheral fields under conditions of divided attention. A single exponential function relating performance to age fits all spatial vision data sets. The function for individual spatial measures lies at different positions along the age scale. The derived aging function with a time constant of ~15 years also fits results from other recent aging studies of acuity and contrast sensitivity. *Conclusions.* Standard visual acuity underestimates the degree of vision function loss suffered by many older individuals under the nonoptimal viewing conditions encountered in daily life. All spatial vision functions show a similar rate of decline with age of the population, but the age at which decline begins varies among measures. (Optom Vis Sci 1999;76:141–158)

Key Words: aging, spatial vision, attention, peripheral vision, temporal vision

The elderly portion of the population is rapidly growing. Since the start of the century, the percentage of Americans aged 65 years or older has more than tripled (4.1% in 1900 to 12.7% in 1997), and the number of older Americans has increased 11 times (from 3.1 million to 34.1 million). The older population will continue to grow. By 2030, nearly 70 million people age 65 or older are projected in this country, more than twice the number in 1997. The elderly population is not only growing, it is aging. Compared to 1900, in 1997 the number of people aged 85 or older was 31 times greater, compared to a 16-fold increase in the 75- to 84-year-old group and an 8-fold increase in the population aged 65–74.[1]

Only a small percentage (4%) of the elderly live in nursing homes; most live in the community and need and want to be self-reliant.[1] Adequate vision is essential for maintenance of independence. There is a general belief that vision, like other functions, declines with age. Nevertheless, a comprehensive description of the vision function of the old, particularly the very old, is lacking.

Many large population-based cross-sectional studies have documented the increase in prevalence of eye disease and visual impairment with increasing age, particularly noted for those over the age of 75 years (e.g., refs. 2–10). However, there is much less information about the vision function in this age group. Typically, visual acuity is the sole measure by which vision is assessed and visual impairment is defined. Acuity is a measure of visual performance under optimal conditions—high contrast and high luminance. Of course, only a few visual targets in the daily environment have such parameters. The visual world is composed of targets varying greatly along many dimensions: spatial frequency, contrast, temporal frequency, spatial location, and color. Viewing conditions also vary greatly in terms of luminance, as well as the presence of glare and fog. Unfortunately, only a few recent large scale vision studies (e.g., refs. 11–13) have measured vision functions other than contrast sensitivity and acuity.

Here we describe the results of testing a large group of individuals over age 55, including a substantial number over age 85, on a large battery of vision function tests. The study thus extends our knowledge of vision function to older ages, as well as to measures of vision function not previously used to describe more fully the visual world of the very old. Because many aspects of vision function were measured in each person, we are able to draw conclusions about the relative rates of aging of various functions, as well as the likelihood that the same mechanisms underlie the observed changes in particular visual functions with age. We find that the change with age of all spatial vision measures can be fit by a common exponential, shifted along the age axis to take into account variation between measures in the age of onset of decline.

METHODS

Sample

We were fortunate to have access to a unique population thoroughly characterized by the Buck Center for Research in Aging. A subsample of the Buck population was selected for the vision study (see below). The Buck population of older residents of Marin County, California, is an unusual sample in that older observers were deliberately oversampled, resulting in more than 500 observers in each of 3 age groups (65 to 74, 75 to 84, and 85+), as well as over 400 in the 55- to 64-year-olds for a total of 2018 people. Respondents aged 55 to 64 were initially identified by telephone random digit dialing; those aged over 65 were identified through the Social Security records maintained by the Health Care and Financing Administration. Sixty-nine percent of those eligible agreed to participate and were tested by the Buck Center in their first assessment.

The Buck Center Health & Functioning Study includes an interview and direct physical assessments. The interview has questions about overall health, sleep patterns, employment, outdoor/indoor activities, diet, oral health, symptoms and ailments, chronic conditions, medications, physical and cognitive functioning, depression, marriage, social networks, activities of daily living, instrumental activities of daily living, voluntary activities, history of smoking and alcohol consumption, and demographic and socioeconomic factors. Respondents also completed a detailed food frequency questionnaire and a battery of direct physical assessments, including measures of balance and walking speed, lower body strength, upper body flexibility and rotation, and fine dexterity, as well as tests of hearing and smell. The Buck Center Study is a longitudinal study; to date each respondent has been seen twice. Baseline measures were carried out between 1989–91; the first follow-up measures took place between 1993–96. The characteristics of this sample have been more fully described elsewhere.[14, 15]

Vision study subsample. A randomly selected subsample of the Buck Center population have participated in the vision study. Individuals were invited to participate when they had completed the longitudinal follow-up evaluation for the Buck Center Health & Functioning Study. There were 1521 of the original subjects available who completed the second Health & Functioning Study follow-up evaluation. The remainder of the original sample of 2018 had either died (319), refused to participate in the Buck Center Study (106), or could not be located (72). Of those who completed the follow-up, 92.7% were invited to participate in the vision study. A random sample of 820 of the 940 under age 80 and all of the participants aged 80 or over (N = 591) were invited for the vision study sample. We were mostly interested in the vision function of the oldest old, which is why only some of the younger observers were invited to participate. Of the 1411 subjects invited to participate in the vision study, 27% refused, 9% had died since completing the Buck Center follow-up, and 64% participated. We had no exclusion criteria other than age (see above), which means that people with ocular disease are included in the sample. We also tried to obtain medical records for the participants. Those who refused to participate in the vision study were generally older and had worse vision. Health & Functioning participants (whether in the vision study or not) had their acuity measured as part of that study. The average visual acuity of those who participated in the vision study was 20/33 [log minimum angle of resolution (MAR) = 0.22], whereas the acuity of those who refused the vision test battery was 20/46 (log MAR = 0.36). The average age of those who refused was 79.7 years (SD 10.2, median 82), whereas the average age of the participants at the time of the vision test was 75.5 years (SD 9.3; median 74.9). The youngest participant was 58 and the oldest 102 years. The age and gender distribution of the 900 individuals in the vision study sample is given in Table 1. The population is primarily Caucasian and fairly highly educated, with an average number of years of education of 14.7 (SD 3.1 years).

This research followed the tenets of the Declaration of Helsinki. Informed consent was obtained from the subjects after explanation of the nature and possible consequences of the study. The research was approved by the local institutional review board.

Vision battery

Each participant was evaluated using a large battery of vision tests. All testing was binocular (except the Amsler grid) with habitual correction in place. We specifically used their own habitual correction either in the form of distance and near glasses or bifocals to allow comparison with their own subjective evaluations in daily life. The luminance on all vision tests (except color tests, see below) was ~150 cd/m^2. Each subject was tested on one day. A vision questionnaire was administered before the test battery; the results from this questionnaire and the relation to the vision measures will be presented in a separate paper. Each subject spent a total of 1 to 2 h depending on the response speed. Most subjects completed all tests within 1 h. Rest breaks were given as requested. All tests were given in the same order for all subjects. In addition to the test battery described here, a reading performance test was given after the Smith-Kettlewell Institute Low Luminance (SKILL) card and walking performance was assessed in a lighted and dark room at the end of the vision test battery; results from these measures are not

TABLE 1.
Composition of vision sample

Age (yr)	Female	Male	Total
55–64	66 (49.3%)	68 (50.7%)	134
65–74	186 (58.9%)	130 (41.1%)	316
75–84	138 (45.7%)	164 (54.3%)	302
85+	94 (63.5%)	54 (36.5%)	148
Total	484 (53.8%)	416 (46.2%)	900

discussed here. The following vision tests were administered in the order that they are listed here.

High contrast distance visual acuity. A Bailey-Lovie high contrast (>90% Weber contrast) wall chart was used at 10 ft. This chart (or versions of it) has been used extensively for clinical research.[16, 17] Scoring was done letter by letter, and each letter has a value of 0.02 log units.[18] On all of the acuity measures, subjects were required to read all five letters of the first line correctly and continue reading until three or more letters of a line were misidentified.

Low contrast distance visual acuity. A low contrast version of the Bailey-Lovie chart was used at 10 ft. This chart has gray letters on a white background with a Weber contrast of ~16 to 18%.[19] It was administered and scored the same way as the high contrast chart (letter by letter).

Contrast sensitivity. The Pelli-Robson chart presents large letters that vary in contrast rather than size.[20] The chart contains two letter triplets per line. The contrast between successive triplets (reading down the chart) decreases ~0.15 log units. The chart was scored letter by letter like the acuity tests, but in this case each letter represents 0.05 log units. The first line had to be read without any errors. Subjects were required to continue until all three letters of a triplet were missed. At the 10-ft test distance, the overall letter size is 1°, requiring a resolution of at least 20/240 (equivalent to 3.6 cpd).

Low contrast, low luminance near visual acuity. The SKILL card[21] is a near acuity card designed for use at 40 cm. To simulate reduced luminance, a 10% reflectance (dark gray) background is used; black letters provide low contrast (~14 to 15% Weber contrast). On the reverse side of the card is a high contrast, high luminance version of the same test (with different letter ordering). The luminance of the light side was ~150 cd/m^2 and the dark side was ~15 cd/m^2. The light side was presented first; the card was then flipped over and the dark side tested. Subjects were instructed to start at the top on the dark chart to allow adequate time for any time-dependent adaptation. Acuity as poor as the Snellen equivalent of 20/630 can be measured. The SKILL score is taken as the number of letters of acuity "lost" on the dark vs. the light side. Each chart is scored in exactly the same manner as the Bailey-Lovie charts, letter by letter, 0.02 log units per letter.

Stereopsis. The Frisby Test[22] is a test of stereopsis that does not require anaglyphs. The test consists of three plates, differing in thickness, each with four square fields of randomly placed picture elements. On each plate, one of the four squares has an area on which the pattern is on the other side of the plate, so that a circle is defined in depth. The contrast of the targets is high. The thickness of the plate defines the fineness of the stereo judgment. The test is given as a 4-alternative forced-choice judgment, and the thinnest plate on which the stereo circle can reliably be seen is determined. Head movements were not allowed during testing. Six presentations were given for each plate. In order to pass a plate, five of the six presentations had to be correct. Disparities of 340, 170, and 85 arc seconds were presented at a 40-cm (16-in) test distance.

Amsler grid testing. Amsler grids were presented at a distance of 40 cm under monocular conditions. A series of standard questions regarding the grid were asked for each eye. The results were graded on a scale of 0 to 4 (0: normal grid; 1: one small peripheral anomaly; 2: more than one peripheral anomaly; 3: central anomaly; 4: central and peripheral anomalies).

