Visual Form Perception from Age 20 through 80 Years

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Purpose. We measured performance on a battery of visual form perception tasks for adults sampled evenly from each decade of adult life from 20 to 80 years.

Methods. Measures were included that are considered to reflect processing at early through intermediate stages of the form processing pathways: collinear facilitation, center-surround contrast effects, global shape discrimination of contours of elements embedded in noise elements, and global shape discrimination in texture (Glass patterns). A total of 38 women and 20 men (mainly Caucasian, low refractive error) participated, aged between 20 and 82 years.

Results. With advancing age, contrast sensitivity decreased linearly ($B = 0.009$, $t(56) = 8.14$, $P < 0.001$), perceptual surround suppression of low contrast stimuli embedded in higher contrast surrounds increased ($B = -0.006$, $t(56) = -3.32$, $P < 0.01$), and coherence thresholds for detecting form in Glass patterns increased ($B = 0.14$, $t(56) = 2.53$, $P = 0.02$). Performance between tasks was not correlated.

Conclusions. Several aspects of form perception alter gradually throughout the adult lifespan, namely context-dependent perception of contrast, and the extraction of global shape from texture. Our results suggested age-dependent differences under natural viewing conditions that are not predictable by standard clinical measures of visual function, and point to changes in neural function that are ongoing throughout adult life. (*Invest Ophthalmol Vis Sci.* 2013;54:1730–1739) DOI: 10.1167/iovs.12-10974

Many changes to vision and visual processing occur across the normal adult lifespan. Some examples of well-studied visual functions altered by aging include spatial contrast sensitivity, dark adaptation, and aspects of temporal processing (for review see the study of Owsley[1]). Age-related decline in the optical quality of the eye is well understood and contributes to increasing visual disorder with age.[2,3] However, numerous studies have demonstrated that altered neural processing is required additionally to explain the level of deficit and characteristics of many age-related alterations to visual function.[4–6] While the mechanisms underpinning age-related human perceptual changes still are being uncovered, the visual neurophysiology of aged primates has revealed aberrant neural function in primary and extrastriate visual cortical areas.[7–9] Specifically, cellular selectivity to orientation and direction are decreased in older animals, while levels of spontaneous neural noise are elevated.[7–9]

In natural environments, the extraction of information about contours and borders is a key stage in object identification and discrimination. Object perception involves hierarchical processing, whereby firstly local information about position and orientation is encoded, followed by linking of local information into contours, then global integration of information across larger areas to determine shapes (for review see the study of Loffler[10]). Numerous recent studies have measured the effects of aging on visual tasks designed to assess the function of various features of the early through intermediate object perception pathway. Human perceptual studies show small changes to orientation discrimination[11] and intact orientation tuning[12,13] with advancing age. The ability to encode local position also is maintained largely in the elderly[14,15]; hence, the ability to encode local form features seems fairly robust to aging.

Once spatial linkages between local features are required for task performance, age-related differences become more apparent. Older adults demonstrate a reduced magnitude of collinear facilitation, whereby the benefit to the contrast detection of a single Gabor by the presence of spatially proximate local flankers is reduced.[16] Suppression effects on perceived contrast created by embedding localized stimuli in high contrast surrounds (the Chubb illusion[17]) are stronger in the elderly.[18,19] The ability to detect and discriminate contours comprised of local elements declines[20] and is more susceptible to the effects of surrounding clutter.[21–23] Age-related differences exist in the perception of shapes defined by texture,[24] and for higher levels of form processing, such as facial matching when faces are displayed from different viewpoints.[25]

Previous studies that have documented age-related changes to form perception generally have included two age groups: younger adults (usually below ages 35 to 40 years) and older adults (typically over the age of 60 years), and have conducted detailed experiments on a specific aspect of form perception (e.g., orientation discrimination,[12] center-surround suppression of perceived contrast,[18,19] contour integration,[22] shape discrimination[26]). Differing experimental designs among studies limit the ability to compare the relative magnitude of age-related change across the many different aspects of form perception. The presence or absence of related magnitudes of performance change between tasks potentially can provide insight into the existence of common or disparate mechanisms altering performance, and indeed underpinning task performance in normal vision. Understanding the relative rate of decline between measures also is useful for predicting the impact of age-related changes on daily vision tasks. The purpose of our study was to measure performance on a battery of visual form perception tasks with a sample of observers included for each decade of adult life from 20 to 80 years. By testing the same observers on all tasks and by including middle-aged adults, we aimed to determine whether age-related change to form perception is task-dependent and whether it differs in terms of age of onset or magnitude.

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Methods

Participants

Participants were recruited via advertisements in community newspapers and e-newsletters to University of Melbourne staff. All volunteers provided written informed consent before participating using a protocol approved by the Human Research Ethics Committee of the University of Melbourne that conformed to the requirements of the Declaration of Helsinki.

A total of 58 individuals participated in the study: 10 in each decade of age from 20 to 70 years, and eight aged 70 to 82 years. Of these, 10 were of Asian descent and the remainder were Caucasian. The sample size was determined by comparison with previous studies from our laboratory that have tested younger (aged approximately 20–40 years) and older (aged approximately 60–80 years) adults on related tasks. Table 1 shows a summary of these previous results, and the estimated sample sizes for a power of 0.80 and an alpha of $P < 0.05$.[16,18,24,27] With the exception of collinear facilitation, the required sample size was less than 20 people in each group (aged 20–40 years and age 60–80 years). We decided to use a sample of approximately 10 per decade for all tasks (resulting in 20 people in the younger and older age groups), given the a priori expectation of some relationship in performance across tasks when tested in the same individuals.

To be eligible to participate, participants were required to meet the following criteria in each eye measured separately: best-corrected visual acuity of better than 6/7.5, refractive error range between −5.0 diopters (D) and +5 D sphere with no more than 2.00 D of astigmatism; intraocular pressures of less than 22 mm Hg as measured by applanation tonometry; and normal anterior eye, optic nerve head, and macula appearance for age as determined via clinical examination by an experienced clinician. Previous cataract surgery was not an exclusion criterion. Age-related cortical and nuclear lens changes were required to be no greater than Grade 2 (Lens Opacities Classification System III[28]). No participants had posterior subcapsular cataract. Participants were excluded if they had any systemic conditions or were taking systemic medications that are known to impact upon ocular health, visual processing or visual pathways. The most common causes of exclusion were diabetes, and neuroactive medications including those for mental health.

