The Effect of Aging and Attention on Visual Crowding and Surround Suppression of Perceived Contrast Threshold

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PURPOSE. The purpose of this study was to study how, in midperipheral vision, aging affects visual processes that interfere with target detection (crowding and surround suppression) and to determine whether the performance on such tasks are related to visuospatial attention as measured by visual search.

METHODS. We investigated the effect of aging on crowding and suppression in detection of a target in peripheral vision, using different types of flanking stimuli. Both thresholds were also obtained while varying the position of the flanker (placed inside or outside of target, relative to fixation). Crowding thresholds were also estimated with spatial uncertainty (jitter). Additionally, we included a visual search task comprising Gabor stimuli to investigate whether performance is related to top-down attention. Twenty young adults (age, 18–32 years; mean age, 26.1 years; 10 males) and 19 older adults (age, 60–74 years; mean age, 70.3 years; 10 males) participated in the study.

RESULTS. Older adults showed more surround suppression than the young (F[1,37] = 4.21; P < 0.05), but crowding was unaffected by age. In the younger group, the position of the flanker influenced the strength of crowding, but not the strength of suppression (F[1,39] = 4.11; P < 0.05). Crowding was not affected by spatial jitter of the stimuli. Neither crowding nor surround suppression was predicted by attentional efficiency measured in the visual search task. There was also no significant correlation between crowding and surround suppression.

CONCLUSIONS. We show that aging does not affect visual crowding but does increase surround suppression of contrast, suggesting that crowding and surround suppression may be distinct visual phenomena. Furthermore, strengths of crowding and surround suppression did not correlate with each other nor could they be predicted by efficiency of visual search.

Keywords: crowding, surround suppression, aging, visual attention, vision, visual search

Healthy normal aging results in performance alterations for a number of spatial visual functions that involve lateral interactions. Some foveal phenomena that have been studied in this context include collinear facilitation,1 surround suppression,2 and contrast sensitivity.3–5 Parafoveal phenomena, namely contour integration,6,7 and surround suppression of contrast,8 have also been studied. Common optical aging effects such as lens discoloration, miosis, and reduced retinal illumination do not explain these perceptual changes,4,9,10 and the neurologic mechanisms behind these observations are only partially understood.

Spatial vision research in the healthy elderly has primarily studied foveal viewing. However, parafoveal vision takes on new importance in many older adults, especially after foveal damage due to conditions such as AMD. A key spatial visual phenomenon in the parafovea is visual crowding, which is typically described as reduced object recognition in a cluttered scene.11–13 Although many studies have shown age-related differences in spatial integration and suppression effects, the literature is less clear with respect to crowding. A study conducted by Scialfa et al.14 reported that older adults (n = 25; mean age, 70.3 years; SD, 7.6 years) had elevated acuity thresholds for resolving the gap of a Landolt C at 6° eccentricity relative to younger adults (n = 20; mean age, 20.6 years; SD, 1.9 years) in the presence of two flanking bars with the same luminance, size, and stroke width as the target in any given trial. However, the groups performed similarly once thresholds were expressed as a ratio of crowded threshold to uncrowded threshold.

Another recent study measured visual crowding at 10° eccentricity from fixation using letter recognition thresholds in 54 adults (aged between 18 and 76 years) and concluded that advancing age did not alter the magnitude of crowding.15 The authors argued that the fact that crowding is unaffected by aging provides support for mechanistic differences between surround suppression and crowding effects in peripheral vision, given that numerous previous studies have shown alterations to surround suppression of contrast in older adults. However, this hypothesis was not tested directly because surround suppression was not measured. Indeed, it is difficult to compare the literature on surround suppression and crowding directly in older adults due to marked differences in the experimental paradigms used between studies and the fact that most studies of surround suppression in the elderly have only assessed performance for centrally fixated stimuli. An exception is the recent study of Nguyen and McKendrick,8 who tested surround suppression at 6° and showed markedly different between-group effects than when measured with central fixation. In brief, older adults had stronger surround suppression for a suprathreshold contrast matching task.
performed foveally, yet reduced surround suppression in the parafovea, relative to younger adults.