Color vision. The Adams desaturated D-15 test was administered under a Macbeth lamp (Illuminant C, ~100 lux). This is a test of color confusion similar to the standard Farnsworth-Munsell D-15 test, except the color chips are less saturated.[23] If the subject made any errors on this test, the standard Farnsworth-Munsell Panel D-15[24] test was administered under identical conditions. Color confusion scores (CCS) were computed.[23] The CCS represent the distance traveled in color space in excess of a perfect arrangement expressed as a percentage. A perfect arrangement receives a CCS of zero. A CCS of 100 represents double the distance traveled in color space. The assumption was made that individuals making no errors on the desaturated test would also make no errors (have a CCS of zero) on the standard test if tested.

Temporal vision: critical flicker fusion frequency (CFF). A square array of centrally fixated red light-emitting diodes (LEDs) generated the flickering stimulus, which had a mean luminance of 55 cd/m^2. The LED array, which subtended 4.7° at the viewing distance of 40 cm, was surrounded by a large red background field of 60 cd/m^2. Modulation threshold was measured for 2 temporal frequencies (4.1 and 17.1 Hz). In addition, CFF was measured for 100% modulation. For each condition, three thresholds were determined using the method of ascending limits and averaged. If the values were very discrepant, an additional threshold was set and the outlier discarded.

Smith-Kettlewell Attentional Field Test. This test consists of a modified Synemed perimeter with a red LED as the fixation point. The peripheral targets are bright green LEDs of fixed intensity. The size of the LED is equivalent to Goldmann size III. The fixed high intensity of the LEDs corresponds to the intensity of Goldmann 4e targets. The background light level was 13 cd/m^2, approximately the same as most perimeters. Targets were presented at 8 locations (10, 15, 20, 25, 30, 40, 55, and 70°) for the 185, 225, 315, and 355° meridia and 7 locations up to 55° for the 60° meridian.

During the "standard" field test, the subject was asked to fixate the red central LED and push a hand-held button whenever a green peripheral light flashed. Three presentations were made (randomly) for each location and the percent correct computed. False positives (i.e., button pushes in the absence of a target) were recorded. During the attentional task, the subject silently counted how often the red fixation LED turned off during the 3.5-min test while responding to the green peripheral targets with a button push. The fixation light turned on and off randomly 39 times during the 3.5-min test period independently of the observer. The mismatch between actual and reported flashes was recorded in addition to the false positive responses. The standard test was always given before the attentional test.

The standard field results were corrected by subtracting the spurious responses multiplied by a weighting factor from the percent correct for each field location. The assumption was made that the spurious responses were independent of test location. The attentional field was corrected for both spurious responses (false positives) and percent correct for the central attentional task. A weighted sum of the spurious responses and the mismatch between actual and reported central red flashes was subtracted from the percent correct for each location. The weighting factor was the same for both the standard and attentional tasks. A location was considered "seen" if the adjusted percent correct for that location was at least 60%.

The radius of the field was computed along each of the five meridia tested. The radius was defined as the most peripheral location at which at least 2 adjacent test points had at least 60% correct. The average of the 5 radii was used as an index of peripheral field extent (with 67° being the maximum possible). In addition, the number of locations seen was measured within three separate zones—the central ±20°, ±25 to 40°, and beyond ±40°. Testing was done without glasses, which may interfere with detection of the most peripheral targets. The test target is easily visible even with 20 D of blur.

Berkeley Glare Test-disability glare. The Berkeley Glare Test[25] consists of a small, opaque triangular low contrast (~10% Weber contrast gray on white) letter chart illuminated from the front and surrounded by a translucent panel behind which is a glare source. The luminance of the white background without the glare is 80 cd/m^2. Test distance was 40 cm. Observers read the chart with and without the brightest disability glare level present (3300 cd/m^2). If the largest line was not correctly identified with the bright glare level, a lower glare level (800 cd/m^2) was used. Sixty-two people (6.9%) of the sample were tested with the medium glare level. The charts were scored as the Bailey-Lovie distance acuity charts. A glare index was calculated. This index is a measure of the number of letters lost in the presence of the glare source that takes glare level into account. In order to estimate the number of letters lost for the highest glare level for those unable to see the largest line at that glare level, a conservative assumption was made of a linear loss of letters with increases in log luminance of the glare source. In other words, if the subject lost 20 letters at the lower glare level that is 1 log unit above the no glare background level, we assumed that they would have lost 32 letters for the highest glare level that is 1.6 log units above the no glare level. For most people (IL Bailey, personal communication), the relationship is actually exponential, with more letters lost at the higher glare levels than predicted by this method.

SKILL card glare recovery. A simple glare recovery or photostress test, using the dark side of the SKILL card as a target, was used. The subject directly viewed the translucent screen that provided the bright (3300 cd/m^2) disability glare source of the Berkeley Glare Test for 1 min. The glare source was then turned off and the time required to read the line two lines larger than the subject's previously assessed SKILL dark chart acuity was measured. We thus attempted to correct for differences in contrast thresholds among observers to primarily determine differences in dynamics of recovery.

RESULTS

Spatial vision

Fig. 1 shows the median performance of each of the spatial vision measures as a function of age. The vertical lines through the data points represent the 25th and 75th quartiles. All of the acuities are presented as logMAR. The more familiar Snellen equivalents of logMAR values are given in Table 2 for reference.

Fig. 1 shows that, although standard high contrast acuity (A) is relatively well maintained even into the oldest ages, under conditions of reduced contrast (B) or reduced contrast and low luminance (C) or with added glare (D), performance is substantially impaired, particularly among the very old. For example, for the oldest age group (94 years and above) the median acuity is 0.48 (20/60) for high contrast, 0.82 (20/132) for low contrast, 1.16 (20/290) for the SKILL dark chart, and 1.69 (20/1000) in the presence of glare. At younger ages, the impact of contrast, luminance, and glare is less pronounced. For the youngest age group (58 to 60 years), the median values are −0.02 (20/19) for high contrast, 0.15 (20/28) for low contrast, 0.51 (20/65) for SKILL dark, and 0.50 (20/63) in the presence of glare. These differences in performance for the various spatial measures for the young age groups do not account for the large differences among measures exhibited by the very old. The large differences among the spatial measures at the oldest ages reflect the fact that the slope of the apparently linear loss over the age range tested varies significantly between measures. For example, median high contrast visual acuity (A) drops ~0.5 log units over our tested age range, whereas contrast sensitivity decreases significantly more, ~0.8 log units (E). This finding suggests differential aging effects on vision functions (see Discussion). It is also evident that the variability increases for all measures with age, as is commonly reported for a wide range of functions (e.g., ref. 26).

Comparison to other studies: high contrast acuity

Fig. 2 shows distance high contrast visual acuity across age from a series of large scale vision studies. In total, the figure shows results from testing 34,713 people. All data points are means to allow comparison among studies since many previous studies did not report medians. Most studies, including ours, indicate that high contrast acuity is very well maintained until age 65 to 70 and then begins to fall off. For the younger ages (50 to 60 years), there is remarkably good agreement among the many studies; discrepancies occur primarily beyond age 70.

Our results are like those of many of the more modern studies,[2, 10, 11, 13] which show that average acuity is well maintained into old age contrary to the results from the older literature.[27, 28] The exception to this is the Beaver Dam Eye Study,[6] whose results are very similar to those of Slataper[27] and Hirsch.[28] The single data point (at age 70) from a Swedish study[29] also falls along the same slope as these studies, showing relatively poor acuity.

The data from the current study (solid squares) appear to follow and extend the slope of the Framingham study data[2] (open diamonds). Our results are also in excellent agreement with those of Taylor et al.[10] (horizontal bars). The recent results of Rubin et al.[13] (solid diamonds), which are also measured with habitual correction, show better acuities than ours or any other study. The data from a random sample in Finland[11] are intermediate between our results and those of the Beaver Dam,[6] Slataper,[27] and Hirsch[28] studies.

Low contrast acuity

The difference between high and low contrast acuity is shown in Fig. 3 as number of letters lost. Our data are represented by the solid squares, which show a linear increasing difference with age. Brown and Lovie-Kitchin[30] measured uncorrected high and low

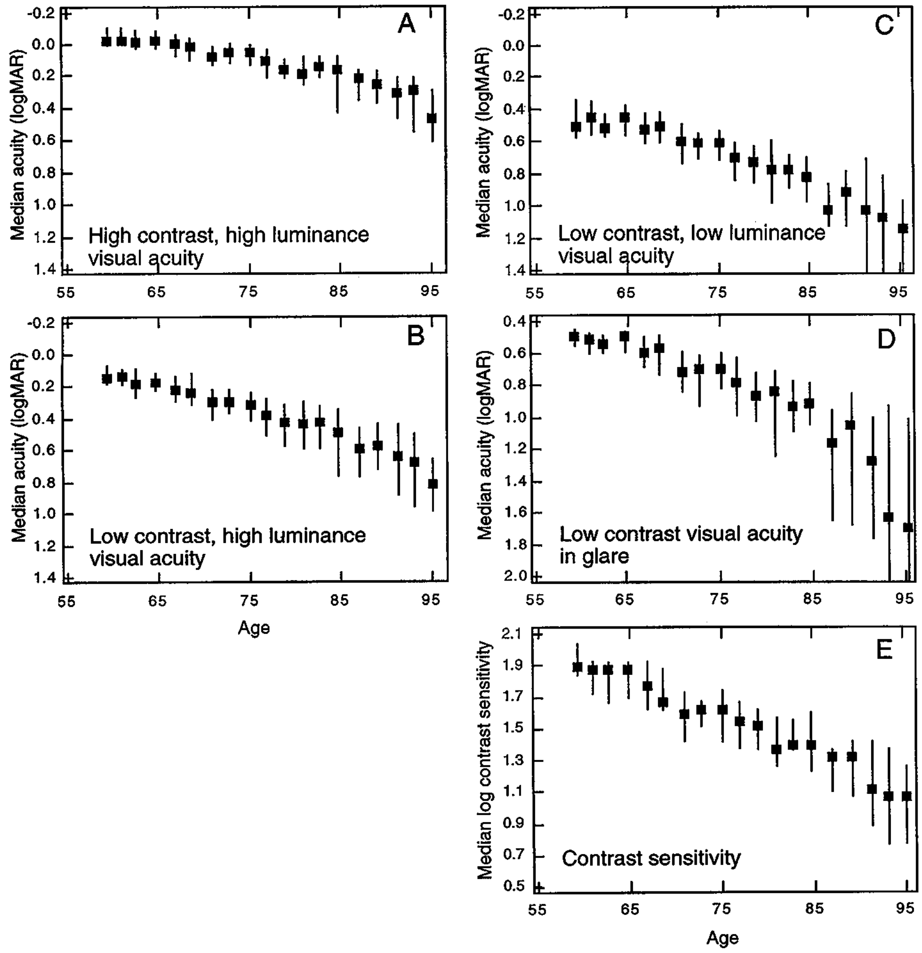

FIGURE 1.