Compliance with the inclusion criteria was determined by a clinical eye examination that was conducted by an experienced practitioner as part of the study protocol. Participants attended for a single test session that was approximately two hours in duration and were reimbursed $AUD20 to defray travel expenses incurred in attending.

Equipment

Stimuli were presented on a gamma-corrected Flatron Plus (795FT) monitor (Frame rate of 100 Hertz, 1024 × 768 pixels, 32.5 × 24 cm, maximum luminance of 100 cd/m^2; LG Electronics, Seoul, Korea). Custom software was written in MatLab R2008a (Mathworks, Natick, MA) to produce the stimuli using a ViSaGe system (Cambridge Research Systems, Ltd., Kent, UK) connected to a desktop computer. Participants viewed the screen binocularly from a distance of 1 meter through appropriate individual refractive correction for the viewing distance. Individual refractive correction was determined via spherocylindric subjective refraction. Head position was stabilized by a chin and forehead rest. All stimuli were positioned centrally on the monitor and participants were instructed to maintain central fixation.

General Approach to Testing

To minimize any differences in nonvisual difficulty factors across tasks, all tasks were two-interval forced choice with 500 ms between each presentation interval. The same button box and response requirements were used for all tasks (left button to indicate interval 1, right button for interval 2). There was no auditory feedback for any task. For each experiment, the thresholding methods were chosen to enable ready quantitative comparison with the previous works shown in Table 1. Individual methods are described for each task below. All participants were made familiar with the requirements of each task and practiced with suprathreshold stimuli until the examiner was satisfied that the requirements of the task were understood. Participants were encouraged to take rest breaks as required. The order of the form perception tasks was quasi-randomized and balanced across age groups. Each task required between 3 and 5 minutes depending on participant responses.

Collinear Facilitation

The collinear facilitation task was based on that described by Polat and Sagi.[29] Contrast detection thresholds were measured for single Gabor elements with a spatial frequency of 3 c/deg presented foveally, and also in the presence of collinear (same orientation and phase) flanking Gabor elements (Fig. 1A). The luminance distribution of a single Gabor ($L[x,y \mid x_o,y_o]$) was determined by the following equation

$$L(x,y|x_0,y_0) = \cos\frac{2\pi}{\lambda}([x-x_0]\cos\theta + [y-y_0]\sin\theta)\exp\left(-\left(\frac{(x-x_0)^2+(y-y_0)^2}{\sigma^2}\right)\right)$$

where x is the position of the Gabor along the horizontal axis, y determined the vertical position vertical axis, (x_o,y_o) was the center of the patch, θ was the orientation of the Gabor in radians, λ was the wavelength, and σ was the standard deviation of the Gaussian envelope.[29]

The contrast of the flanking elements was 40%, and all three Gabors were aligned vertically with the center-to-center distance of the individual Gabors separated by a distance of 4λ. The presence of flankers either masks or facilitates the contrast detection of the central stimulus depending on the interstimulus distance.[29] A distance of 4λ was chosen as peak facilitation occurs at, on average, 4λ for the 3 c/deg stimulus used herein.[16] The original work of Polat and Sagi suggested a critical distance of 3λ for peak facilitation of a 13 c/deg stimulus.[29] Subsequent data have shown that the critical inter-element distance for maximal facilitation increases with decreasing spatial frequency.[30]

In each interval, two small (0.86° visual angle) horizontal white lines (95 cd/m^2) were positioned laterally (offset by 2° from the center of the screen) to assist in directing fixation to the center of the monitor. For the baseline condition (measuring contrast thresholds in the absence of flanking elements), on each trial, one interval (chosen at random) presented the central Gabor patch on a background of uniform mean luminance, whereas the other interval showed the uniform background only. For the flanker condition, each interval presented the flankers, but only one interval also contained the central patch. Intervals of 90 ms in duration were separated by a 500 ms interstimulus interval and were marked with a brief auditory tone. Observers were required to determine the interval where the central patch was present, and indicated their judgment via a button press.

Thresholds were determined using dual interleaved staircases of four reversals. Three sequential correct responses within a single staircase resulted in a 20% decrease in contrast, whereas each incorrect response resulted in a 20% increase. The three-down, 1-up strategy resulted in an estimate of threshold that was approximately the 79% probability of seeing.[31] The result of each staircase was determined as the average of the last two reversals. The procedure was repeated twice (a total of 4 staircases were completed), with the final estimate of threshold being the average of all four staircase results.

Center-Surround Perceived Contrast Suppression

The perceived contrast of a patch of grating depends upon the context in which it is presented. For example, relative to when presented on a uniform background, gratings surrounded by a high contrast annulus of the same orientation and spatial frequency appeared typically to be of lower perceived contrast.[17,32] Our specific center-surround perceived

Table 1. Summary Data from Previous Studies that Have Used Variants of Similar Form Perception Tasks

	Younger Adult, Mean ± SD	Older Adult, Mean ± SD	Previous Study Sample Size	Sample Size for Power = 0.80, $P < 0.05$, 2-Tailed Test
Contrast sensitivity,[16] %, 3 c/deg Gabor	1.45 ± 0.61	2.84 ± 1.29	20 younger, 15 older	9
Collinear facilitation,[16] log threshold elevation	−0.19 ± 0.16	−0.08 ± 0.16	20 younger, 15 older	35
Center-surround perceived contrast,[18] suppression ratio	0.81 ± 0.08	0.70 ± 0.07	18 younger, 17 older	9
Global contour discrimination,[27] *n* elements	11.5 ± 1.1	12.78 ± 1.4	15 younger, 17 older	16
Global contour discrimination,[27] shape aspect ratio	1.11 ± 0.05	1.17 ± 0.07	15 younger, 17 older	17
Glass pattern coherence,[24] %	16.3 ± 4.2	28.6 ± 7.0	14 younger, 14 older	6

Data are from previous studies of the authors as the full datasets were available.

contrast stimulus was similar to that we have described previously.[19,33] The central grating patch was a 40% contrast sinusoid of 4 c/deg and had a radius of 0.67°. The 4° radius annular surround also was a 4 c/deg vertical sinusoid but of 95% contrast.