Crowding and surround suppression share a number of features such as radial–tangential anisotropy16,17 and increased strength in the parafovea,18,19 which suggests some commonality of neural mechanisms. However, there are also several key features that are different. First, an asymmetrical effect of flanker position appears to be a unique property of crowding.20 Petrov et al.20 showed that, under crowded conditions, target identification was more difficult with an outer flanker (flanker position away from fixation) than an inner flanker (flanker position closer to fixation). This asymmetrical effect of flanker position was not seen with surround suppression. Petrov and Meleshkevich21 further demonstrated that the flanker asymmetry of crowding disappears with attentional manipulations to the target and suggested that crowding is governed by attentional input beyond the primary visual cortex. The inference is that crowding has an attentional component, whereas surround suppression does not.

The neural mechanism of crowding is not clearly understood despite decades of study. A number of models have been proposed.13,22 One explanation is that crowding is a result of the limitation of the spatial resolution of attention.23,24 In this model, stimulus features are taken into account and crowding occurs only when flankers share the defining dimension of the target (e.g., color or spatial frequency). Thus, when two or more items are within the smallest possible selected region of attention and share a defining feature, the individual item is not identified. Although little is known about crowding in healthy older adults, it is known that older adults take longer to spot a target among distractors than younger adults in visual search tasks.25 The extent to which poorer visual search performance may be directly related to altered visual crowding with healthy aging is not known. Although neural circuits of visual attention are incompletely understood, it is well recognized that peripheral vision guides our attentional shift.26 Understanding the role of attention is key to understanding peripheral visual functions. To our knowledge, ours is the first study to investigate the relationship of attention to crowding and suppression in an older group of observers. Given that attention is considered important mechanistically for both crowding and visual search, altered spatial visual attention in the elderly might result in alterations to both visual search capability and crowding.

The first aim of our study was to investigate the relationship between crowding and surround suppression in peripheral vision in older adults to determine whether there is a common link (e.g., related to processing of contrast) or whether these spatial visual processes are relatively independently altered with age. We used stimulus conditions for crowding and surround suppression that have previously differentiated features of these visual phenomena, specifically (1) flanker position20 and (2) spatial uncertainty as a method of modulating the visuo-spatial attentional demand of the task.21 It is widely accepted that aging impairs visual spatial attention.27 With a more distributed spatial attentional demand for the crowding task (by adding spatial jitter), we expected older adults to have greater difficulties to perform the task compared with younger adults. Our second aim was to determine whether the strength of either crowding or surround suppression in older adults correlates with performance on a classic visual search task. If surround suppression were to strongly predict slower visual search in the elderly, the results would point to lower level visual processing as a limiting factor for visual search in older adults, rather than top-down attentional control, because surround suppression is thought to be processed at lower levels of the visual pathways. Conversely, a strong relationship between crowding and visual search, in the absence of a link between surround suppression and visual search, would relate changes in crowding to deficits in top-down attentional issues (i.e., beyond early stages of the visual pathway), rather than early visual processing. Either relationship can shed light on which level of visual processing alters in senescent brain.

**Methods**

**Participants**

Participants were recruited via the University of Melbourne staff e-newsletter and newspaper advertisements, in addition to a database of previous laboratory participants. Participants signed a consent form, and the study was approved by the University of Melbourne Human Research Ethics Committee according to a protocol consistent with the Declaration of Helsinki. Twenty-one younger adults (age, 18–32 years; mean age, 26.1 years; 10 males) and 20 older adults (age, 60–74 years; mean age, 70.3 years; 10 males) participated. Subjective refraction was conducted to determine their refractive error, and only volunteers with refractive error of no more than 5 diopter (D) spherical and less than 2 D astigmatism and monocular best-corrected visual acuity better or equal to 6/9 were included. Ocular health was assessed using a slit-lamp bio-microscope and ophthalmoscope and was required to be normal for age. Participants underwent a 24-2 Swedish Interactive Thresholding Algorithm (SITA) standard visual field test (Humphrey Visual Field analyzer; Carl Zeiss Meditech, Dublin, CA, USA), and normal results across the central 24° of visual field were required for inclusion.