Spatial vision test scores across age. Data are plotted for 2-year age groups starting at age 58. Median values are shown (solid squares). Vertical lines delineate the upper and lower quartiles. To facilitate comparisons between measures, the ordinates of the plots all span 1.6 log units. A log MAR of 0 corresponds to Snellen acuity of 20/20, 0.3 to 20/40, 0.5 to 20/63, and a log MAR of 1.0 is equivalent to 20/200 (see Table 2). The ranges for panels A to C are from −0.2 to 1.4 log MAR. For low contrast acuity in glare (D), the scale is from log MAR 0.4 to 2.0, as performance on this test is worse for the older age groups.

TABLE 2.
Snellen equivalents of logMAR values

logMAR	−0.2	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8
Snellen acuity 20/	12.5	20	32	50	80	125	200	320	500	800	1250

contrast acuity in a group of 86 people aged 17 to 74 years, using the same acuity charts and scoring techniques, and similar light levels to those used here. Individuals with ocular disease were excluded. Their measurements were made monocularly. They also present their data across age in terms of the difference between high and low contrast acuity. The dashed line in Fig. 3 is the best fit to their data. Those authors report that this difference between high and low contrast acuity was essentially constant across age.[30] At all ages, low contrast distance visual acuity was approximately 13 letters worse than high contrast acuity. However, that sample contained only 12 people aged 60 or older. Similar results of a fixed difference between high and low contrast were reported by Owsley et al.,[31] who monocularly tested a group of 30 older adults (mean age 70) using Regan charts with varying contrasts. On the other hand, Richards[32] found an increasing difference between high (90% contrast) and low (11% contrast) acuity with age. His youngest group (16 to 25) lost about 17 letters at a chart luminance of 10 FtL, whereas the oldest group (66 to 75) lost about 27 letters. He does not specify whether one or two eyes were used, but the assumption is that binocular testing was done. Taub and Sturr[33] tested two groups of older observers (N = 46, mean age 72.5, good self-reported ocular health; N = 33, mean age 73.2; poor self-reported ocular health) binocularly using Regan charts of varying contrasts and compared the results to a group of younger observers. Reading off their graphs, we estimate that the young observers (N = 71, mean age 18.9 years) lost on average 9 letters when lowering the contrast from 96 to 11% (Weber contrast), whereas the two older groups combined lost on average 15.5 letters. Our results (Fig. 3 solid squares, line) on a much larger random sample of older individuals wearing habitual correction, tested binocularly

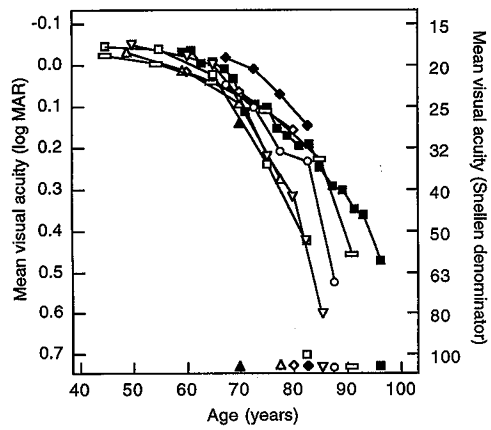

FIGURE 2.
Mean high contrast acuity across age: comparison between previous studies and the present study (solid squares). Open symbols indicate that subjects were tested with optimal refractive correction (best corrected). Solid symbols indicate that habitual correction was worn during testing: Rubin et al.[13] (solid diamonds, N = 2520), Aninansson et al.[29] (solid triangles, N = 957), Häkkinen[11] (open circles, N = 601), Weymouth[28] (open squares, N = 1675), Slataper[27] (inverted open triangles, N = 17,386), the Framingham study[2] (open diamonds, N = 2477), the Beaver Dam Eye Study[6] (open triangles, N = 4926), and Taylor et al.[10] (horizontal bars, N = 3271). Symbols along the abscissa indicate the age of the oldest test group of the corresponding study. See text for additional details.

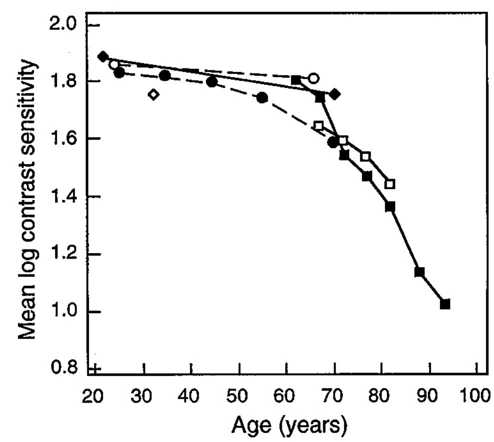

FIGURE 4.
Mean contrast sensitivity across age: comparison between previous studies and the present study (solid squares). All measured contrast sensitivity using the Pelli-Robson chart. Included are norms of Beck et al.[34] (open diamond), data from Elliott and Bullimore[35] (open circles, broken line, plotted at mean age of the two age groups), data of Rubin et al.[13] (open squares), data of Elliott and Whitaker[36] (solid circles), data of Elliott et al.[37] (solid diamond, solid line), and the present data (solid squares, solid line). See text for additional details.

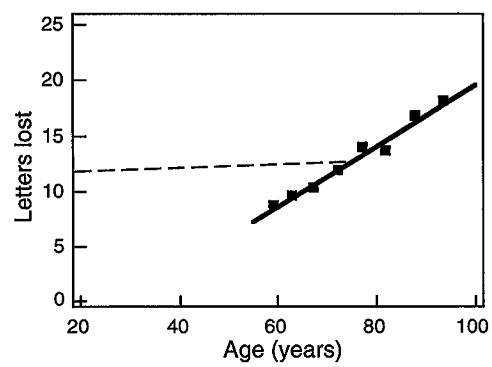

FIGURE 3.
Difference between high and low contrast distance acuity, plotted as letters lost (with reduced contrast), across age. Solid squares are the medians for each 5-year age group. Solid line is the regression fit to the data set (not to the medians). The dashed line is the fit to the data of Brown and Lovie-Kitchin.[30] See text for additional details.

show an increasing difference between high and low contrast acuity with age over a range of predominantly older ages. The difference between high and low contrast acuity is 8 letters for our youngest subjects (<60 years) and 18 letters for our oldest subjects (>90 years). Our results for 73-year-olds are similar to that of Taub and Sturr,[33] taking into account the different contrast of the chart used in our study.

Contrast sensitivity

Fig. 4 shows the results from several studies[13, 34–37] that used the Pelli-Robson chart to measure contrast sensitivity. Unlike high contrast acuity, contrast sensitivity shows very good agreement among studies, despite differences in test distance (4 m,[34] 3 m in the current study, and 1 m for all others included in the figure[13, 35–37]), sample composition (clinical vs. random), monocular vs. binocular, and best-corrected vs. habitually-corrected viewing conditions. The better agreement among studies may be due, in part, to the more similar luminance levels among studies and the use of the same test chart. There appears to be little change in contrast sensitivity throughout adulthood until about age 65. At older ages, contrast sensitivity shows more decline. For the entire age range of overlap, our contrast sensitivity results and those of Rubin et al.[13] (open squares) are in good agreement. In our sample, the correlation coefficient between Pelli-Robson chart contrast sensitivity and high contrast acuity is $r = 0.86$. Considering this high correlation between contrast sensitivity and visual acuity, it is unclear why the contrast sensitivities for our data and Rubin's overlap, whereas the high contrast visual acuities are discrepant.

Disability glare

The effect of surrounding glare on low contrast acuity for individuals at different ages is shown in Fig. 5. The difference in low contrast acuity with and without a 3300 cd/m^2 glare source is plotted in Fig. 5A, expressed as letters lost in glare (5 letters/line). Using the same test, Bailey and Bullimore[25] studied 75 people from 18 to 81 years clustered in 2 groups. Those authors concluded that there is a linear increase in the number of letters lost in the presence of glare with age, shown here as the dashed line, but noted an exponential would fit the data just as well. Our data (solid squares, curve) show that there is an accelerating increase in the effects of glare with age beyond age 65 to 70. The exponential fit to our data by least squares indicates that less than one line is lost at young ages. This "prediction" was confirmed. We found on average a 4-letter loss in 12 healthy individuals in their early 20s tested by one of the authors (GHP, open circle). In contrast, the same level of glare produces more than 5 lines loss (>25 letters) in low contrast acuity for the oldest age group.

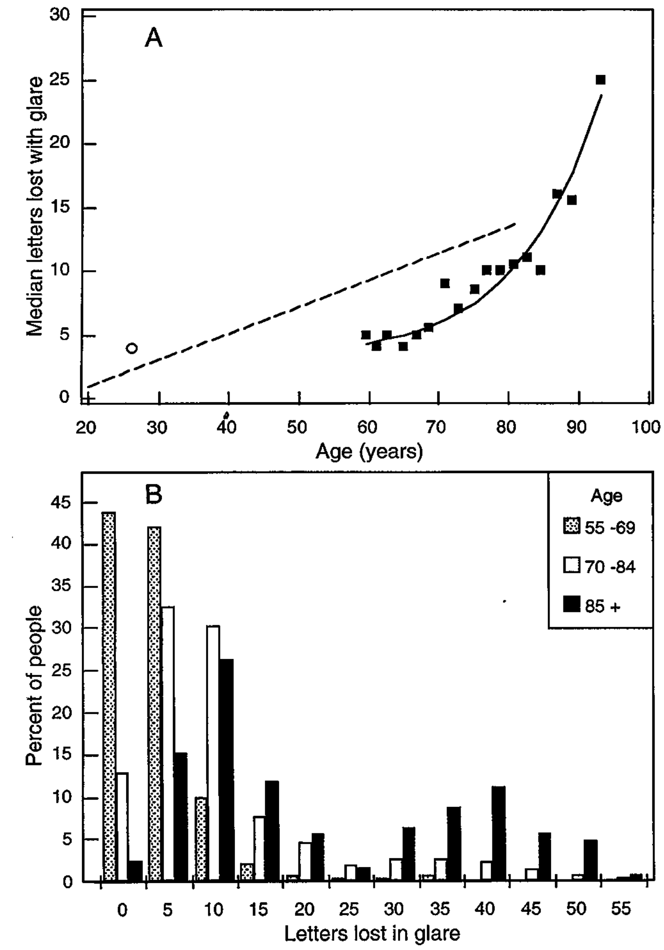

FIGURE 5.

Disability (surrounding) glare. A: Median number of letters lost in glare across age, in 2-year intervals (solid squares). Solid curve is best fitting exponential to our median data. Dashed line is regression line fit by Bailey and Bullimore[25] to their data, also obtained using the Berkeley Glare Test with a glare level of 3300 cd/m^2. The open symbol is mean data from 12 individuals in their 20s tested by one of the authors (GHP). B: Distribution of letters lost in glare by people in each of three age groups (young-old: 55 to 69; middle-old: 70 to 84; and old-old: 85 years and older) given as percent of people in each age group.

