Visual Psychophysics and Physiological Optics

Shape Perception Is Altered by Normal Aging

Anne E. Weymouth and Allison M. McKendrick

Purpose. To compare the effects of aging on two shape-discrimination tasks: a closed shape task (radial frequency [RF] patterns) and a Glass pattern coherence task (discrimination of global shape signal from textured noise). We hypothesized that aging would impair the extraction of shape from texture more than the discrimination of closed shapes, consistent with evidence that aging impairs the ability to suppress irrelevant information when segmenting contours from noise.

Methods. Fourteen younger (19–38 years) and 14 older (62–72 years) adults participated. Contrast-detection thresholds were measured for the RF and Glass stimuli, and then shape-discrimination tasks were performed using stimuli of 5-fold each individual's contrast threshold. The threshold sinusoidal amplitude for the discrimination of an RF3 (triangular) versus an RF4 (square) was measured, in addition to the threshold signal coherence level for the discrimination of concentric from radial Glass patterns.

Results. Older adults had elevated shape-discrimination thresholds: RF: mean older = 27 second arc, younger = 18 second arc, $t(26) = -3.14$, $P < 0.01$; Glass patterns mean coherence: older = 29%, younger = 16%, $t(26) = -5.67$, $P < 0.01$. Relative to younger adult performance, the *Z*-scores for older adult performance on the Glass task were higher than the RF task (paired *t*-test; $P < 0.05$).

Conclusions. Shape perception is not robust to the effects of aging. Greater deficits were manifest for the discrimination of shape from texture than for the discrimination of closed contours. (*Invest Ophthalmol Vis Sci.* 2012;53:3226–3233) DOI:10.1167/iovs.11-8807

An important daily visual task is the correct interpretation of information about shape. Previous studies of shape perception in the elderly have generally been interested in whether aging alters the detection of linked contours,[1–3] or the discrimination of closed shapes from circles (for reviews see Refs. 4–7). These types of tasks are regularly used to study early through intermediate stages of form processing in normal vision (for review see Ref. 8), and are considered to require neural processing consistent with that necessary to encode closed-shape objects in the natural world (e.g., the outline of faces or head shape). Previous reports indicate minimal or small changes in closed-shape discrimination for clearly visible (suprathreshold contrast) circular objects.[4–7] The observation that aging largely spares the detection of deformation from circular structure (a hyperacuity) has led to the development of shape-discrimination tasks involving radial frequency patterns being used to detect pathologic changes to shape perception.[9]

Shape information can also be encoded by texture. A common stimulus used to study this type of shape extraction is the Glass pattern,[10,11] which consists of pairs of dipoles (dot pairs) that are aligned according to a polar global shape rule (see Fig. 1 for examples of concentric and radial Glass patterns). The correct interpretation of Glass pattern structure requires the correct grouping of local dipoles, encoding of the orientation of the different dipole orientations, and then integration across the pattern to extract the dominant global form rule. The exact mechanisms that enable the extraction of weak form signals from Glass pattern dipoles, while suppressing incorrect pairings, are still being understood.[12,13] The total orientation content within a series of randomly generated Glass patterns of the types shown in Figure 1 are, on average, identical. It is the organization of the dipoles according to the global rule that creates the concentric or radial appearance. Performance is typically measured by substituting some of the signal dipoles with noise pairs (randomly oriented), or unpaired noise dots, and measuring the minimum number of signal pairs (Glass pattern coherence threshold) to extract the global shape from noise. In natural vision, the processing of shape from texture is likely useful for the identification of shape within textured natural objects (e.g., certain plant foliage), is thought to underlie our ability to segment figure from ground, and may also provide oriented form information that contributes to disambiguating motion direction (so-called motion streaks; for review see Refs. 14 and 15).

The purpose of our study was to compare the effects of normal aging on the discrimination of Glass patterns to those of closed-shape discrimination. There is convergent evidence that the key brain regions for processing these stimuli are similar (the ventral stream, particularly V3a and V4[16–19]). Both types of intermediate form-perception task require the correct encoding of component orientation and position information (presumably in pathways from retina through to V1) prior to integration of the global shape. Given that closed-shape discrimination has been previously shown to be intact with aging, and that aging minimally impairs orientation discrimination[20–22] and the ability to perform spatial position judgments,[23,24] both intermediate form-perception tasks might predictably be minimally affected by age. However, it is also possible that aging may differentially alter task performance. Discriminating closed shapes uses information from neural mechanisms involved in the segmentation of linked contours and edges (often studied using contour integration or contour facilitation tasks[25]). Oriented texture detection requires correct pairing of local dipoles, and minimization of spurious dot pairings to extract the dominant global form signal from noise.[11,18,26] It has recently been shown that older adults have difficulty with visual tasks that involve the extraction of contour information embedded in noise elements,[27] with the authors arguing that their results indicate abnormalities with

From the Department of Optometry and Vision Sciences, The University of Melbourne, Parkville, Victoria, Australia.