A two-interval forced choice (2IFC) procedure was used to determine a perceived contrast match. In one interval (chosen at random) the 40% contrast central patch was presented within an annular surround (Fig. 1B). The other interval contained a test patch of variable contrast, where the contrast was modulated via a 1-up, 1-down staircase. Observers were asked to indicate, via a button press, which of the intervals contained the higher contrast central patch. Each "higher" response reduced the contrast of the test patch by 20% and each "lower" response increased it by the same amount. Each experimental run contained two interleaved staircases, each of six reversals. The final four reversals of each staircase were averaged to provide an estimate of the contrast at which the patches were equivalent perceptually. The procedure was run twice, with the final matching estimate determined as the average of 4 staircases. Thresholds also were determined for the case where a central patch alone appeared in both intervals (the no-surround condition).

Global Contour Discrimination

Our methods were similar to those described by Levi et al,[34] which were used to explore contour integration in amblyopia. Stimuli were comprised of Gabor patches aligned to form circular or elliptical global contours (Fig. 1C). Each individual Gabor had a spatial frequency of 1.5 c/deg, with an envelope SD of 0.33° and a contrast of 50%. Global

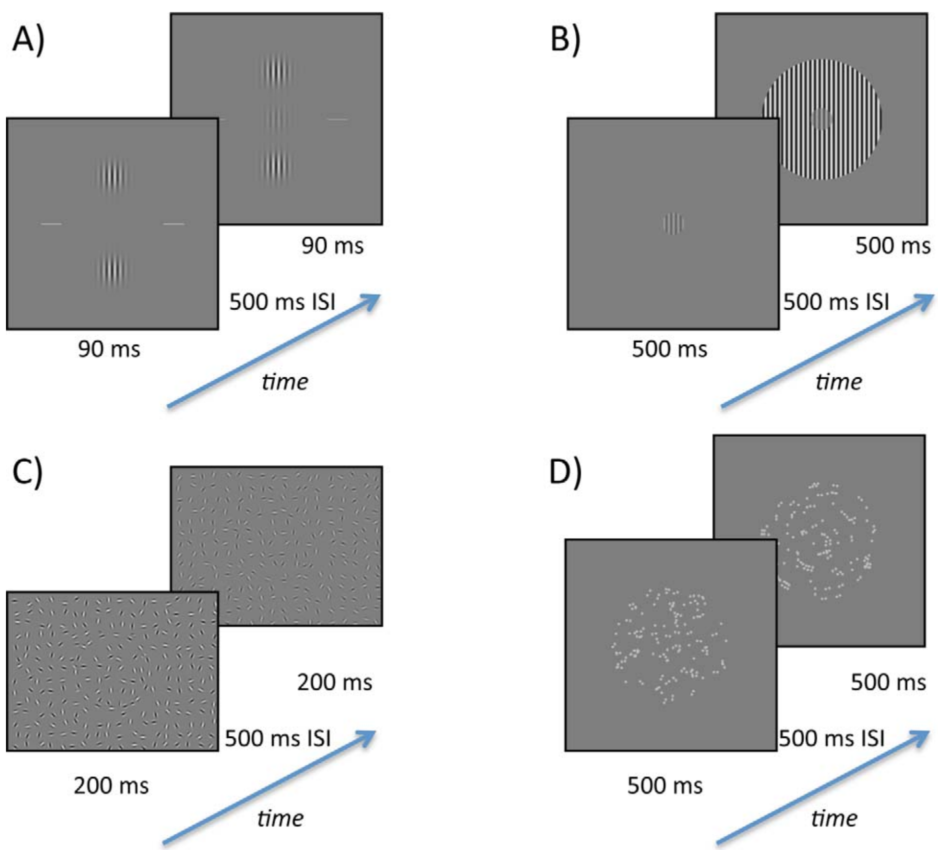

Figure 1. Schematics of stimuli used in the form perception tasks. Each task was presented in a two-interval forced choice paradigm. The order of the intervals (test or reference stimulus) was selected randomly on each presentation. (**A**) Collinear facilitation: the observer was required to choose the interval in which the central Gabor patch was present. (**B**) Surround suppression: the observer was required to choose the interval in which the central patch appeared higher in contrast. (**C**) Contour integration global shape task: the observer was required to choose the interval with the elliptical contour. (**D**) Glass pattern coherence: the observer was required to choose the interval that presented the coherent pattern (concentric).