This is made more clear in Fig. 5B, which shows the distribution of number of letters lost in glare for the sample considered as 3 age groups: young-old (55 to 69), middle-old (70 to 84), and old-old (85 and over). The young-old (gray) show a narrow, unimodal distribution. Close to 90% of this age group lose less than 10 letters (2 lines) in the presence of glare. The two older age groups show bimodal distributions. This is more pronounced in the oldest age group (black), which shows peaks at 10 and 40 letters (2 and 8 lines). A Kruskal-Wallis one-way analysis of variance revealed that the distributions for the 3 age groups were significantly different ($\chi^2 = 251$, $p < 0.001$). One would immediately suspect that the group of 85+ year-old subjects losing few letters have had their cataracts removed, whereas those in the other peak of the distribution have not. Future evaluation of medical records will determine if this is the case. Furthermore, the extreme bimodality of the distribution for the oldest group explains the large ranges for these age groups shown in Fig. 1D. The non-normality of these distributions also highlights the appropriateness of medians, rather than means, as the measure of central tendency. Nonetheless, very few individuals lose 15 to 25 letters, the range of medians for the oldest of the 3 age groups (85+), so even the medians are somewhat misleading.

Glare recovery

Disability glare, discussed above, refers to the performance *during* exposure to a near-target glare source, whereas glare recovery (or photostress) refers to the time taken to recover vision *after* extinction of a centrally viewed glare source. Fig. 6A compares our glare recovery results (solid squares and solid exponential) to those of Elliott and Whitaker[38] (dashed line is best fitting polynomial to their data). Both studies measured recovery time for a criterion level of performance. They tested 61 subjects aged 19 to 78, including only 22 over age 60, screened for ocular disease and having visual acuity of 20/30 or better. They measured recovery time needed to read one line larger than best high contrast Bailey-Lovie acuity after exposure to a 2-ms white flash from a commercial low-powered flash gun light source 15 cm from the subject (light output and glare source angular size not specified). Retinal light exposure was made more constant across observers by attenuating the flash for younger observers (who have larger pupils and clearer ocular media). Despite the large procedural differences, the agreement between the two studies is very good.

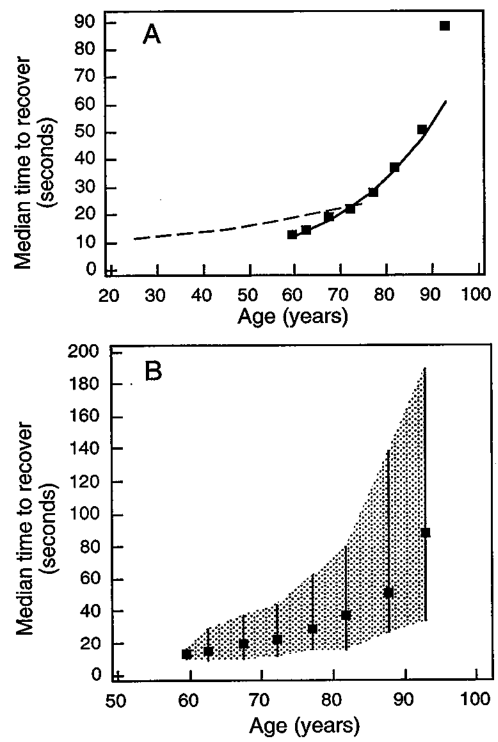

FIGURE 6.

Recovery from glare. A: Squares are medians for 5-year age intervals. The solid line fit to the data points is the best fitting exponential. The dashed line is the polynomial fit by Elliott and Whitaker[38] to their glare recovery data. Both studies measured time of recovery to a fixed level above acuity threshold. B: Variation among subjects. Data points are replotted medians and vertical bars and shaded area extend to 25th and 75th percentiles. See text for additional details.

Fig. 6B shows the median glare recovery time from our study with the 25th and 75th percentiles indicated. The median recovery rate increases by ~0.7 log units over the age range that we tested. Again, the variability increases dramatically with age so that quartiles for the oldest group (>90 years) are 30 to 190 s—a range of 0.8 log units. Thus, more than 25% of very old people take longer than 3 min to recover after only 1 min of bright light exposure. Note that we corrected for individual differences in contrast threshold by measuring how long it took to see letters a fixed size above that individual's threshold before glare. In daily life, the ability to see an object of fixed low contrast and size after bright light exposure is likely to be even worse for the oldest groups because their contrast thresholds before glare are also significantly elevated compared to the younger groups.

Stereopsis

We find, as others have reported (e.g., refs. 12, 13, 39, 40), that stereoacuity is quite poor among the elderly. Fig. 7 compares our data (dark bars) to those of Wright and Wormald[40] (open bars), who also used the Frisby Stereo Test. The upper figure (Fig. 7A) shows the percent of individuals in each age group who pass the finest of the plates, that is, have stereoacuity of 85 arc sec or better. Only a small number meet this lenient criterion. For reference, 40 arc sec is a common clinical criterion for normal stereoacuity. Nonetheless, only 60% of 70-year-olds and 20% of 90-year-olds meet the 85 arc sec criterion. Wright and Wormald[40] reported even lower pass rates.

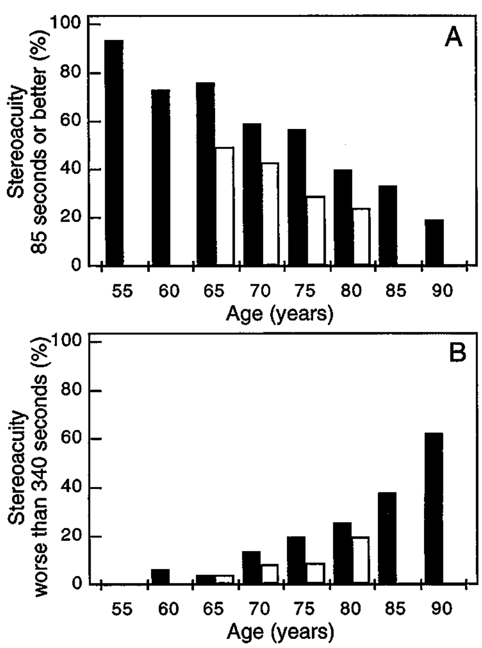

FIGURE 7.

Stereopsis across age. A: Percent of people in each age group passing all three plates of the Frisby Stereo Test (i.e., having stereoacuity better than or equal to 85 arc sec). B: Percent of people in each age group not passing any plates of the Frisby Stereo Test (i.e., having stereoacuity worse than 340 arc sec). Closed bars: present data set. Open bars: data from Wright and Wormald.[40] Note: data of the "80+" age group of Wright and Wormald are plotted at 80 years; the authors do not specify the age distribution or upper age limit of this group.

Fig. 7B shows the percentage of people in each age group who fail the coarsest plate of the Frisby Test. A large number of people have very poor stereopsis, particularly among the very old. Sixty percent of 90-year-olds cannot detect a disparity of 340 arc sec.

Color vision

The results for the *standard* Farnsworth Panel D-15 color arrangement test are shown in Fig. 8. Recall that if the subject made no errors on the desaturated D-15, they were not tested on the standard D-15 but were given a CCS of 0 and are included in the analysis and results in Fig. 8. Males with congenital color defects have been removed from this analysis (N = 13). Our mean CCS (solid squares) are compared to mean values from Bowman et al.[41] (open circles) in Fig. 8A. He tested 120 subjects free of ocular and systemic disease and having 20/20 or better visual acuity and no congenital color defects. The gray zone indicates ±1 SD for our data. Over the age ranges of overlap, the data are in excellent agreement consistent with the small amount of ocular disease in our younger age groups. Both data sets indicate very few errors until after age 70. In fact, 25th, 50th, and 75th percentiles for CCS was zero up to age 75 years in our data set. This test, designed to detect only defects sufficiently severe to influence performance in daily life,[24] is relatively insensitive to age changes below age 75.

Fig. 8B shows the failure rate on the standard Farnsworth Panel D-15 as a function of age in our sample. CCS values worse than 30 were considered failing (gray line in Fig. 8A). One crossing of the color circle or 2 single space errors will produce a color confusion score less than 30. Only after age 70 do a significant number of people fail. In the oldest 2 age groups, more than 50% of observers fail. The defect type for those who failed was determined according to the vector analysis (in CIE LUV uniform chromaticity space) developed by Vingrys and King-Smith.[42] Confusion angles between −70 to −100° and +70 to +100° were considered blue-yellow, whereas angles between −25 and +25° were considered red-green. Defects not falling in these zones were considered nonspecific. As many others have reported, the vast majority who fail show blue-yellow error patterns (Fig. 8C). This is not surprising considering all the age-related ocular diseases such as age-related maculopathy, cataract, glaucoma, diabetic retinopathy, and other vascular diseases that are known to produce blue-yellow defects (e.g., refs. 43 to 48).

Temporal sensitivity

Mean CFF is shown in Fig. 9A for our data (solid squares) and those of Tyler[49] (and personal communication, open squares), which represent 804 subjects between the ages of 5 and 50 and 110 over age 50. The vertical lines show ±1 SD for our data. Both studies used very similar test conditions (red LEDs) with near-equiluminant surrounds. CFF decreases nearly linearly across age. The amount of change is quite small, about 20%, from ~50 to ~40 Hz over a 70-year age span. Our data show a drop in CFF of only 0.07 log units between the ages of 60 and 95 years (~0.02 log units/decade) but a significantly larger (~0.5 log unit) decrease in modulation sensitivity for 4 and 17 Hz flicker (Fig. 9B) over the same age range. Log transforms were applied to each of the three measures of temporal sensitivity. Linear regression analysis demonstrated that the slope for each of them was significantly different from zero. An analysis of covariance showed that the slopes of the three temporal sensitivity measures were statistically different. Separate t tests with the Bonferroni correction for multiple comparisons revealed that the slope for modulation at 17 Hz was significantly different from that of CFF ($t = 8.5$, $p < 0.003$) and that for 4 Hz ($t = 7.1$, $p < 0.003$) but that the slope for 4 Hz was not different from CFF ($t = 2.1$, $p > 0.05$). The large population

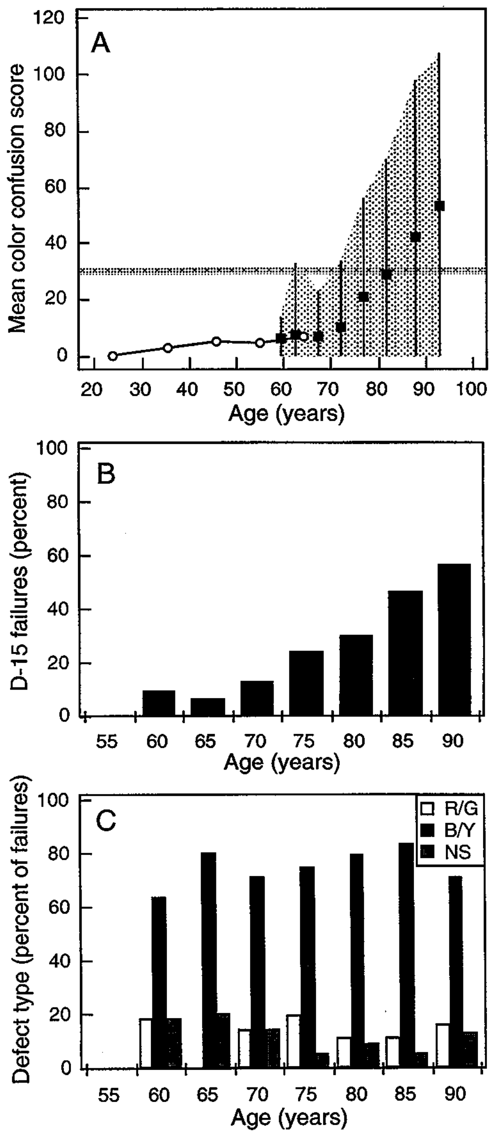

FIGURE 8.