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Corresponding author: Allison M. McKendrick, Department of Optometry and Vision Sciences, The University of Melbourne, Parkville, Vic. 3010, Australia; allisonm@unimelb.edu.au.

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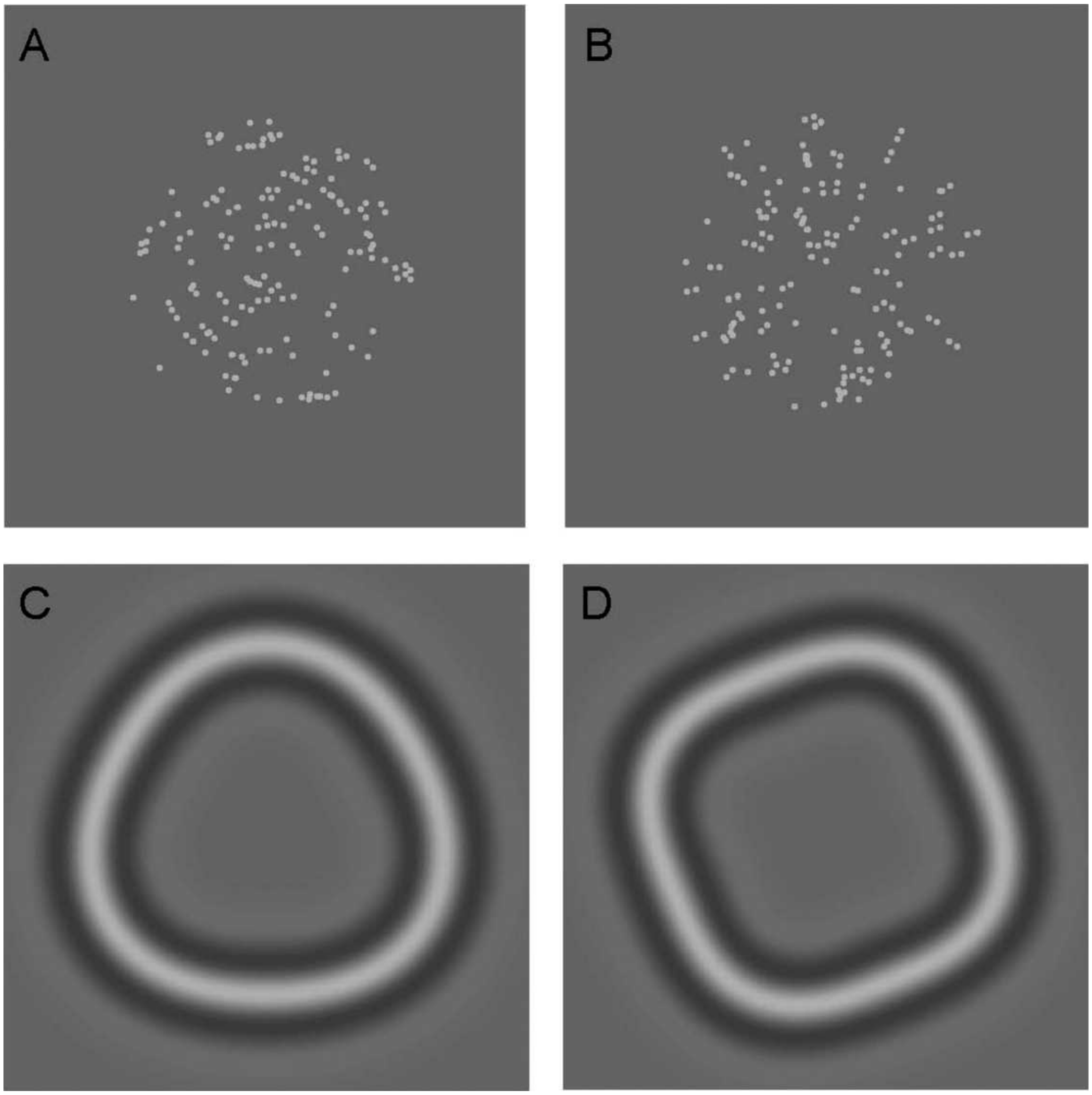

FIGURE 1. (**A**, **B**) Examples of concentric and radial Glass patterns respectively with 50% coherence. (**C**, **D**) Examples of RF3 and RF4 patterns.

suppressive mechanisms. Given that Glass pattern coherence thresholds depend on the ability to extract signal pairings from noise, we hypothesized that normal aging would interfere with the discrimination of shape from texture more than that of closed shapes. Our results confirm that these intermediate shape-perception tasks are differentially affected by aging.