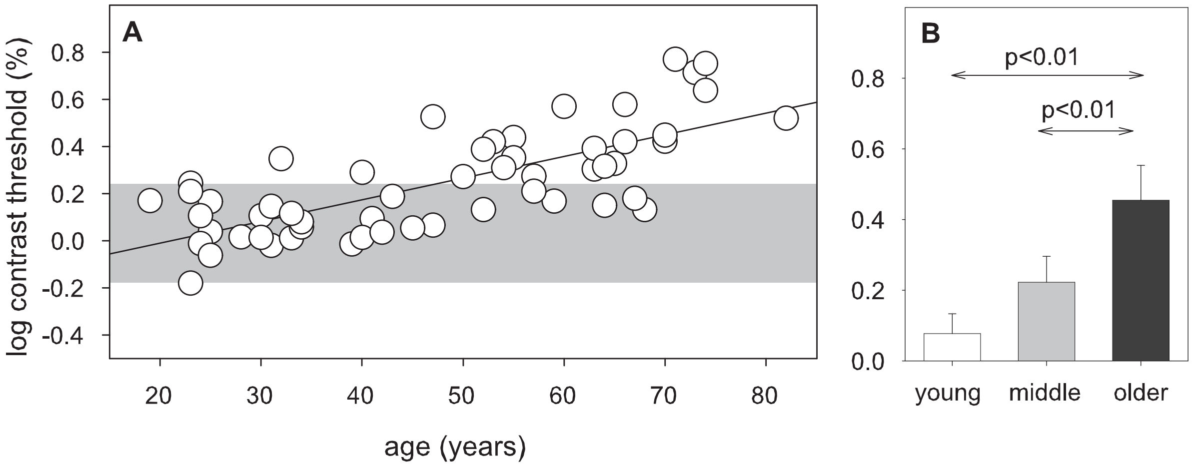

FIGURE 2. Log contrast detection thresholds for a single Gabor patch as (**A**) a function of age for each participant, and (**B**) for participants grouped in younger (aged 20–39), middle aged (aged 40–59), and older (aged 60–82) adults. The statistically significant *regression line* is shown in (**A**). The *shaded area* denotes the limits of performance for the youngest age group (aged less than 29 years). (**B**) Data are shown as mean + 95% confidence interval of the mean.

circular contours were 4° in radius. The positioning of elements for elliptical contours was such that all contours had approximately equivalent geometric area. Contour elements alternated in spatial phase (0° or 180°), and were surrounded by random noise elements (Gabors of the same characteristics but random orientation). The entire monitor area was divided into a grid of 14 × 10 squares (each approximately 1.25° × 1.25° of visual angle). Only one Gabor was allowed within each grid, to avoid density cues to the position of the contour. The center of the Gabor was jittered within ±0.5 grid square. All elements were computed for each presentation, resulting in varied random noise grids.

One interval of each 2IFC presentation pair contained a circular contour, and the other interval an ellipse of variable aspect ratio embedded in noise. The aspect ratio was defined as the ratio of the major and minor ellipse axes, hence an aspect ratio of 1 denotes a circle, whereas an aspect ratio of 1.2 would indicate a 20% difference between the major and minor axes. The observer's task was to choose the interval with the elliptical contour.

Two versions of the experiment were run: one in which the number of elements was fixed at 15 elements and the aspect ratio varied, and one in which the aspect ratio was fixed (three times each observer's individual threshold) and the number of elements was varied to measure the threshold number of elements required to discriminate the shape.

For the first variant, the aspect ratio of the ellipse was adjusted via a 3-down, 1-up staircase where the aspect ratio was altered by 20% increments at each staircase reversal. Each staircase terminated after four reversals with the final 2 reversals averaged to provide a single staircase estimate of aspect ratio threshold. Each run contained two interleaved staircases, with the final aspect ratio estimate being calculated as the average of four staircases (two experimental runs). For the second variant, the same staircase procedure was used; however, the staircase step-size was one element at each reversal.

Glass Pattern Coherence Thresholds

Thresholds were measured for the ability to discriminate a structured Glass pattern (concentric or radial) from a noise pattern. Glass patterns were constructed of dot pairs (dipoles) arranged according to a global rule.[35] The right hand panel of Figure 1D shows a concentric glass pattern. Dots were white (75 cd/m^2) and were presented on a grey background of mean luminance (50 cd/m^2). Each dot was 6 minutes of arc in diameter and was separated by 9 minutes of arc from its dipole pair. There were 100 dot pairs presented within a 5° diameter circular window. A variable proportion of the dot pairs (the signal dipoles) were arranged according to a global rule (either radial or concentric). The remaining dots from the total of 200 were uncoupled from their pair and placed as random noise dots. Within each two-interval presentation, one interval (chosen at random) contained a signal stimulus (500 ms) and the other interval a noise stimulus (500 ms). Noise stimuli were created with the same number of dipoles as the matching signal stimulus; however, the dipoles were placed at random orientations. As per the signal stimuli, the remaining dots were placed randomly within the patterns. Participants were required to indicate the interval with the coherent pattern.

Glass pattern coherence thresholds were defined as the threshold percentage of dipoles required to discriminate the coherent pattern from a noise pattern. Thresholds were determined by averaging two experimental runs of two interleaved 3 down–1 up staircases of four reversals each. The initial staircase step-size was eight signal dot pairs, which was reduced to four pairs at the first reversal and two pairs for subsequent reversals. The threshold estimate from each staircase was calculated as the average of the last two reversals, with the final threshold estimate for an individual being taken as the average of all four staircase estimates. Thresholds were measured separately for concentric and radial Glass stimuli.

Data Analysis

Statistical analysis was performed using SPSS 20.0.0 (IBM Corp., Armonk, NY). Since most previous literature investigating form perception in the elderly has compared group mean performance in younger and older adults, for some of the analyses we binned the data into three age groups: younger (20–39 years), middle (40–59 years), and older (60–82 years) to aid in comparison with previous work. Between-group comparisons then were performed using ANOVA. Linear regression also was used to determine whether age was a significant predictor of performance for each task. Age-related change in performance was compared between tasks by converting individual performance for those 30+ years into a z score relative to performance of those aged in their 20's. A P value of less than 0.05 was set as the criterion for statistical significance.

RESULTS

Contrast Detection Thresholds

Figure 2 shows contrast detection thresholds (log contrast) for the 3 c/deg centrally fixated Gabor presented in the absence of