Color vision across age. A: Performance on the standard Farnsworth Panel D-15 test of color vision, as color confusion score, an index of the number and size of arrangement errors is shown across age. Data are plotted at 5-year intervals. Solid squares are mean data of the present study. Vertical lines and shading indicate ±1 SD. Open circles are mean data from Bowman et al.,[41] who tested subjects spanning a range of relatively younger ages. Horizontal line at CCS = 30 indicates our criterion for passing/failing. B: Percent of individuals in each 5-year age group failing the D-15. C: Relative frequencies of red-green (open), blue-yellow (solid) and nonspecific (gray) color defects among those in each age group failing the D-15. Males with congenital red-green color defects in the present study (N = 13) are excluded from all color vision analyses.

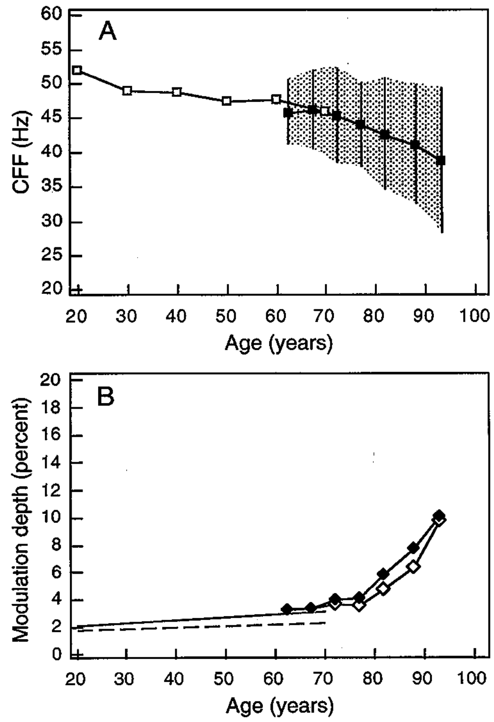

FIGURE 9.

Temporal sensitivity across age. A: CFF across age. Solid squares are means from the current study; vertical lines and shading indicate ±1 SD. Open squares: mean results from Tyler[49] (N = 914). B: Modulation thresholds for flicker of 4.1 Hz (open diamonds) and 17.1 Hz. Solid line represents Tyler's mean data for 20 Hz and the dashed line is Tyler's mean results for 5 Hz.

variance for 4 Hz no doubt contributed to the lack of statistical significance. Lachenmayr et al.,[50] who tested 130 normal subjects between the ages of 9 and 86 years, also found a small linear decrease in CFF with age; their results showed a steeper slope with age (−0.038 log units/decade). Target size, color, and retinal location differences may account for the difference in slopes; they used a 1° yellow target presented at various locations in the visual field, whereas ours was 5°, centrally fixated, and red. Others have also found larger losses for lower frequencies than for very high temporal frequencies,[51] even though this finding is not universal.[52]

Visual fields

Fig. 10 shows the visual field results. These are not threshold measurements but represent detection of a supra-threshold stimulus. Fig. 10A shows visual field extent (median average radius) both in degrees and as a percent of maximum for the standard (open squares) and attentional (solid squares) test conditions. The error bars and shaded areas indicate the 25th and 75th quartiles. For the youngest group, attentional peripheral fields are as large as standard fields, indicating very little restriction due to attentional load. Whereas standard field extent changes little with age, attentional field size decreases dramatically, accompanied by enormous increases in variability. Twenty-five percent of the oldest age group have *no* peripheral fields under conditions of divided attention.

Not only does the extent of the field diminish, but the residual

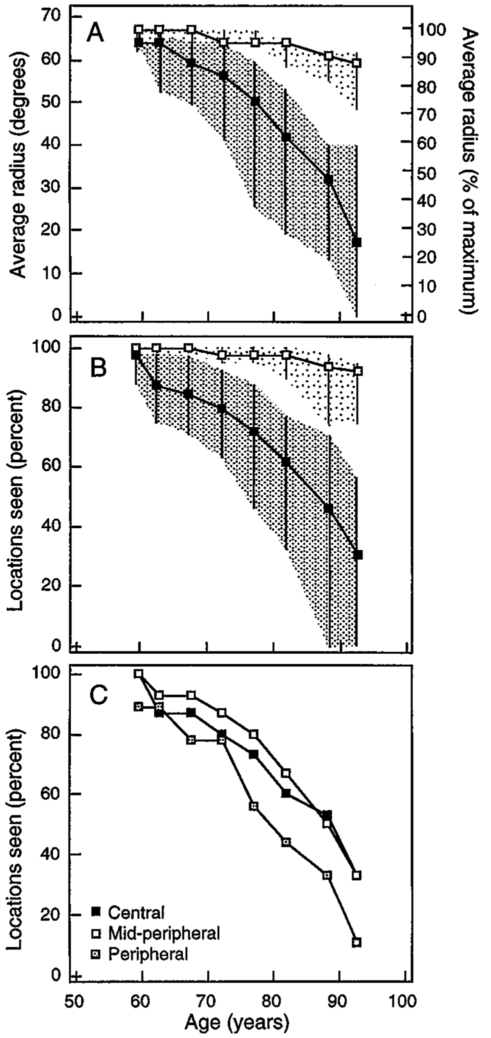

FIGURE 10.

Visual fields across age. A: The median average radius (average of all meridia) of standard (open symbols) and attentional (closed symbols) visual fields across age. Gray and black vertical lines span the 25th to 75th percentiles of the standard and attentional fields, respectively. Average radius as percent of the maximum average radius (67°) is given on the right ordinate. B: Percent of the total tested locations seen for standard (open symbols) and attentional (solid symbols) fields across age. C: Percent of locations seen in the central (solid), midperipheral (open), and most peripheral (gray) locations tested for the attentional field measure.

attentional field shows reduced integrity, i.e., has holes. Fig. 10B shows the percent of locations seen under both standard and attentional conditions. Of course, the more restricted the peripheral extent of the field, the fewer locations that would be detected. However, the number of locations seen is generally less than would be expected on the basis of peripheral field extent. For example, the 80-year-olds as a group have a median radius of 41°. If no locations within the remaining field were missed, 80% of all locations should be seen. Only 61.5% are actually seen in this age group (Fig. 10B). So, for this age group, nearly 20% of locations within the "intact" field are missed. Fig. 10C shows, surprisingly, that the patchiness of the attentional field is slightly more pronounced within the central 20° than at midperipheral locations for most of the age groups.

Amsler grid

The Amsler grid results are tabulated in Table 3. A total of 148 people (16.4%) showed Amsler grid abnormalities in at least 1 eye that were graded 2 or more and were considered significant. Only 45 (5%) showed abnormalities graded 2 or more in both eyes. Sixty-four (7%) received the worst grade of 4 in 1 eye, whereas only 15 (1.7%) were given scores of 4 in both eyes. As expected, the vast majority (75 to 80%) of those who showed significant Amsler grid abnormalities were over the age of 75, consistent with the increased prevalence of ocular disease with age (see Table 3).

DISCUSSION

Visual acuity

Our results confirm those of previous studies of acuity in the young-old, which all show that high contrast acuity is very well maintained on average until age 65 to 70. At later ages, our results, like others, show that acuity declines. However, the rate and amount of decline seen at older ages varies considerably among studies. There are many factors that may contribute to acuity differences observed at older ages between studies, including type of population (random vs. clinical vs. normal only), selection bias in the population, cohort effects, the acuity chart used, monocular vs. binocular testing, refractive error correction (best corrected vs. wearing habitual correction), scoring techniques, and light level.

The relatively older data of Slataper[27] and Hirsch[28] show a rather severe and rapid decline in acuity with age. Both data sets used best-corrected monocular data from clinical samples, although Slataper attempted to eliminate those with obvious pathology. Hirsch randomly selected patients from his practice and used no exclusion criteria. The use of clinical samples may contribute to these fairly poor "best corrected" acuities. The fact that Slataper used relatively low light levels (~30 cd/m^2) compared to the more modern studies that use light levels above 100 cd/m^2 undoubtedly contributed to the poor acuities that he obtained. In addition, there may be cohort effects. An individual aged 80 in 1950 is likely to be different from an 80-year-old in 1996. The more contemporary 80-year-old is more likely to be healthier, with better maintained vision function. Cohort differences in physical function have been reported among older cohorts even when spaced less than a decade apart (e.g., ref. 53).

Over the common age ranges tested, the data of the more recent Beaver Dam Study[6] are in very good agreement with those of Slataper[27] and Hirsch.[28] The rather poor acuities of the Beaver Dam Study[6] are surprising given that study used an Early Treatment of Diabetic Retinopathy Study (ETDRS) chart at fairly high

TABLE 3.

Amsler grid abnormalities (N and % in Amsler score category)

Score	Ages 58–74	Ages 75 and over
2 or more in one eye	36 (25%)	112 (75%)
2 or more in both eyes	9 (20%)	36 (80%)
4 in one eye	14 (22%)	50 (78%)
4 in both eyes	3 (20%)	12 (80%)

light levels to test a random sample, monocularly, with best correction in place, and scored results letter by letter. As pointed out by Rubin et al.,[13] the unusually high participation rate (80%) of individuals eligible for the Beaver Dam random sample may have contributed to the poorer acuities obtained. We and others find that those who refuse to participate tend to be older[6, 13] and have poorer vision than those who agree to participate. The median age of those who refused to participate in the present study was 4 years older than those who participated. Nonparticipants had high contrast visual mean acuity 0.14 log MAR (1.5 lines) worse than that of participants. Inclusion of the nonparticipants would not, however, make our data show as poor an acuity in the older ages as the Beaver Dam Study.