METHODS

Participants

Participants responding to written advertisements at the University of Melbourne and in local community newspapers were screened for eligibility based on normal ocular health and the absence of known systemic disease. They were required to have binocular visual acuities no worse than 6/7.5, intraocular pressures below 22 mm Hg, normal anterior eye, macula, and optic nerve head appearance, and refractive errors between −5.00 diopters (D) and +5.00D sphere with no more than 2D of astigmatism. The anterior segment was assessed with slit-lamp biomicroscopy and the posterior segment was examined using direct and indirect fundoscopy by an experienced practitioner. An exclusion criterion was any sign of ocular disease or abnormal aging. Any sign of age-related macular degeneration or any ocular risk factor for glaucoma gave rise to exclusion. Previous cataract surgery was not an exclusion criterion and age-related cortical and nuclear lens changes were required to be no greater than Grade 2 (Lens Opacities Classification System III[28]; no one had posterior subcapsular cataract).

Fourteen younger (9 female and 5 male; mean age: 28 years, SD = 6 years; range: 19–39 years) and 14 older (10 female and 7 male; mean age: 66 years, SD = 3; range: 62–72 years) participants were included. The desired sample size was determined using Glass pattern and Glass line coherence threshold data collected in previous studies[29,30] and is similar to other recent studies that have revealed age-related differences in performance on spatial visual tasks (for reviews see Refs. 20, 27, 31, and 32). The mean refractive error in the younger group was −1.00DS and −0.5DC (spherical equivalent range from +1.00 to −4.50D). In the older group, the average refractive error was +1.25DS and −0.5DC (spherical equivalent range of +4.00 to −2.50D). The poorest monocular acuity was missing two letters on the 6/7.5 line in one eye of one older observer. The majority of participants had balanced acuities in the two eyes. For the younger adults, 12 of 14 had equivalent acuity or less than one line difference in acuity. Two of 14 participants had a one-line difference in visual acuity (VA) between the eyes. For the older group, 10 of 14 had the equivalent or less than a one-line difference in VA; 3 had a one-line difference in VA; and 1 had a two-line difference in VA between eyes.

All experiments were approved by our institutional Human Research Ethics Committee and complied with the tenets of the Declaration of Helsinki. All participants provided written informed consent prior to participation.

Stimuli and Procedures

Observers participated in two shape-discrimination experiments: (1) Glass patterns; and (2) radial frequency (RF) patterns. The order of the two tasks was alternated between participants.

Stimuli were presented on a gamma-corrected 21-inch monitor (resolution: 1408 × 1056 pixels; frame rate: 70 Hz; maximum luminance: 95 cd/m^2; G520 Trinitron; Sony, Tokyo, Japan). Custom software was written in a commercial high-level technical computing language (Matlab 7; The MathWorks, Natick, MA) interfaced with a computer graphics system (ViSaGe Visual System; Cambridge Research Systems, Ltd., Kent, UK) running on a personal computer.

The monitor was viewed binocularly using a chin and forehead rest to maintain viewing distance. Glass patterns were viewed at 1 m and RF patterns were viewed at 7 m. Participants were optimally refracted for viewing distance and wore corrective lenses in a trial frame where necessary. Participant responses were communicated via a button box (model CB6; Cambridge Research Systems).

Glass pattern stimuli were constructed as a circular 10° aperture containing 100 pairs of white dots (90 cd/m^2) centered on a gray achromatic background (45 cd/m^2). Pairs of 8 minute arc diameter dots were separated by 9 minutes of arc (between the dots within a dot pair) and arranged as "dipoles," in either a concentric (Fig. 1A) or radial (Fig. 1B) configuration. Dots that did not contribute to the signal pairs were placed at random within the pattern, to reduce the signal coherence. The overall dot density was 3.5%. The threshold measure was the percentage of dipoles in the signal orientation required for discrimination between the concentric or radial arrangements.

Radial frequency patterns were constructed to be consistent with those used in previous research.[33] A sinusoidal modulation was applied to the radius of a circular contour centered on a gray achromatic background (45 cd/m^2). The base circular contour had a radius of 0.5° and varied in cross-sectional luminance profile according to a D4 (fourth derivative of a Gaussian), with a peak spatial frequency of 4 c/deg. The radius of the circular contour was deformed through superimposition of a sinusoid (equation 1) with a radial frequency (ω) of either 3 (Fig. 1C) or 4 (Fig. 1D). The radial distance of the center of the image to the midpoint of the contour is given by

$$r(\theta) = r_0(1 + A\sin(\omega\theta + \varphi)) \qquad (1)$$

where $r(\theta)$ is the radius at polar angle θ, which is a function of the mean radius r_0, the radial modulation amplitude A, the radial frequency ω, and the angular phase φ.