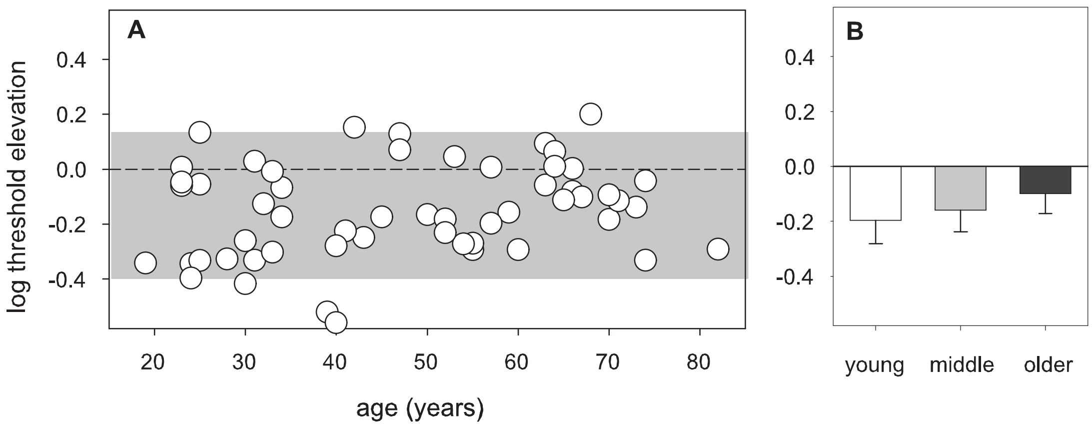

Figure 3. Collinear facilitation (log threshold elevation ratio: negative numbers are facilitation, positive are masking). Figure 3 is formatted like Figure 2. *The horizontal dashed line at zero* indicates no effect of flankers, that is, no facilitation or masking effect.

flankers. Contrast detection thresholds for the older adult group were elevated relative to the younger and middle aged groups (ANOVA, main effect of group $F(2, 56) = 26.55$, $P < 0.001$; post hoc Tukey $P < 0.05$ for older compared to younger, and older compared to middle-aged). Age significantly predicted contrast thresholds ($B = 0.009$, $t(56) = 8.14$, $P < 0.001$), and explained a significant proportion of variance in the contrast threshold measures ($R^2 = 0.54$, $F(1, 56) = 60.26$, $P < 0.001$).

Collinear Facilitation

Figure 3 shows the log threshold elevation ratio for each participant (Fig. 3A) and for participants grouped by age (Fig. 3B). Log threshold elevation *(E)* was determined as $E = log(T_f/T_{nf})$, where T_f indicates the contrast detection threshold for the flanked condition, while T_{nf} represents the non-flanked threshold. This measure allows direct quantitative comparison with previous work.[16]

Negative values indicated facilitation, whereas positive values denoted masking. On average, facilitation was present for each age group (Fig. 3B). There was a trend for less facilitation as participants became older consistent with previous work[16]; however, this did not reach statistical significance (ANOVA, no significant main effect of group, $P = 0.06$). If it is assumed based on previous findings that older adults should have less rather than more facilitation (i.e., that a one-tailed analysis is appropriate), the older adult group mean facilitation is statistically significantly less than that of the young adult group (one-tailed *t*-test, $P = 0.03$). Regression results were nonsignificant.

Center-Surround Perceived Contrast Suppression

Figure 4 shows the suppression ratio (contrast match for the surround condition divided by that measured in the absence of the surround) in the same format as Figures 2 and 3. Ratios of value less than 1 indicate that the perceived contrast was reduced in the presence of the annulus (suppression). The suppressive effect of the annulus on perceived contrast was significantly greater for the older adult group than either the younger or middle-aged groups (ANOVA, main effect of group $F(2, 56) = 6.23$, $P = 0.01$; post hoc Tukey $P < 0.05$ for older compared to younger, and older compared to middle aged). Age significantly predicted the suppression ratio ($B = -0.006$, $t(56) = -3.32$, $P < 0.01$), and explained a significant proportion of variance in the ratio measures ($R^2 = 0.17$, $F(1, 56) = 11$, $P < 0.01$).

Global Contour Integration

Figure 5 shows the aspect ratio thresholds for the global contour integration task in the same format as the preceding figures. There was a trend for older adults to require larger aspect ratios, but this did not quite reach statistical significance: $F(2, 56) = 3.05$, $P = 0.05$. Aspect ratio thresholds were not predicted by age (linear regression, $P > 0.05$); however,

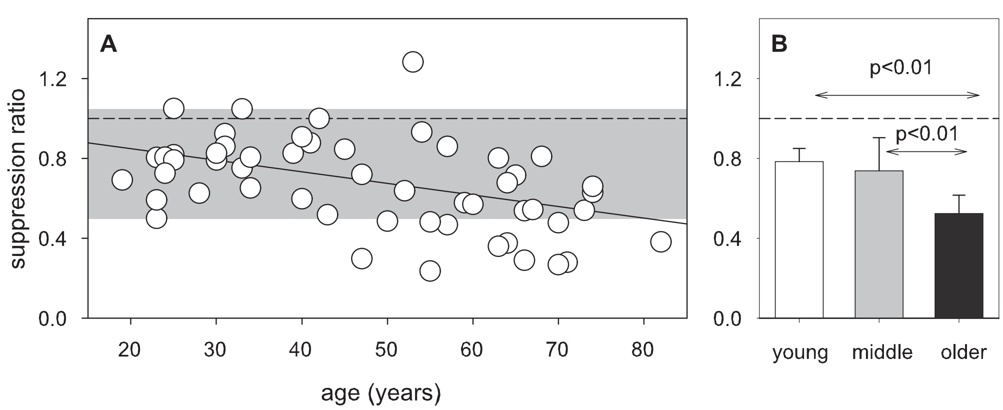

Figure 4. Center-surround contrast discrimination suppression ratio. Figure 4 format is similar to Figure 2. The *horizontal dashed line* indicates a suppression ratio of 1, indicating that the surround had no effect on the perceived contrast of the stimulus. A value less than 1 indicates suppression, whereas a value greater than 1 indicates facilitation.