**Stimuli and Procedures**

Stimuli were presented on a λ-corrected CRT monitor (G520 Trinitron; Sony, Tokyo, Japan; used at frame rate of 100 Hz with a resolution of 1264 × 947 pixels). Custom software was written in Matlab 7 (Mathworks, Natick, MA, USA) interfaced with a ViSaGe system (Cambridge Research Systems, Ltd., Kent, UK). Responses were recorded via a button box (CB6; Cambridge Research Systems). Stimuli were viewed binocularly with position held steady using a head and chin rest at 100-cm viewing distance for tasks 1 and 4 and at 70 cm for tasks 2 and 3 (tasks are explained below). For tasks 1, 2, and 3, the stimulus duration was 150 ms, whereas in task 4 (visual search), each stimulus was present until the participant responded. Refractive error was corrected for viewing distance using a trial frame. Participants received approximately 5 minutes training before formal data collection to ensure that they understood the task. Regular breaks were given during testing to minimize fatigue. In total, testing required approximately 3 hours, which was completed across two visits. Everyone completed all tasks except one younger subject, who did not complete task 4.

For tasks 1, 2, and 3, two-alternative forced-choice (2AFC) procedures were used with no auditory feedback. Two interleaved 3-down, 1-up staircases with six reversals were used, and the average of the last four reversals was taken as the threshold estimate corresponding to approximately 79% probability of correct response.28 Task order was randomized between participants.

**Tasks 1 and 2: Crowding and Surround Suppression**

For these tasks, we used methods similar to those of Petrov et al.20 except that stimuli were presented at 8° eccentricity...
instead of 9° due to screen size limitations (Fig. 1A). In task 1 (crowding), the threshold spatial frequency to discriminate orientation was estimated for a single Gabor by varying the Gabor wavelength, \( \lambda \). The 45% contrast grating was oriented at 45° clockwise or counterclockwise from vertical. Participants were required to identify the orientation of the Gabor as clockwise or counterclockwise from vertical (2AFC). The Gabor \( \lambda \) was altered along with the flanker size and the target–flanker separation using an adaptive staircase procedure as described above. To assess crowding, the task was repeated in the presence of a flanker that was constructed of two orthogonal overlapping Gabors (approximately 90% contrast). Data were collected for both left and right visual fields in two separate blocks with the flanker closer (inner flanker) and away from (outer flanker) fixation (Fig. 1A). Thresholds for left and right visual fields were averaged, and the crowding ratio was calculated as the ratio of the flanked to unflanked threshold. A crowding ratio of 1 denotes no crowding.

In task 2 (surround suppression), target contrast was the variable, and \( \lambda \) was fixed at 0.67°. Contrast detection threshold was determined for the target Gabor alone and also in the presence of a larger surrounding flanker. Gabor orientation was vertical with its phase aligned with the flanker, which was a half annulus with 2\( \lambda \) inner radius and 8\( \lambda \) outer radius (Fig. 1B). Inner and outer flankers were tested in separate blocks. Participants chose whether the target Gabor appeared left or right of fixation (2AFC). The suppression ratio was calculated as the ratio of the flanked to the unflanked contrast detection threshold. A suppression ratio of 1 denotes no suppression.