The threshold parameter was the amplitude of the sinusoid (A) for discrimination between an RF3 or RF4 pattern. Low radial frequency patterns (few lobes) were chosen to ensure the requirement of global contour processing, because previous research shows that sensitivity to departures from circularity cannot be explained by local processes alone for low RF patterns.[25,34] Previous work shows that detection thresholds for RF3 and RF4 patterns from true circles are approximately equivalent.[33]

Contrast threshold for both types of stimulus was determined using a two-interval forced choice methodology with a three-down, one-up staircase without auditory feedback. Stimuli were presented for 200 ms. The staircase adjusted the stimulus contrast by 20% at each reversal, and terminated after six reversals, with the final threshold estimated as the average of the final four reversals. The contrast threshold was calculated from the mean of three staircase estimates. Stimuli for the subsequent experiments were then presented at 5-fold the measured contrast threshold to approximately balance low-level visibility of the stimuli between older and younger observers. A contrast multiplier of five was chosen to ensure that the stimuli were suprathreshold for all observers, but to avoid ceiling effects.

For both Glass patterns and RF patterns, shape discrimination was tested using a Method of Constant Stimuli (MOCS). A two-alternative forced choice stimulus paradigm was presented at seven MOCS levels: for Glass patterns, the level of coherence was varied and for RF patterns, the sinusoid modulation amplitude (A) was varied. MOCS levels were interleaved and presented 10 times at each level in any given run. A minimum of 4 runs were completed by each participant, resulting in psychometric functions with a minimum of 40 trials at each MOCS level.

Prior to formal data collection, all participants received training on each task until the examiner (author AEW) and the participant were confident that the task was being performed correctly. During the training phase for the Glass pattern task, participants were initially shown examples of the stimuli at higher coherence levels (similar to those in Fig. 1) presented for 1 second each and were instructed to decide for each presentation whether the stimulus looked more "circular like onion rings" or "radial like a bursting firework or bicycle spokes." Similarly, for the RF task, participants were shown 1-second-duration examples of significantly suprathreshold amplitude modulation stimuli (see Fig. 1) and asked to determine whether the stimuli appeared more like "rounded triangles" or "rounded squares." After this, a single run of each experiment was performed where the difficulty was increased, prior to formal data collection. MOCS levels were determined idiosyncratically for each observer and this practice run was used to approximate the appropriate range for testing.

Data Analysis and Modeling

Psychometric functions were modeled with a logistic function:

$$f(x) = 0.5 + 0.5 \Big/ \left[1 + \exp\left(\frac{a-x}{b}\right)\right] \qquad (2)$$

where a corresponds to threshold as represented by 75% correct response level and b is a measure of the spread of the function (inversely proportional to the slope). Model fitting was achieved using the Marquardt–Levenberg routine for analysis of data (GraphPad Prism v5; GraphPad Software, Inc., San Diego, CA).

Statistical analysis was performed using a commercial data analytical system (SPSS 17.0; SPSS Inc., Chicago, IL). A value of $P <$ 0.05 was considered statistically significant. Values of P are reported numerically throughout except for very small probabilities, where a criterion judgment of $P < 0.001$ was applied.

Results

Contrast Thresholds for the Detection of Glass and RF Patterns

Contrast thresholds for the Glass pattern and RF pattern stimuli were significantly elevated for older adults [Fig. 2, two-way repeated-measures ANOVA, $F_{(27,110)} = 23$, $P < 0.001$]. For both age groups, contrast thresholds were higher for Glass patterns than those for RF patterns [$F_{(1,110)} = 137$, $P < 0.001$]. There was also an interaction between stimulus pattern and age group whereby there was a greater difference between the age groups for the Glass than for the RF patterns [$F_{(27,110)} = 3.9$, $P < 0.001$].

Age Affects Glass Pattern and RF Pattern Contour Discrimination

Parameter extraction from modeling the psychometric functions (equation 2) is summarized in the Table and Figure 3. Older participants required a greater level of Glass pattern coherence to be able to discriminate between concentric and