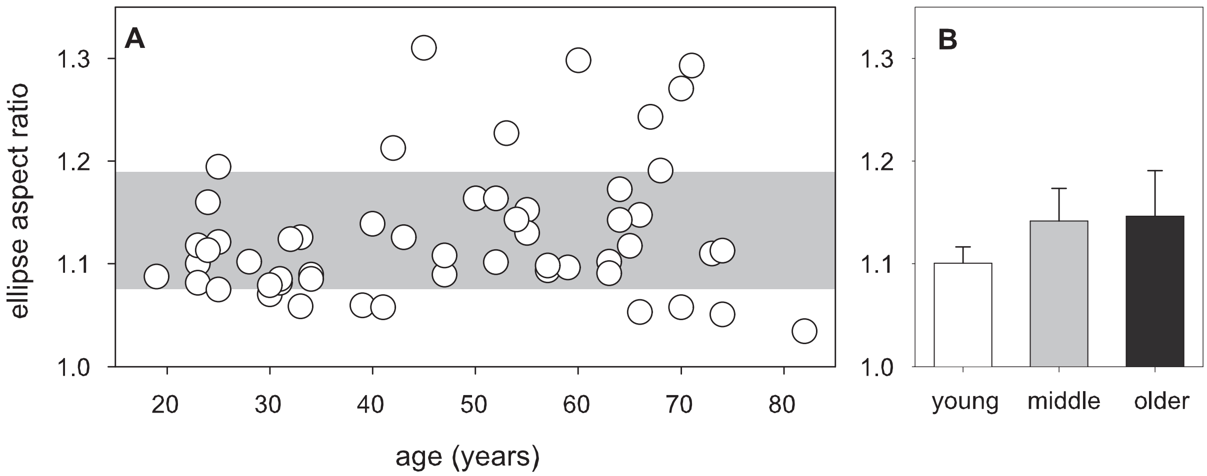

Figure 5. Global contour integration aspect ratio thresholds for discriminating between a circular contour and an elliptical contour embedded in noise elements. Figure 5 format is same as in Figure 2.

there were several individuals over the age of 40 with aspect ratio thresholds that were markedly outside the 95% confidence limit of younger adult performance (as denoted by the grey shaded region in Fig. 5). There was no difference in the number of elements required for contour discrimination between groups: $F(2, 56) = 1.58$, $P = 0.21$ (data not shown).

Glass Pattern Coherence

Figure 6 shows that glass pattern coherence thresholds were elevated in the older adults relative to the other groups (main effect of group $F(2, 56) = 3.77$, $P = 0.03$; Tukey post hoc comparison, older compared to younger $P < 0.05$). Data are shown for radial glass pattern performance; however, similar results were shown for the concentric glass pattern task ($F(2, 56) = 4.80$, $P = 0.012$; older versus younger $P < 0.05$). Coherence threshold was predicted by age ($B = 0.14$, $t(56) = 2.53$, $P = 0.02$), and explained a proportion of variance in the ratio measures ($R^2 = 0.09$, $F(1, 56) = 5.56$, $P = 0.02$).

Comparison of Performance across Tasks

Table 2 shows Pearson correlation coefficients between all tasks and the resulting *P* values. Those correlations with a *P* value of less than 0.05 are denoted with asterisks. The strongest correlation was between concentric and radial Glass pattern performance ($r = 0.70$, $P < 0.001$). This is to be expected, but confirms that individuals were able to perform consistently on similar tasks that obviously are assessing similar visual processes. The correlation between the two variants of the contour integration task (varying the number of elements to discriminate the elliptical contour, varying the aspect ratio to discriminate the shape of the elliptical contour) approached significance ($r = 0.24$, $P = 0.07$).

The analysis in the preceding section shows that contrast sensitivity, center-surround suppression, and Glass pattern coherence thresholds differed between the older and younger groups. Significant correlations should be expected between any tasks that are affected significantly by age, even if the age-related decline is caused by different age-affected mechanisms. Hence, we compared the rate of change with age between these tasks.

In Figure 7 we show the data for individuals aged over 30 years after conversion to a *z* score relative to performance of the 10 individuals aged 20 to 29 years. Data are shown only for those tasks that showed significant regression results for the raw data. As the raw units of measurement for the tasks are quite different, analyzing the *z* scores allows a comparison of the magnitude of age-related change in similar units (standard deviations of younger adult performance). When converted to

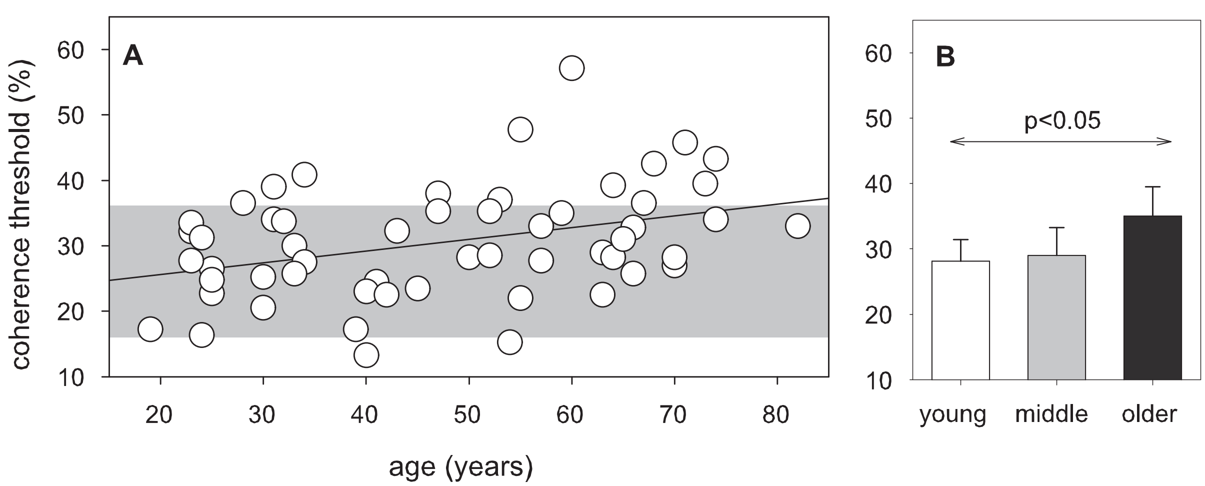

Figure 6. Coherence thresholds for the detection of radial structure within Glass patterns. Figure 6 format is same as in Figure 2.