Most recent studies (e.g., refs. 10, 13), including this one, tend to find that acuity is better maintained at older ages than reported by the earlier studies. The less recent Framingham Study[2] also found relatively well maintained acuity. Our results fall along and seem to extend those of the Framingham Study and are also in excellent agreement with those of the recent study of Taylor et al.[10] The agreement between this study and the Framingham is somewhat surprising, given that our data were obtained using binocular testing and habitual correction, whereas the Framingham data represent best corrected acuity obtained (presumably) monocularly. Neither study had exclusion criteria. The similarity of our results to those of Taylor et al.[10] is less surprising, given the more similar methods. They examined 3268 randomly selected people living in Melbourne, Australia, using Bailey-Lovie charts at 4 m and ETDRS procedures[54] (chart luminance not specified). Although most of their population was younger, with an average age of about 60, the sample did include 145 people between ages 80 and 90 and 16 over the age of 90 years. It should be noted that those authors present their data as a table of the distribution of acuities. We estimated their mean acuity (better eye with habitual correction) from this published distribution. It is with this derived acuity function that the present data are compared.

Rubin (personal communication) used virtually identical techniques to those of the present study (random sample, ETDRS-type charts scored letter by letter, and binocular testing with habitual correction, similar light level) and reported acuities that are better (3 to 4 letters) than those of this study. Some of the differences—perhaps 1 to 1.5 letters—can be ascribed to the different charts used; the Bailey-Lovie charts with British letters on average yield slightly worse acuities than the ETDRS charts with Sloan letters.[55] Another factor that can influence the results is response rate, which in our study was lower; this should lead to better acuities in our study. The socio-economic level in our study is also considerably higher than that of the SEE study, which would be expected to give better acuities in our study (e.g., ref. 7). The reason for the discrepancy is thus not clear.

The discrepancies among all acuity studies increase with age. There are several factors that may contribute to the increased interstudy variation with age. As is evident from comparison of data presented in panels B and C of Fig. 1 across age, the effect of test luminance on acuity is larger at older ages. Test luminance differences between studies would thus spread data out most at oldest ages. However, other factors appear to be at least as important as luminance. For example, Aninansson et al.[29] measured acuity at fairly high luminances in his random sample. Nonetheless, his reported acuities are relatively poor. Other methodological differences such as the type of chart used, the spacing of the letters, and the criteria used for scoring can all contribute to differences between studies. Disease prevalence increases in old age are likely to increase differences between studies that use random vs. normal (pathology excluded) and clinical samples. The disease-produced increase in population variability will also increase sample bias-caused differences among "random samples."

Low contrast acuity

The studies that have compared high and low contrast acuity with aging using monocular testing have found that they decline in parallel;[30, 31] that is, the difference between the measures is constant. The studies that used binocular testing,[32, 33] including our study, found an increasing difference between the two measures at the older ages (>70 years). Age-related changes in binocular summation might contribute to these findings. If binocular summation decreases with age *and* there is normally more binocular summation for low contrast acuity than high contrast acuity, would the difference between the measures increase with age? Home[56] has shown that there is more binocular summation in the acuity domain for low contrast letters compared to high contrast letters. A similar result was found by Cagenello et al.,[57] who concluded that the percentage of binocular acuity enhancement is lower for high contrast letters than for low contrast letters because the binocular enhancement occurs in the contrast domain. Owsley and Sloan[58] and Pardhan[59] have reported decreased binocular summation with age for contrast sensitivity, whereas Derefeldt et al.[60] found no change. It is thus possible that a contributing factor to the discrepancies between monocular and binocular studies is binocular summation changes with age. One cause of decreased binocular summation with age is an increasing difference in function between the two eyes.[61] Because we only tested binocularly, we cannot assess interocular differences in our population.

For those studies that tested monocularly and found a fixed difference, it would be reasonable to conclude that measuring low contrast acuity is redundant to the high contrast measure as those authors did. However, our results using binocular testing, which more closely resemble normal viewing conditions, show an increasing difference between high and low contrast acuity, suggesting that it is worthwhile to measure low contrast acuity in addition to high contrast acuity. The older the observer, the more severe is the loss of function, as the contrast of objects in the environment is reduced. Even though the group data show an orderly increase in the difference with age, on an individual basis, it is difficult to predict a person's low contrast acuity from his high contrast acuity. The decline in low contrast acuity with age is likely to be due to a combination of decreased transmission through the pupil and ocular media, resulting in reductions in retinal illuminance, neural changes in the retina and visual pathways,[62] cortical changes that result in decreased binocular summation, and the presence of increasing amounts of ocular pathology with age.

Contrast sensitivity

The contrast sensitivity results from the various studies agree remarkably well, much better than the acuity data. The use of the same chart and similar fairly high light levels no doubt contributed to the similarity of the results. Contrast sensitivity for letters is essentially unchanged until age ~65 years and then undergoes significant loss with increasing age. The contrast sensitivity as measured with letters starts to fall off ~12 years before high contrast visual acuity (see aging function below).

To a first approximation, merely sinking the contrast sensitivity functions on log/log coordinates by 0.8 log unit can account for the 0.5 log unit change in high contrast acuity and the 0.8 log unit loss of contrast sensitivity between our oldest and our youngest age groups. The differential loss of contrast sensitivity and acuity is due to the shape of the contrast sensitivity function. Decreases in retinal illuminance caused by pupil size changes with age, and loss of media transparency can account for some of this loss but neural changes must also be present.[62, 63] Reducing light level from moderate to high photopic levels causes the contrast sensitivity function to initially "sink" and, with further reduction, to shift down and left on the spatial frequency axis.

SKILL dark chart acuity

The median SKILL dark acuity data show a loss of about 9 letters/decade (0.18 log units; ~2 lines), whereas high contrast, high luminance acuity shows a loss of 5.5 letters/decade (0.11 log units; ~1 line). In addition, the increase in variance with age is larger for the SKILL acuity (see Fig. 1). This increase in variance may reflect more variation in the age at which the individual starts changing along one shape-invariant aging function (see below) if you assume that individuals will follow the population shape and/or can reflect more eye disease among the older participants. Clearly, decreases in pupil size and media clarity, as well as retinal changes, will have more of an effect on this task of reading low contrast letters under reduced local luminance than on standard high contrast acuity, which is fairly insensitive to many age-related changes including disease. Reducing the contrast and the luminance places the older observers at a significant disadvantage. Large discrepancies between high contrast acuity and acuity for low contrast and low luminance may also lead to a lack of recognition of problems the senior may encounter in daily life.

Disability glare

We find that the impact of glare on low contrast acuity increases significantly with age. Median letters *lost* with glare in our population is 5 letters per decade or 0.10 log unit loss/decade. These results are quite different from those of Rubin et al.,[13] who report a minimal change with age, only 1 letter per decade. Rubin et al.[13] measured loss of contrast sensitivity for large targets using the Pelli-Robson chart letters as targets. Thus, the 1-letter loss corresponds to a contrast sensitivity loss of 0.05 log units per decade, half the loss we find for our measure, low contrast acuity. Other procedural differences undoubtedly contribute to the differences in results. Those authors used large targets (Pelli-Robson letter) and the medium setting of the Brightness Acuity Tester, which has a less intense glare source (350 cd/m^2); this is further removed from the target than that of the Berkeley Glare Test. On the basis of their small changes in glare sensitivity with age, Rubin et al.[13] conclude that this vision function is insensitive to age effects and is of little value. Our results indicate that the Berkeley Glare Test is more sensitive and that with it large age-related increases in glare disability occur. The large variability among subjects at a given age, and the bimodality of the function at the older ages also speak to its sensitivity. Poor test repeatability could contribute to increased variability with age, but the repeatability of the Berkeley glare test is quite good.[35]

The argument has been made that because of high correlation between standard acuity and acuity in the presence of glare, this measure is redundant. Letters lost in glare (a difference measure) may be a better measure because it is not as highly correlated with acuity. However, in daily life, letters lost in glare are not necessarily the appropriate measure. Our results show a better correlation between problems with glare as reported in the vision questionnaire and acuity in the presence of glare than with the letters lost in glare. This result suggests that acuity for low contrast objects in the presence of glare should be used to assess functional impact. This value shows a large change with age, 10.5 letters/decade or 0.21 log units/decade. Thus, the average 90-year-old can be expected to have acuity in the presence of glare that is >0.6 log units worse (a factor of 4 times worse) than the average 60-year-old.

Glare recovery

We measured time to recover to a fixed amount (two lines) above the individual's low contrast low luminance acuity previously measured that day. Given that low contrast low luminance acuity falls off markedly with age, the size of the recovery test targets is much larger for the very old than for the younger old. Nonetheless, the time to recover sensitivity after exposure to a bright glare source—glare recovery—increases considerably with age. This measure evaluates the dynamics of recovery by eliminating contrast threshold differences and likely reflects retinal effects. Median recovery time increases by more than a factor of 8 over the age range tested, from about 10 to nearly 90 s. Had we measured recovery to a fixed target size, the decrement with age would have been even more dramatic. Even after correcting for threshold differences, 25% of the oldest age group took more than 3 min to recover sensitivity. This represents a significant functional impairment given that the glare exposure is brief (1 min) and not that intense (4 log Td assuming 2-mm pupil). These individuals would be debilitated for many minutes when coming indoors on a bright day. The poor adaptational ability of the older individuals underscores the need for bright light protection such as sunglasses and hats when going outdoors. By avoiding bright light exposure, older people can maintain better function when returning indoors.

Stereopsis

Our results showing significantly decreased stereopsis with age are similar to many others (e.g., refs. 12, 39, 40). We cannot determine to what degree the poor stereopsis is caused by decreased acuity in one eye because all vision measures were done binocularly. The Amsler grid was the only test done monocularly. The vast majority (>85%) of people with good stereopsis (at least 85 arc sec) showed no abnormalities on the Amsler grid, whereas close to 50% of those who failed the coarsest plate (<340 arc sec) had significant abnormalities on the Amsler grid in at least one eye.