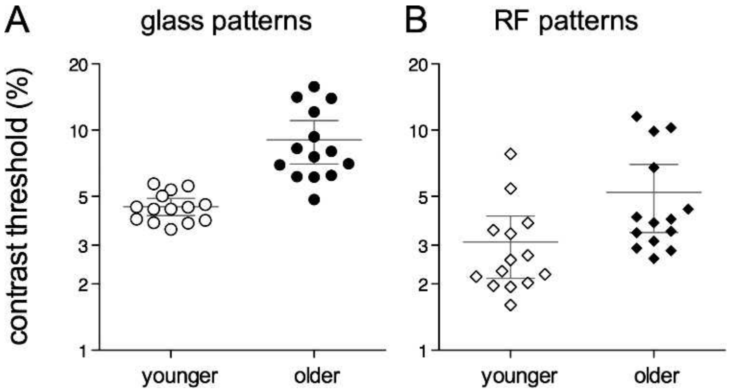

FIGURE 2. Stimulus contrast threshold of Glass patterns (**A**) and RF patterns (**B**) for younger (*open symbols*) and older (*closed symbols*) participants. Symbols represent individual participant measures; error bars indicate mean ± 95% confidence interval of the mean.

radial stimuli (Fig. 3A, parameter a, equation 2). Similarly, greater deformation of RF patterns (increased A, equation 1) was needed for discrimination between RF3 and RF4 stimuli (Fig. 3B, parameter a, equation 2) by older participants. The slopes of psychometric functions tended to be flatter for older participants (as indicated by elevated parameter b, equation 2; Figs. 3C, 3D), although this reached statistical significance only for the Glass pattern stimuli.

To compare whether contour discrimination was more difficult for older participants in either the Glass pattern or RF pattern stimuli, effect sizes (d, equation 3) for parameter a (Figs. 3A, 3B) were calculated:

$$d = \frac{\mu_O - \mu_Y}{(\sqrt{\sigma_O^2 - \sigma_Y^2})/2} \qquad (3)$$

In equation 3, effect size, d, is a function of the mean, μ, and standard deviation, σ, of parameter a (equation 2) for older (O) and younger (Y) participants. Effect sizes were calculated as 2.1 and 1.2, respectively, for Glass and RF patterns. We also calculated Z-scores for each older observer relative to younger adult group performance for each of the tasks. For both the Glass and RF tasks, the distributions of both older and younger adult group performance did not depart from that of a normal distribution (Kolmogorov–Smirnov tests, all $P > 0.05$); thus z-scores are a meaningful metric. For the older adults, z-scores were on average higher for the Glass task than for the RF task [paired $t(13) = 2.18$, $P < 0.05$], indicating that the difference between group means was greater for the Glass pattern task than that for the RF task.

Can the Results Be Explained by Reduced Low-Level Visual Quality in the Older Adults?

The data shown in Figure 3 were measured using stimuli that were presented at 5-fold each individual's contrast threshold. Although this procedure will approximately equate suprathreshold contrast detectability, depending on the slope of an individual's contrast detection response function, 5-fold threshold will result in slightly different suprathreshold conditions between observers. The multiplicative nature of the calculation assumes that those with higher thresholds have flatter psychometric function slopes that have been shown for other tasks such as luminance increment thresholds.[35] To explore whether the data are suggestive of the difference between groups being driven by stimulus contrast, we plotted shape-discrimination thresholds against physical contrast for each of the participant groups (Figs. 4A, 4B). Within each group, there was no significant correlation between stimulus contrast and shape-discrimination thresholds (all $P > 0.05$).

Figure 4C compares performance of the older adults across the two shape-discrimination tasks to observe whether the worst-performing observers were the same individuals. There was no correlation between the Z-scores (relative to younger adult performance) for Glass and RF tasks (Pearson correlation, $r = 0.2$, $P = 0.48$).

All participants included in this study were required to have good binocular VA; however, the older adults did have on average one-line poorer VA than that of the younger adults. The acuity inclusion criterion (6/7.5 binocularly) is equivalent to a resolution of 1.25 minutes of arc, substantially smaller than the 8 minutes of arc diameter of the individual dots within our dipoles; thus, the older observers should have easily resolved the individual dots. To ensure that performance for the Glass patterns was not precisely dependent on perfect optics and high-contrast stimuli, we tested three observers for the following conditions: (1) artificially reduced acuity (via spherical blur) to 6/7.5 (from their baseline of 6/4.8); (2) artificially reduced acuity to 6/24; (3) substantially reduced contrast stimuli of 2-fold contrast threshold. All other aspects of the experiments were the same as for the main experiments. Performance for these observers is shown in Figure 5, where it can be seen that small reductions of VA (to the level of our worst older observers) and substantial reductions in stimulus contrast, have no effect on performance.

TABLE. Psychometric Function Parameter Summary

	Younger (μ ± SD)	Older (μ ± SD)	Two-Tailed Unpaired Comparison	
Glass a (threshold, %)	16.2 ± 4.2	28.6 ± 7.0	$P < 0.001$	Mann–Whitney $U = 8$
Glass b (spread, %)	7.7 ± 2.1	12.2 ± 5.4	$P < 0.001$	Mann–Whitney $U = 40$
RF a (threshold, sec of arc)	18.4 ± 5.1	27.4 ± 9.5	$P < 0.01$	*$t = 3.14$, *$df = 20$
RF b (spread, sec of arc)	6.1 ± 3.5	8.9 ± 4.1	$P = 0.057$	$t = 1.99$, $df = 26$

* Welch-corrected.