Table 2. Pearson Correlation Coefficients Showing the Relationship of Performance across Tasks

	Contrast Threshold	Collinear Facilitation	Contour Element Number	Contour Shape	Glass Concentric	Glass Radial	Center-Surround Suppression
Contrast threshold		$r = 0.09$, $P = 0.46$	$R = 0.12$, $P = 0.36$	$r = -0.25$, $P = 0.85$	$r = 0.51$, $P < 0.001$*	$r = 0.40$, $P < 0.01$*	$r = -0.51$, $P < 0.01$*
Collinear facilitation			$R = 0.16$, $P = 0.23$	$r = 0.18$, $P = 0.17$	$r = 0.17$, $P = 0.21$	$r = 0.20$, $P = 0.14$	$r = -0.04$, $P = 0.80$
Contour element number				$r = 0.24$, $P = 0.07$	$r = -0.19$, $P = 0.17$	$r = -0.14$, $P = 0.32$	$r = 0.10$, $P = 0.48$
Contour shape					$r = 0.005$, $P = 0.97$	$r = 0.20$, $P = 0.14$	$r = 0.04$, $P = 0.78$
Glass concentric						$r = 0.70$, $P < 0.01$*	$r = 0.23$, $P = 0.10$
Glass radial							$r = -0.22$, $P = 0.11$

* $P < 0.05$.

z scores, task performance on all three tasks was predictable by age (see Table 3 for the regression results). Note that the sign of the slope is reversed for center-surround suppression ratio. Comparison of the unsigned rate of change with age shows that contrast threshold decline was steeper than that for the Glass pattern task (no overlap in the 95% confidence interval for the regression slope). When comparing to the center-surround task, there was a trend toward a steeper regression for the contrast sensitivity decline (marginal overlap in the 95% confidence intervals). Inspection and comparison of Figures 2 and 4 shows that many more older adults were outside the range of performance of younger adults for contrast sensitivity, than for the center-surround contrast task.

Because the unsigned rate of change was similar for the surround suppression task and the Glass pattern shape discrimination task, we performed a correlation analysis to determine the extent to which performance was related directly between individuals. The surround suppression Z-scores were not correlated significantly with either radial or concentric glass *z* scores (Pearson Product Moment correlations, $P > 0.05$).

Discussion

Our cross-sectional study aimed to explore the magnitude and rate of age-related performance changes throughout adulthood for a variety of early through intermediate form perception tasks. We chose tasks where the presumed underlying neural mechanisms are considered key building blocks underpinning our ability to perceive shape and form in natural visual environments. Our data confirmed that contrast sensitivity declines linearly with advancing age.[4,36,37] We included contrast sensitivity as a subcomponent of the collinear facilitation task; however, the main focus of the study was to determine aging effects on tasks that measure aspects of spatial interactions in early-intermediate form processing. Center-surround effects on perceived contrast and the ability to detect shape within Glass patterns showed the most significant age-related change of the form tasks included. In both cases, age-related change appeared linear across the adult lifespan. Task performance was not correlated between these two measures, providing indirect support for different underlying causes.

To our knowledge, this study is the first to perform a sequence of form perception tasks in individuals selected from each decade of life. Similar methods (two-interval forced choice) were used for all measures, minimizing the likelihood of performance differences between tasks arising due to age-related difficulties with procedural aspects of the task. The high correlation between separate measures of coherence thresholds for radial and concentric Glass patterns illustrates that individuals performed consistently on a given task.

Performances on the center-surround suppression task and the Glass pattern coherence task were correlated significantly with contrast sensitivity. This does not imply causality, as any two measures that vary linearly with aging will be correlated even if the mechanisms are entirely separate. We have shown previously that Glass pattern coherence thresholds are relatively robust to blur and reduced contrast provided that the centroid of the dots still can be determined.[24] For the center-surround task, it also has been shown that altering the stimulus contrast in younger observers to be approximately equivalent to the effective contrast an average older adult does not result in surround suppression consistent with the older adult data.[18,19] Furthermore, the absence of a significant correlation between the Glass coherence thresholds and center-surround suppression measures in our study provided additional support for the age-related changes not being

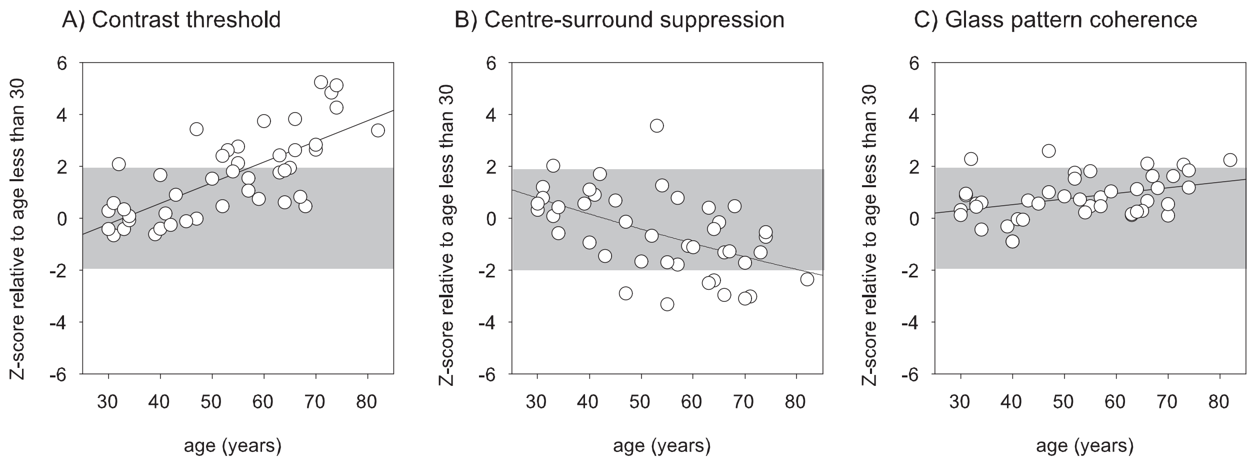

Figure 7. *z* Scores of all participants aged over 30 years, relative to the performance of those under age 30. The *shaded band* indicates ±1.96 Z-score, which are the parametric 95% confidence limits of the younger group.

entirely explicable by a common factor of reduced contrast sensitivity.