**Task 3: Crowding With Spatial Uncertainty**

To determine the influence of manipulating the spatial attentional requirements of the crowding task, we utilized methods similar to those of Petrov and Meleshkevich, with the target Gabor and the flanker being similar to that of task 1.
(Fig. 1C). Stimuli were simultaneously presented at 8° left and right of fixation with the participant reporting the location where the target Gabor was oriented at 45°. The spatial frequency to discriminate the 45° from 135° orientation was determined by varying the stimulus scale. Inner and outer flanker positions were tested in different blocks. The same procedure was repeated adding 1° of horizontal jitter toward or away from the fixation (same direction in left and right stimuli at a given trial) to the stimuli to determine crowding with reduced spatial certainty. Stimuli were presented at 7°, 8°, or 9° on a trial-by-trial basis. The crowding ratio for the fixed stimuli (8° eccentricity) was calculated as the ratio of the flanked thresholds to unflanked thresholds, whereas for jittered stimuli (1° horizontal jitter), the crowding ratio was calculated as the ratio of flanked threshold of jittered stimuli to the unflanked threshold of fixed stimuli.

Task 4: Visual Search

Task 4 was a variant of the classical visual search paradigm, involving both conjunction and feature searches. In conjunction search, the target was defined by a conjunction of features (orientation and size) and in feature search just by a unique feature (orientation) (Fig. 1D). We again used Gabor stimuli in this task. The target was a small vertical Gabor (angular subtense = 0.46°; spatial frequency = 4 cycles/degree [c/deg]). For feature search, the distractors were horizontal Gabor of the same size as the target, whereas in conjunction search, in addition to the small Gabors, there were larger horizontal and vertical Gabors (angular subtense = 0.92°; spatial frequency = 2 c/deg). Observers were free to make eye movements and were asked to make a rapid judgement whether the target was present or absent. Set sizes of 16, 32, and 64 elements were tested 64 times in a pseudo-random sequence. Reaction times (ms) were measured separately for target present and absent conditions.

Data Analysis

Data were analyzed using SPSS 20.0. A Kolmogorov-Smirnov normality test and Mauchly’s sphericity test were used to determine normality and sphericity of data. Repeated-measures ANOVA was conducted to compare between-group effects for the various within-subjects factors detailed in the results section and for the between-subjects factor (older versus younger). A P value of 0.05 was considered as the criterion for statistical significance.

RESULTS

Crowding and Suppression Ratios

First, we compared the ability of the two groups to perform the discrimination and detection tasks in the absence of flankers. The discrimination (task 1) and detection (task 2) of the target stimuli are shown in Figures 1A and 1B, respectively. On average, there was no significant difference in discrimination thresholds between age groups (Mann-Whitney U test, P = 0.076; Fig. 2A), although the older group showed significantly higher contrast detection thresholds compared with the younger group (Mann-Whitney U test, P < 0.001; Fig. 2B).

To estimate the magnitude of crowding and surround suppression, the threshold ratio between masked to unmasked threshold for inner and outer positions was calculated separately for each individual. Two subjects (one younger and one older) showed suppression ratios greater than 4 SDs from the mean ratio and were excluded from analysis as outliers. The mean crowding ratio did not differ between groups (F[1.39] = 0.05, P = 0.82; Fig. 3A), whereas the mean suppression ratio was increased in the older group relative to the younger group (main effect of group: F[1.37] = 4.21, P < 0.05; Fig. 3B). The position of the flanker was important to the strength of crowding for the younger group with stronger crowding for the outer flanker position (flanker position × age group, F[1,39] = 4.11, P < 0.05; Fig. 3A). However, flanker position did not influence the suppression strength (flanker position × age group, F[1,37] = 0.57, P = 0.45; Fig. 3B).