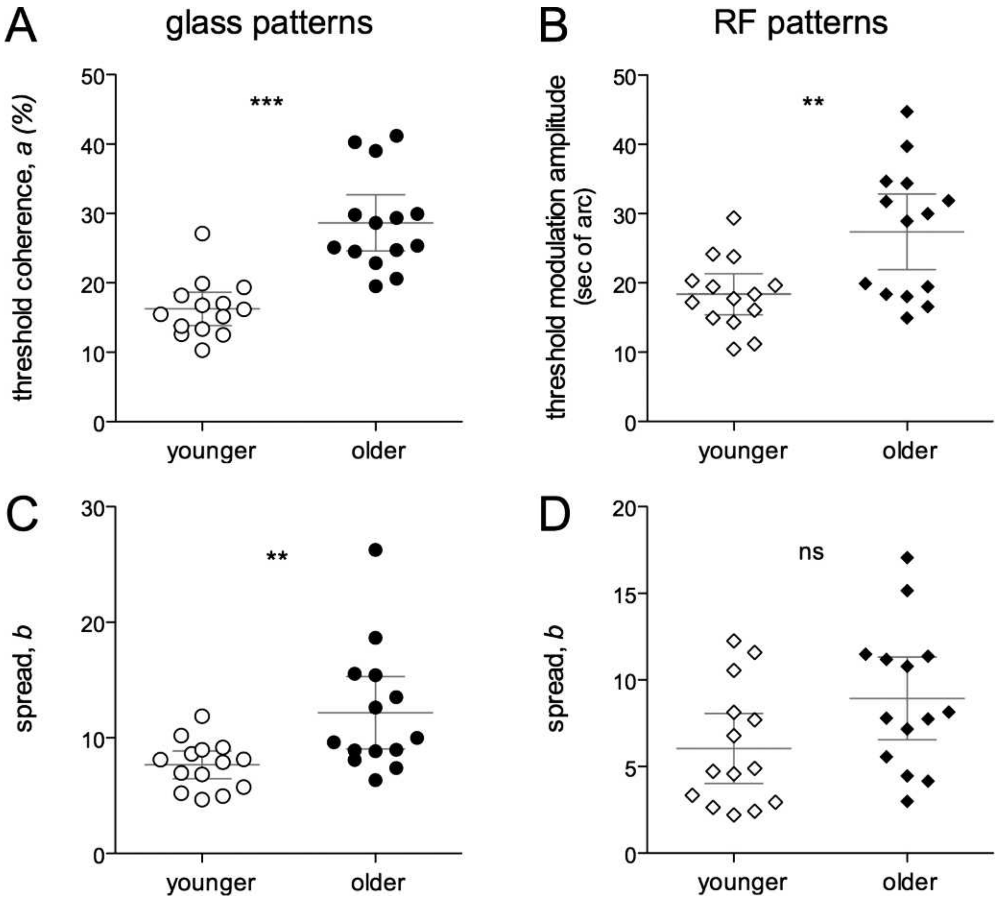

Figure 3. Data for individual participants and mean ± 95% confidence limits for parameters *a* and *b* (equation 2) for individual fits of Glass (**A**, **C**) and RF (**B**, **D**) pattern psychometric functions for younger (*open symbols*) and older (*closed symbols*) participants.

Equivalence of Sensitivity to Concentric and Radial Glass Stimuli

It has previously been reported that sensitivity to concentric Glass stimuli is higher than that for radial stimuli,[11] although equivalent sensitivity has also been reported.[29] Our shape-discrimination task required observers to discriminate between the two Glass types on each presentation, and thus is truly a discrimination task only if the sensitivity to the two choices within the forced choice procedure are approximately equally detectable. To explore this issue we retested six younger observers and eight older observers. The stimuli were the same as those used in the main experiments, although for these experiments the two-interval forced choice procedure involved the detection of the coherent pattern (either radial or concentric, measured in separate runs) from a noise pattern (same number of paired dipoles as the signal pattern, but oriented randomly). Thresholds were collected using a three-down, one-up staircase, where the number of signal dots