Those who had a score on the Amsler grid of 2 or worse in at least one eye had a median stereoacuity of only 340 s, whereas those scoring better than 2 in both eyes had a median stereopsis of at least 85 s. There are, however, many people with no abnormalities on the Amsler grid who still show poor stereopsis, suggesting that stereopsis decreases with age even with maintained foveal function in each eye. Rubin et al.[13] report that having five or more lines difference in acuity between the two eyes not surprisingly results in complete loss of stereopsis. They do not report on the level of stereopsis in people with equal (and good) acuity in each eye. Wright and Wormald[40] found a large loss of stereopsis with age even when they only included those with equal and good acuity in each eye. Fifty percent of 65- to 69-year-olds in their selected group passed all 3 plates (at least 85 arc sec), whereas <20% of the 80+ group with equal and good acuity in the two eyes were able to pass all 3 plates. Brown et al.[39] also showed a loss of stereopsis thresholds from about 16 arc sec in young observers to 27 arc sec in older observers aged 60 to 70 with good and equal acuity in the two eyes. It should be noted that another study[64] found no statistically significant difference in stereothreshold on the Randot test between a young (N = 24; mean age 19.5 years) and an old group (N = 24; mean age 68.4 years) when the 4 older observers who had no stereopsis were excluded, even though a trend for worse thresholds among this fairly young old group was found (mean = 33.75 arc sec for the young group and 44.4 arc sec for the older group). Functionally, loss of stereopsis may impair walking stairs, pouring liquids, threading needles, and doing other near tasks, and parking a car (e.g., ref. 65).

Color vision

For the age ranges of overlap, our results and those of Bowman et al.[41] agree. Performance on the Farnsworth D-15 shows little change with age until about age 70, when significant blue-yellow color defects are found. Reduced retinal illuminance caused by pupil size changes and age-related yellowing of the media in combination with retinal receptor losses with age can account for much of the color discrimination loss. Another factor is the increased prevalence of ocular diseases that are known to cause blue-yellow defects. The D-15 was designed by Farnsworth[24] to be insensitive to subtle color vision loss, and to identify those observers who had problems with color discrimination in daily life. People with congenital defects that are mild to moderate will usually pass the D-15. Only severe anomalous trichromats and dichromats fail the test. After age 70, more than a third of older observers who do not have congenital defects fail the D-15. Functionally, older observers should not be required to make blue-yellow discriminations, particularly for desaturated or washed-out colors.

Temporal vision

Our results show only 0.07 log units change in CFF, whereas modulation threshold for 4 and 17 Hz shows much larger losses of around 0.5 log units over the age range that we tested. Tyler[49] models his results for flicker sensitivity for ages 20 to 70 by a very small loss of sensitivity coupled with an overall slowing of the temporal response. Our data are not consistent with this change because there is considerably more loss of modulation sensitivity for low and intermediate temporal frequencies with much less change in CFF. In fact, the results for the oldest group match that of the youngest group if the young group results are shifted straight down by ~0.5 log unit on a graph of log modulation sensitivity vs. linear temporal frequency. No additional slowing of the response needs to be postulated. The 0.5 log unit loss of sensitivity is likely caused by several factors. Pupil diameter differences between the ages of 62 and 93 (the ages of the youngest and oldest age groups) are expected to decrease retinal illuminance by about 0.25 log units. Expected pupil sizes for our subjects were derived from the results of Winn et al.[66] The average expected pupil diameter for the youngest group of 4.93 mm[66] would produce a retinal illuminance of 1047 Td from the target which has a luminance of 55 cd/m^2. The older group's expected pupil size of 3.69 mm[66] would give a retinal illuminance of 588 Td assuming no lens changes (log 1047 − log 588 = 0.25 log units). Assuming a linear relationship between log modulation sensitivity and log luminance,[67] some other factor must be responsible for the other 0.25 log unit. The yellowing of the lens and the increased scatter with age should have minimal effect on these results because red light was used. Instead, neural losses in the retina or beyond are more likely to be the cause.

Visual fields

The visual field results show small changes in the standard fields with age, consistent with a small percentage of people with disease in our population. At the youngest ages, adding an attentional load has minimal impact on the peripheral fields but with increasing age, a dramatic loss of attentional fields was found. The variance for the attentional fields is also dramatically increased, indicating that some older observers have no trouble with the divided attention task, whereas others essentially show no peripheral fields while focusing on a central task. Based on our results and the results of studies of the "Useful field of view" (e.g., ref. 68), we expect a serious functional impact under conditions that require dual processing, such as driving. Surprisingly, the remaining visual field is not intact but shows "holes." The central ±20° area is more likely to show holes than the midperiphery for many of the age groups. Of course, the most peripheral locations are the ones most likely not to be seen.

Aging function for spatial vision

Fig. 11A shows our median high contrast, low contrast, low contrast in glare and low contrast, low luminance acuities vs. age fit with a linear equation. Fig. 11B shows our median contrast sensitivity and its best linear fit. Over the age range that we tested, all spatial vision measures are very well fit by a linear equation. The solid lines indicate the best fitting regression lines. r^2 for all of the fits are greater than 0.92 (range 0.92 to 0.98). The slopes, presented in the legend of Fig. 11B, are significantly different for the different functions. The differences in slope suggest that aging differentially affects the different measures. High contrast acuity shows a loss of 5.5 letters/decade, whereas low contrast acuity in glare declines at about twice that rate, 10.5 letters/decade. Other spatial measures show intermediate losses. However, even within our data set, there are indications that a linear function is not going to describe spatial vision over the entire lifespan. See, for example,

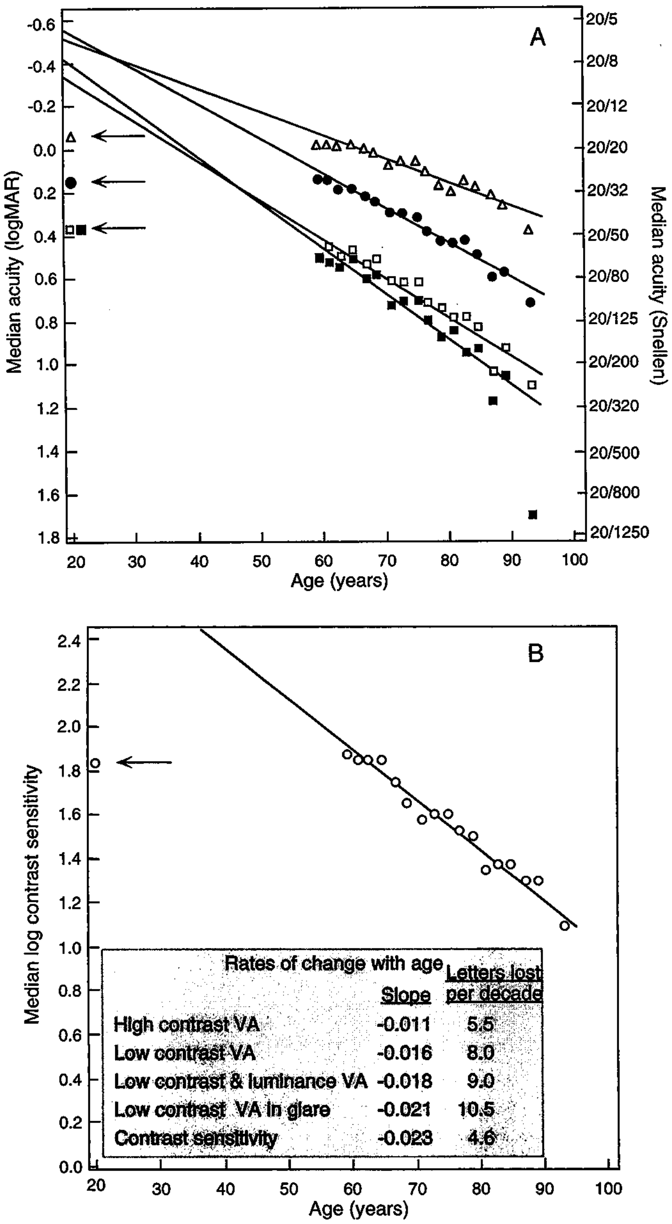

FIGURE 11.

A: Comparison of slopes of linear regression lines for high contrast (open triangles), low contrast (solid circles), low contrast low luminance (open squares), and low contrast acuity in glare (solid squares) expressed as log MAR and Snellen acuity vs. age. Data points represent the median values, and are plotted at 2-year intervals. Lines are regression lines fit to the median values at each age group. The data point for acuity in glare for the oldest age group was not included in the linear fit. B: Best fitting linear regression to the median log contrast sensitivity data. Values in the legend are slopes, which represent number of letters lost per year (1 letter = 0.02 log MAR and 0.05 log contrast sensitivity).

high contrast acuity which begins to plateau for the youngest ages that we tested. It is well-known that all of the functions reach an asymptote in young people. The arrows near the y-axis in Fig. 11 point to asymptotic values from the literature for 20-year-olds for each of the functions. It is clear that linear extrapolation to younger ages from our best fitting linear regression lines would result in much better values than those actually measured. Linear functions thus fail to account for the asymptotic values at age 20. This suggests that bilinear or exponential functions would fit the data better over the lifespan (at least from the early 20s and up). Bilinear functions have been shown to give better fits than linear functions to other aging and vision measures).[69, 70] Nevertheless, we chose to use exponential functions to improve the fit over the entire life span from the 20s and up.

Best fitting exponential functions were fitted using least squares techniques to the median values for each spatial vision measure in our data set. Fig. 12 shows the results for high contrast acuity (A), low contrast acuity (B), low contrast, low luminance acuity (C), low contrast acuity in glare (D), and contrast sensitivity (E). All results are plotted in log units. The best fitting exponentials are virtually identical for all of the measures. The exponential functions have a time constant of around 15 years. There is no statistically significant difference between the linear fits and the exponential fits for any of the measures over the age ranges in our study.

Fig. 13A shows the best fitting exponentials for each of the spatial vision measures from Fig. 12. The symbols on this figure are not data points but only serve to identify the measure. All the curves are placed correctly on both axes except that the acuity data have been flipped (multiplied by −1) to allow comparison of the shapes with that of contrast sensitivity. Fig. 13B shows the same functions shifted only vertically to eliminate the different asymptotic levels. It is clear that low contrast acuity, for example (solid circles), falls off at a later age than contrast sensitivity (open circles) or acuity in glare (solid squares). Fig. 13C shows the same functions also shifted laterally (to the right) for best fit by eye. The figure illustrates that one fixed shape aging function can describe each of the different spatial vision measures well. Acuity in glare and contrast sensitivity begin their fall-off at the same age about 12 years before high contrast acuity, whereas SKILL dark acuity had to be shifted 9 years, and low contrast acuity had to be shifted 7 years to coincide with the curve for high contrast, high luminance acuity.