Crowding With Spatial Uncertainty

We calculated crowding ratios for fixed and jittered stimulus conditions for both inner and outer flanker positions. Jitter condition (fixed versus jitter) and flanker position (inner versus outer) were within-subject factors and age group was the between-subjects factor. The crowding ratio of fixed and jittered stimuli are shown in Figures 4A and 4B, respectively. There was no significant main effect of spatial jitter (F[1,39] = 1.32, P = 0.26) or flanker position (F[1,39] = 1, P = 0.32). There was a trend for less crowding in the older group (F[1,39] = 3.15, P = 0.08). There was no significant interaction between group and spatial jitter (F[1,39] = 1.67, P = 0.2) nor for an interaction of group and flanker position (F[1,39] = 1, P = 0.32). In contrast to task 1, here we did not observe a significant flanker asymmetry in the younger group.

Visual Search

Individual mean reaction times (ms) were calculated for target present and absent conditions for each set-size (16, 32, and 64) (Fig. 5). All participants performed with accuracy better than 80%, and only correct responses were used in calculations. Target presence (present or absent) and set size (16, 32, and 64) were within-subject factors and age was the between-subjects factor. Mean reaction time difference between conjunction and feature searches was calculated, and it was greater in absent trials compared to present trials (F[1,38] = 48.4, P < 0.001) and increased with set size (F[1,2,3.57] = 39.5, P < 0.001). There was a significant two-way interaction between target presence and age group (F[1,38] = 7.4, P = 0.01) and target presence and set size (F[1,17.65] = 48, P < 0.001). The effect of set size × age group (F[1,2,44.7] = 3.7, P = 0.053) approached conventional statistical significance, indicating a trend for increasing reaction time with greater set size in the older group. These age-related differences are consistent...
with the literature, but our specific aim was to determine whether either crowding or suppression was correlated with performance on the visual search task.

Relationships Between Crowding, Surround Suppression, and Visual Search

For comparing performance in visual search with that in crowding and suppression tasks, reaction time difference between conjunction and feature search tasks for the highest (64) set size in the target present condition was taken as the measure. There was no significant correlation between visual search response time and crowding ratio (Spearman's $R = 0.01$, $P = 0.94$; Fig. 6A) or suppression ratio (Spearman's $R = 0.14$, $P = 0.39$; Fig. 6B) or between crowding and suppression ratios (Spearman's $R = 0.03$, $P = 0.85$; Fig. 6C), supporting the view that crowding and suppression are distinct phenomena.

DISCUSSION

Our main finding is that visual crowding is relatively less affected by healthy aging compared with surround suppression of contrast. This result is consistent with previous studies on crowding in peripheral vision using resolution acuity and surround suppression studies in central vision using contrast matching tasks; however, ours is the first direct measurement of crowding and suppression in the same older individuals and specifically using stimuli designed to allow such comparison across tasks. Our observed absence of a correlation between crowding and surround suppression is consistent with previous suggestions of distinct mechanisms underpinning these spatial visual phenomena.

Our data suggest that crowding strength is influenced by flanker position for the young adult group. Consistent with Petrov et al., only crowding shows this asymmetry and not surround suppression, although this effect was relatively weak.
in our data. Although their study reported a fivefold higher crowding ratio for the outer flanker compared with the inner flanker, we observed approximately only a two-fold change. Flanker asymmetry for crowding has also been previously observed by Bouma, who reported that in a word or an unpronounceable letter string, the outermost letter is more easily identified than an inner letter tested at parafoveally. A proposed explanation for the flanker asymmetry is the gradual change in cortical magnification in primary visual cortex (V1) with eccentricity. An outer flanker would be closer to the target in cortical space than the inner flanker influencing target identification, although these distances in visual space are identical. Petrov and Meleshkevich identified the flanker asymmetry property as a characteristic that can be used to assist in disentangling the neural mechanism of crowding. They showed that the asymmetrical flanker effect can be eliminated by manipulating spatial attentional demands and interpreted this observation as evidence for an attentional mechanism contributing to the asymmetry effect. Our data (Fig. 4B) demonstrate an absence of flanker asymmetry for the jittered stimuli, but we did not observe a strong flanker asymmetry effect for the non-jittered condition either. Indeed, we observed the asymmetry effect only in younger adults when there was no spatial uncertainty (Fig. 3). Petrov and Meleshkevich argued that their observed flanker effect was too strong to be simply due to a V1 cortical magnification effect and instead argued for a role of top-down attention on crowding strength, as suggested by a few other studies. Although not directly supportive, our data are not inconsistent with an attentional argument. We identified asymmetry in younger adults for the condition where there was no spatial uncertainty about the position of the target (task 1), and older adults may not manifest such effects if the relevant aspects of attention that influence crowding are altered by the aging process.