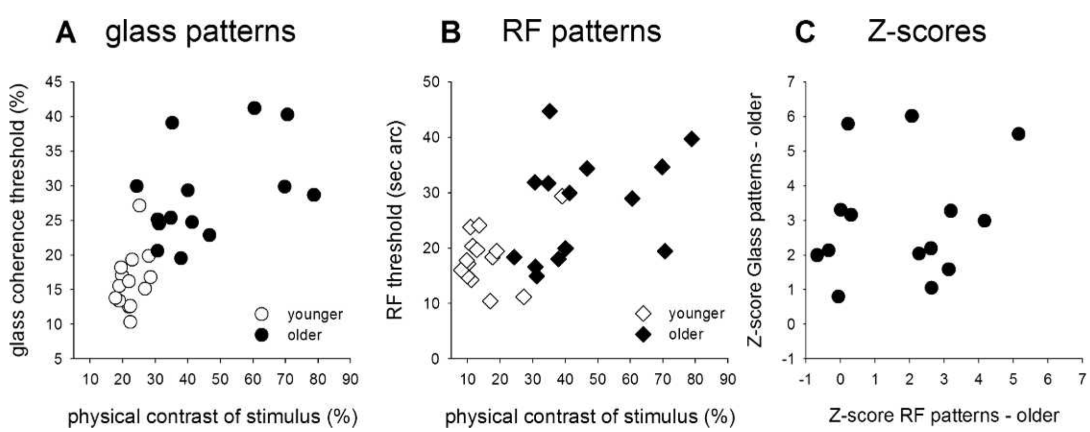

Figure 4. Performance of the individual observers on the tasks. (**A**, **B**) Plots of shape-discrimination thresholds against the physical contrast of the stimulus. (**C**) A comparison of older observer *Z*-scores (calculated relative to the younger adult group performance) for the two shape-discrimination tasks.

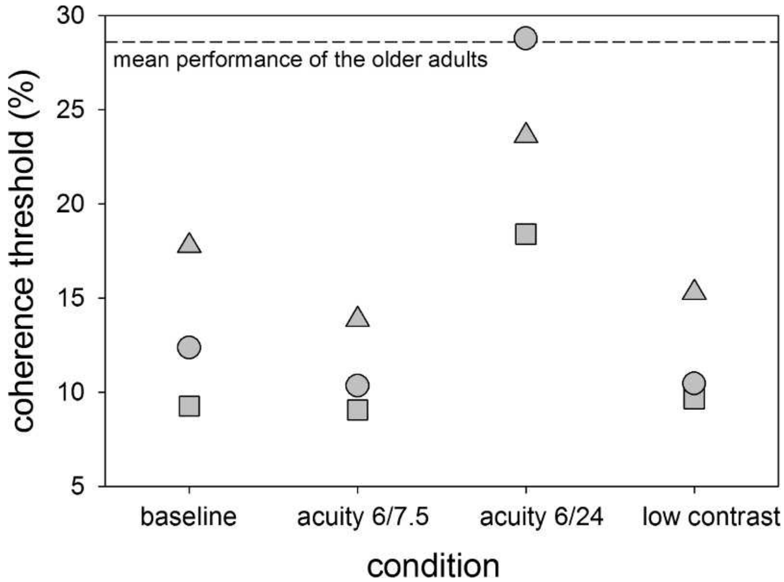

FIGURE 5. Performance of three observers (aged 24 [*circles*], 28 [*triangles*], and 41 [*squares*]) in the presence of artificially reduced binocular acuity (blur), and for low-contrast stimuli (2-fold contrast threshold). The *dotted line* indicates the mean performance of the older adult group from the main experiments.

decreased after three sequential correct responses and increased after each incorrect response. The staircase step size commenced at four dots, and was halved at each of the first two reversals to a final step size of one dot. Staircases terminated after six reversals, with the thresholds being the mean of the final four reversals. Two staircases were interleaved in each run, with the final threshold being the average of two runs (four staircases) for each condition (concentric and radial). Performance is presented in Figure 6, which shows the thresholds for radial and concentric stimuli for each observer. There was no significant difference in detection performance between the radial and concentric tasks [paired *t*-test, $t(13) = -0.49$, $P = 0.62$]. Importantly, the data are tightly clustered around the $y=x$ line, showing that performance within all individuals regardless of age was highly repeatable.

DISCUSSION

Older adults have elevated global shape-discrimination thresholds when compared with younger adults. Even when approximately matched for effective stimulus contrast, older participants perform significantly worse than younger adults on global form tasks, suggesting that the differences between groups are unlikely to result from differences in stimulus visibility.

We approximately matched the effective stimulus contrast between observers to account for the well-established differences in contrast sensitivity that arise with aging. Contrast sensitivity is reduced in older adults both due to poorer optics, but also due to neural changes.[36,37] A well-studied optical change due to aging is elevated scatter in the eye.[38] Although our methods will approximately account for the overall effect of that scatter on the stimulus-specific contrast sensitivity measure, it is worth noting that they do not necessarily result in equivalent stimulus conditions between age groups. Increased scatter will result in an extended point-spread function in the older adults, which may be particularly noticeable for individual dots within the Glass patterns. However, the centroids of the dots should remain true. Figure 5 illustrates that Glass pattern performance is quite robust to optical imperfection (in the case of blur) and reductions in stimulus contrast. Given that previous studies have shown that position coding is minimally altered by aging,[23,24] and that our stimuli were presented well above threshold contrast, we assume that the effect of scatter on individual dots within the Glass patterns was not the limiting factor for task performance.