The common exponential curve was placed on the high contrast acuity results from different studies (from Fig. 2) and shifted for best fit by eye to the recent studies including our data. This curve is shown as a solid line in Fig. 14A. The fit to the more recent studies is reasonably good. The dashed line shows best fit to the older studies using the same-shaped function. The fit of this standard template to the data from Slataper,[27] Hirsch,[28] and the Beaver Dam Study[6] is not as good as the fit to more recent data; the fall-off is too shallow for intermediate ages. It is clear that a more steeply shaped exponential would be required to fit these data sets. The same exponential was also placed by eye for best fit on the composite contrast sensitivity results (from Fig. 4). Fig. 14B shows that this same shaped curve well describes most of the published contrast sensitivity data from our and other studies.

It should be noted that these exponential functions describe the population data. Without a longitudinal study, we have no knowledge about the path an individual might take. One hypothesis is that individuals are changing along the same-shaped function but starting the decline at different times. The large increase in variance with age could be accounted for by this hypothesis. This explanation would also account for very non-normal distributions that are asymmetric with long tails. For all the measures, there is a ceiling effect on how good vision function can be but there is no limit on

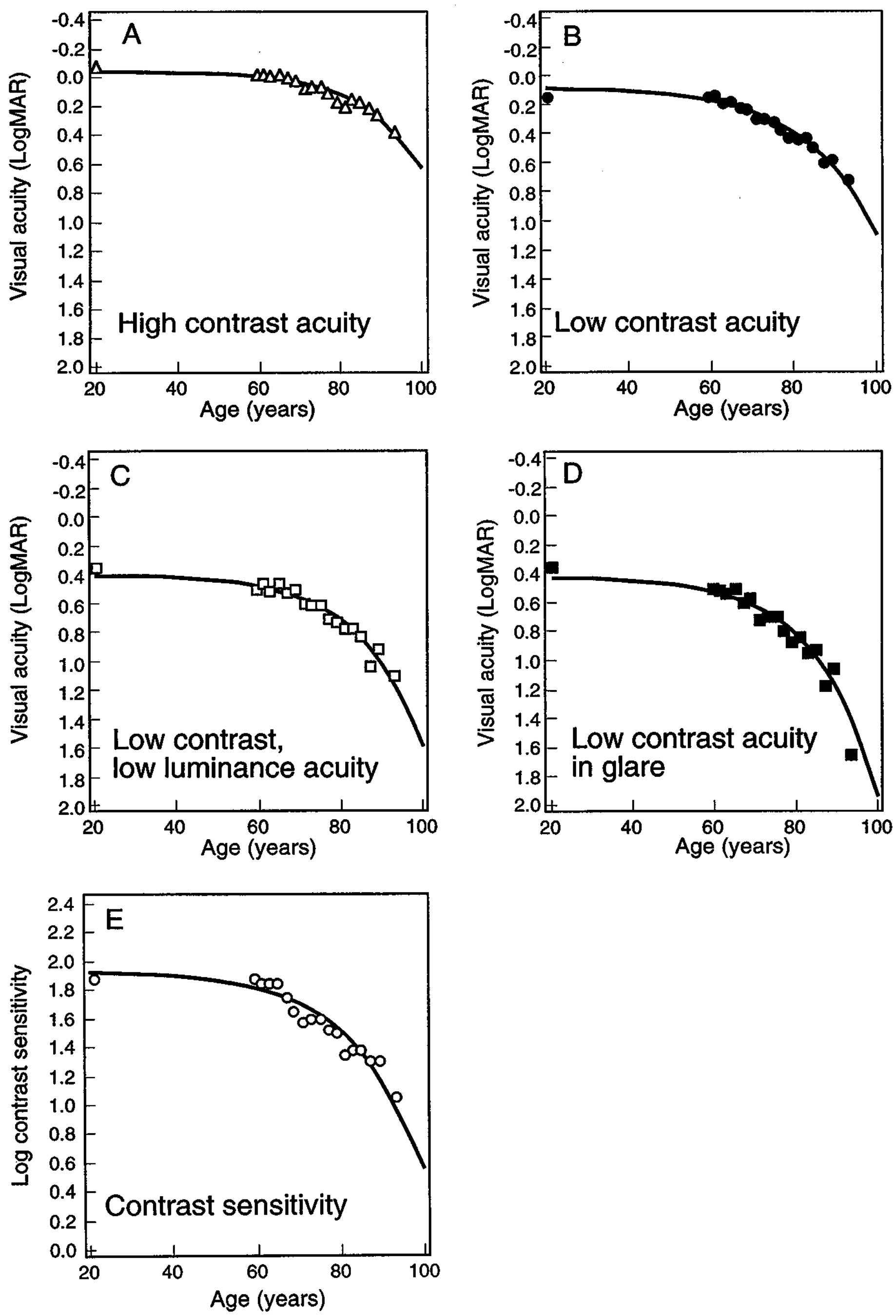

FIGURE 12.

Best fitting exponentials (by least squares) to median high contrast acuity data (A, open triangles), low contrast acuity data (B, solid circles), low contrast low luminance acuity (C, open squares), low contrast acuity in glare (D, solid squares), and contrast sensitivity (E, open circles). All data are expressed in log units. The asymptotic values at age 20 which were not included in the fits demonstrate that these curves derived from ages 58 and above describe function well across the life span. The best-fitting exponentials are virtually identical with a time constant of ~15 years.

how poor function can become. Alternatively, individuals may change with very different-shaped trajectories and this, combined with increased prevalence of disease, could account for the large increase in variance with age.

CONCLUSION

This cross-sectional study has shown significant losses in nonstandard vision measures in old age. Reducing the light level or the contrast, or adding glare significantly decreases the measured function in older observers. In view of the fact that those who refused to participate had worse visual acuity and would be expected to perform even worse on the nonstandard tests, our results are likely to underestimate the extent of vision loss among older observers. Because these other vision functions are not usually measured clinically, the elderly themselves may be unaware of how impaired their vision function is under less than optimal conditions. The spatial vision changes combined with loss of color vision and stereopsis, as well as constriction of the peripheral visual fields under

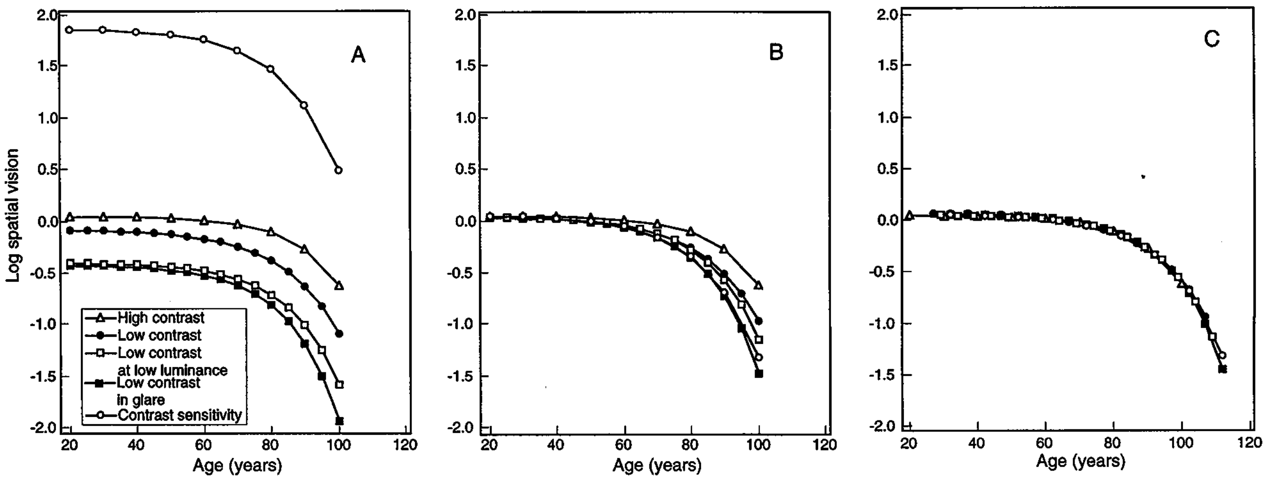

FIGURE 13.

A: The derived exponential curves for all spatial vision measures from Fig. 12. The symbols do not represent data but only identify the curves. The curves are placed correctly on both axes except that the log acuity functions (lower 4 curves) have been flipped (multiplied by −1) to allow shape comparisons with log contrast sensitivity. B: Same curves as in A but shifted vertically to coincide at the youngest age. C: Same curves as in B but shifted only laterally (to the right) for best fit to each other. It is evident that each spatial vision function vs. age is well described by one shape (see text for details).

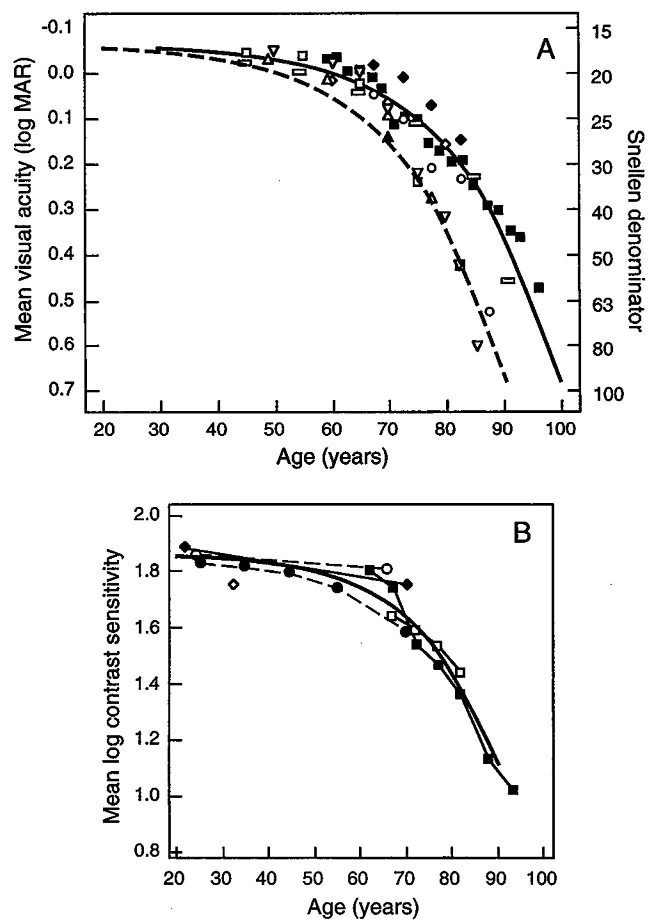

FIGURE 14.

A: The aging function from Fig. 12 placed on the composite high contrast visual acuity data from Fig. 2 and adjusted for best fit by eye to the current data and other recent studies (solid line). The dashed line shows the same-shaped function but placed to fit the older data sets of Weymouth[28] and Slataper.[27] The two curves are separated laterally by 12 years. B: The aging function from Fig. 12 placed on the composite contrast sensitivity data from Fig. 4 and adjusted for best fit by eye to the results from all the studies.

conditions of divided attention, will combine uniquely in an individual with expected significant impact on function in daily life.

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