We included in our study a visual search task. Previous visual search experiments have used a range of stimulus types: for example, rectangular shapes, circles and squares, and letters T and L. We used Gabor stimuli in our experiment to maintain similar low-level image content between all our tasks. Similar to previous literature, we found a trend for the older group to require longer search times with increase in set size than the younger group (P = 0.053). Furthermore, older adults were significantly slower in target absent trials than in target present trials. We included visual search as it is a well-studied task that is understood to provide a measurable metric for visuo-spatial attention. If crowding magnitude is strongly influenced by top-down attention, then crowding strength may correlate with visual search performance. Alternately, a more bottom-up interpretation is that crowding and surround suppression may influence the saliency of the visual features in a visual search task, which would also predict correlated performance between visual search and crowding (and/or suppression) tasks. However, our data did not reveal such a relationship. Our data do not rule out a relationship between attentional change in older adults and some aspect of crowding performance (e.g., the absence of a flanker asymmetry) because an alternate attentional resource than assessed in the visual search task can still be relevant. We also found no relationship between crowding and suppression ratios, which further suggests that these visual phenomena have distinct mechanisms. The absence of a correlation between these tasks also makes it unlikely that our observed age-related differences to surround suppression are mediated by some other nonvisual factors.
factor (such as difficulty with task complexity), which would be expected to affect each task similarly.

In general, surround suppression of contrast detection in the fovea is weak and increases with eccentricity. On the other hand, surround suppression of suprathreshold perceived contrast is strong foveally, provided that the center and surround stimulus areas have similar orientation and spatial frequencies and are also robustly measurable psychophysically in the parafovea. Here we show an increased strength of surround suppression of contrast detection in the parafovea in older adults. Interestingly, it has recently been shown that surround suppression of suprathreshold perceived contrast is weaker in older adults in the parafovea, whereas previous studies of foveal suprathreshold contrast matching have shown stronger surround suppression of perceived contrast in older adults. Perceived contrast is thought to depend on the mean level of responses, whereas detection depends on the signal-to-noise ratio of neural responses. Numerous other studies have explored alternate measures of surround suppressive effects with differing results. For example, Bett et al. measured motion discrimination thresholds in young and older adults and showed that older adults require a briefer stimulus duration for high large high contrast stimuli compared with younger adults. Similarly, center-surround contextual effects such as the tilt illusion are also altered in older adults. The majority of these studies were performed with central fixation rather than in the parafovea as here. The parameter space for exploring these types of perceptual phenomena is very large, and the mechanisms of some effects are more established from a neurophysiologic perspective than others. Although the neurobiological basis for the perceptual changes that arise from healthy normal aging is still being understood, a clear pattern emerges from the literature that contextual perceptual phenomena are altered by the aging process.

In conclusion, our experiments demonstrate that surround suppression of contrast detection is increased in older adults compared with younger adults, whereas visual crowding remains relatively unchanged in parafoveal vision. The attentional aspects we measured did not correlate with crowding or surround suppression, but our experimental findings do not rule out a role for attention in the magnitude of crowding. Our findings suggest that crowding and surround suppression of contrast are distinct processes. Both are likely to be relevant to remediation strategies using parafoveal vision in older individuals with macular disease. Age-related changes to surround suppression may be important to be considered in the context of predicting outcomes and possible training paradigms.

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References