Figure 4C shows no relationship between the performance of individuals across the RF and Glass pattern-discrimination tasks. A significant correlation would suggest that a common mechanism results in increased thresholds for the two tasks, although this was not the case. Such related mechanisms need not be within the visual system, but could be due to participants having difficulty with the demands of the psychophysical methodology, issues with attention, or other observer-related factors.

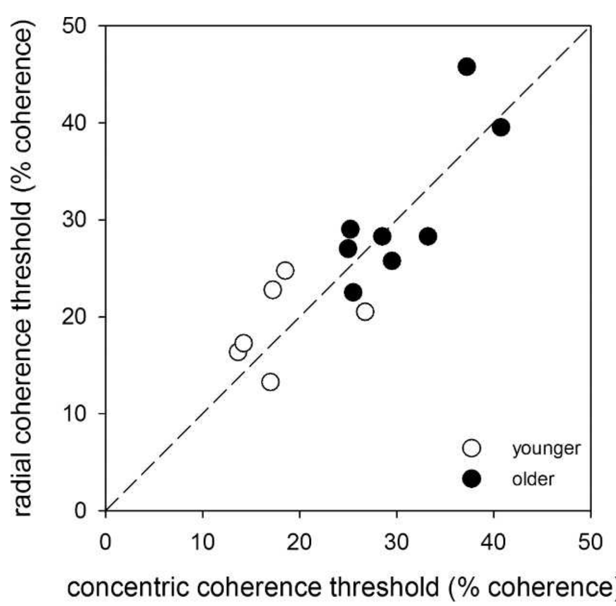

FIGURE 6. Comparison of detection thresholds for radial and concentric glass patterns (relative to noise patterns).

Our older group demonstrated a reduced ability to discriminate between RF3 and RF4 shapes compared with younger participants (Fig. 2B, Table). Two previous studies have investigated aging effects on shape discrimination using RF patterns[4,5] and concluded that RF discrimination is not significantly altered by age. There were some key stimulus differences between those studies and our methods. A main difference was that we measured the ability of observers to discriminate between an RF3 and an RF4 stimulus, rather than between an RF pattern and a circle. This was a deliberate choice because we sought to measure shape discrimination not detection. We specifically chose RF3 and RF4 patterns because low RF patterns (few lobes) engage global mechanisms rather than being encoded simply by the detection of localized orientation and position shifts due to the lobes.[25] We also kept the stimulus presentation time brief (200 ms) to preclude saccadic eye movements that might enable searching for local cues. The study reported by Wang[5] used significantly longer-duration stimuli that potentially allowed participants to search for local deformations of the contour. However, Habak et al.[4] found no difference between older and younger adults for the discrimination of an RF5 from a circle for stimulus durations of 40, 120, and 360 ms.

Older adults have greater difficulty extracting global shape information from texture than for contrast-defined closed shapes (RF patterns). A key difference between these tasks is the necessity to accurately match corresponding dipole pairings in the Glass task, while suppressing the contribution from spurious pairings. Primate neurophysiology of aged animals shows neural functional changes consistent with reductions in inhibitory function as well as increased spontaneous neural firing in older visual cortex and extrastriate areas.[39–42] It is possible that elevated neural noise might result in increased spurious pairings; thus, the requirement for a higher signal to noise ratio for shape discrimination. Several human studies of motion perception and orientation discrimination have found data that are consistent with models of either increased baseline noise and/or increased multiplicative noise (that is, scaled by the magnitude of the signal) with age.[21,43,44] Further studies specifically designed to estimate internal noise within the aging form perception system are required to clarify these potential contributions to impaired oriented texture discrimination.

This study demonstrates that the mechanisms involved in the interpretation of global shape tasks are altered as we age. Despite aging having minimal effects on orientation processing and position coding, the overall ability to discriminate global shapes is reduced. Consistent with previous studies, our data support the notion that aging more significantly impairs performance for tasks that require the extraction of shape signals embedded within noise. The mechanisms involved in extracting shape from texture are believed to be important to segmenting figure from ground, perceiving a three-dimensional shape,[45] and may contribute orientation information to assist with the disambiguation of motion perception.[15] The results of our study suggest that the intermediate-level processes that contribute to these higher-level tasks are altered by healthy normal aging.

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