There are previous reports of differences in mean performance between younger (typically aged below 35 years) and older (typically aged above 60 years) groups for all the tasks included in our study (collinear facilitation,[16] center-surround suppression,[18,19] contour integration,[21–23,38] Glass pattern coherence thresholds[24]). In this dataset, the main effect of group approached significance for the collinear facilitation task and the contour integration tasks. In both cases, if a one-tailed statistical test is used (based on predicted direction of findings from these previous results) the difference between older and younger adults reaches conventional definitions of statistical significance ($P < 0.05$). A direct comparison with results from several previous studies is available by comparing our data to the means and SDs from previous studies shown in Table 1. Table 1 and the trends within our dataset suggested that with additional participants in each age group, a significant age-related change in performance is predicted for collinear facilitation and contour integration tasks. Establishing a difference between older and younger observers on those tasks was not the aim of our study, as such differences had been demonstrated previously. Rather, we were interested in comparing the relative effects of age across tasks in the same group of individuals. In the case of collinear facilitation, the previous study tested a range of interelement distances and, hence, was able to use a repeated measures ANOVA design that increased the statistical power significantly. We also have reported previously that older adults require more closely spaced elements for a global contour integration task similar to that reported here.[20] In our current study, variability between individuals increased beyond middle age but the mean thresholds did not differ between groups. In summary, the current data were not inconsistent with previous reports, but rather illustrated that age has a smaller and more variable effect on performance for these two tasks compared to aging effects on center-surround contrast perception, and global form extraction from texture.

Previous literature suggests that collinear facilitation mediates contour detection in contour integration tasks.[29,39,40] Models of collinear facilitation also include facilitory and suppressive effects depending on element factors, such as contrast and orientation, and may invoke mechanisms related to those involved in the suppression of perceived center-surround contrast.[29,39–41] Our previous work shows that aging results in increased masking and reduced facilitation of contrast thresholds measured in the presence of either closely or more widely spaced flankers, respectively.[16] We suggested that this finding was consistent with an increase in suppressive effects, consistent with reports of increased surround suppression in older adults,[18,19] but did not have data in the same participants to determine direct relationships. In our current data, collinear facilitation performance was not correlated with performance on either the global contour tasks, or the center-surround suppression measure. It is possible that the center-surround suppression measure would be related more closely to collinear masking at close interelement distances as the center and surround are immediately abutting. There are a number of other key stimulus differences, such as contrast and spatial extent. It is not clear how perceived contrast relates to contrast threshold measures. A thorough investigation of the relationship between collinear facilitation and the other measures requires different planned experiments.

Our study shows a gradual age-related increase in the strength of surround suppression of perceived contrast. Previous work has shown that surround suppression of perceived contrast is increased in older adults for textured[18] and drifting stimuli,[42] and cannot be explained readily by reduced contrast sensitivity.[18,19] Center-surround mechanisms are complex and occur at multiple stages of visual processing. Recent models of center-surround suppression in V1 involve inhibitory horizontal connections in V1 as well as excitatory feedback to inhibitory horizontal connections from extrastriate

Table 3. Linear Regression Statistics for the Data Shown in Figure 1

	B	*t*-Statistic	R^2	*F* Ratio
Contrast threshold *z* scores	0.076; 95% confidence interval, 0.061 to 0.10	7.38, $P < 0.001$	0.54	54.46, $P < 0.001$
Suppression ratio *z* scores	−0.047; 95% confidence interval, −0.069 to −0.02	3.60, $P = 0.001$	0.23	12.96, $P < 0.01$
Glass coherence *z* scores	0.016; 95% confidence interval, 0.001 to 0.03	2.22, $P = 0.03$	0.03	4.92, $P = 0.03$

B is the slope of the regression line. All *t*-tests were performed with 56 degrees of freedom; *F* ratio with degrees of freedom of 1, 56.

areas.[43–45] Surround suppression also is a feature of retinal ganglion cells and those of the lateral geniculate nucleus, with some features of cortical surround suppression being inherited from these earlier stages.[46] While there are reductions in the number of retinal ganglion cells with age,[47] more marked neural changes occur at a cortical level. Neurophysiologic study of aged primates has shown decreased stimulus selectivity and increased spontaneous firing of some neurons in primary visual cortex.[7–9] Furthermore, some broadly tuned cells in aged primate visual cortex have reduced suppression indices (measured from size-tuning curves of cellular responses to optimally oriented 80% contrast stimuli).[48] A possible perceptual analogue is the observation that older adult humans show decreased perceptual surround suppression for drifting stimuli of increasing size, and matched high contrast in the center and surround.[49] The task involves measuring the minimum stimulus duration required to discriminate correctly the stimulus motion direction. In general, it is more difficult to detect the direction of drift of a large, high, contrast stimulus than for a low contrast stimulus—an effect attributed to surround suppression.[50] However, this effect is reduced in older adults. In our task, however, the center and surround differed in contrast, and our data showed increased, rather than decreased perceptual effects of the center on the surround in the elderly. There is evidence for different mechanisms of surround suppression in striate cortex depending on whether the classic receptive field is driven by high or low contrast.[45] However, increased contrast surround-suppression in older adults also has been measured for stimuli where the central contrast was 70% and the surround 40% contrast; hence, the pattern of findings cannot be explained by alterations to low contrast mechanisms alone.[19]

Our inclusion criteria were deliberately strict, in an attempt to minimize the influence of age-related optical deterioration on performance. We required our participants to have acuity of better than 6/7.5 (minimum angle of resolution [MAR] of 1.26) in all age groups. For comparison, the population in the study of Owsley et al[36] that were aged in their 60s had an average visual acuity of 1.27 MAR, which is equivalent to our cut-off rather than mean acuity. Our data likely underestimated changes to form perception for older adults in the community where greater optical decline and systemic comorbidity are common.

In summary, key changes to early-intermediate form perception across the adult lifespan include increases in the strength of perceptual surround suppression for lower contrast stimuli embedded in higher contrast backgrounds, and decreases in the ability to extract shapes from noise in texture. Form perception tasks involving spatial linkages between elements at either threshold (collinear facilitation) or suprathreshold (contour integration) are relatively more robust to advancing age.

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