Aging and Visual Crowding

Charles T. Scialfa, Sheila Cordazzo, Katherine Bubric, and John Lyon

Department of Psychology, University of Calgary, Calgary, Alberta T2N 1N4, Canada.

Objectives. The ability to perceive high spatial frequencies (i.e., fine detail) is impaired when contours are placed near the detail to be resolved (Bouma, H. [1970]. Interaction effects in parafoveal letter recognition. Nature, 226, 177–178. doi:10.1038/226177ab; Flom, M. C., Weymouth, F. W., & Kahneman, D. [1965]. Visual resolution and contour interaction. Journal of the Optical Society of America A, 53, 1026–1032. doi:10.1364/JOSA.53.001026.). This visual crowding is more pronounced outside of central vision and may be more pronounced in older adults. Thus, the motivation for the present study.

Method. Younger (M = 20.95 years) and older adults (M = 70.32 years) detected gap orientation in a Landolt C presented at 3° or 6° either alone or flanked by bars of the same spatial scale.

Results. Both age groups demonstrated a visual crowding effect, in that acuity deteriorated in the flanking condition, an effect that grew with eccentricity. Older adults exhibited a larger crowding effect, particularly at 6°. Younger adults tested at reduced illumination did not show the crowding effect of older adults. Thus, age differences do not appear to result from reduced retinal illumination. When the crowding effect was operationalized as the ratio of crowded to uncrowded acuity, age differences were eliminated at both 3° and 6°.

Discussion. These data have implications for understanding age differences in functional vision, including reading and visual search.

Key Words: Age differences—Visual crowding—Visual acuity—Peripheral acuity.

The human visual system possesses a remarkable capacity to extract information about the features of an object such as its contrast, orientation, and critical details in form. Yet, sensitivity assessed for isolated objects often does not generalize to more naturalistic viewing conditions. One example of this lack of correspondence is found in a class of phenomena known collectively as visual crowding. Visual crowding refers to the observation that various indices of performance (e.g., acuity, contrast sensitivity, and orientation tuning) deteriorate when the feature to be discerned is in close proximity to other contours (Bouma, 1970; Jacobs, 1979; Loomis, 1978). Older adults often demonstrate a disproportionate loss in measures such as perceptual span (Rayner, Castelhano, & Yang, 2009) and visual search (Scialfa & Joffe, 1997) that are influenced by crowding (Pelli et al., 2007; Polder & Wagemans, 2007) and so, in the present study, we examined age differences in crowding effects in a spatial resolution task.

An early demonstration of visual crowding was reported by Flom, Weymouth, and Kahneman (1963), who showed that visual acuity in the fovea was sharply reduced when the “target” was flanked by high-contrast bars and that beyond some separation, predicted by uncrowded acuity, flankers had no effect on resolution. Extending this work, Bouma (1970) presented letters at retinal locations ranging from 0° to 8° from fixation. For foveal presentations, flanking with other letters reduced accuracy by 20%. At 6°, flanking reduced accuracy by 75%. Bouma estimated that flanking letters detracted from performance until separation from the critical stimulus was 0.5E, where E is the retinal eccentricity. Thus, the area over which crowding occurs was shown to increase with distance from the fovea (see also Jacobs, 1979). Andriessen and Bouma (1976) extended this work by demonstrating that crowding effects could be seen on both orientation and contrast difference thresholds.

Continuing investigations have been directed toward determining the causes, magnitude, and spatial extent of crowding. As summarized by Pelli, Palomares, and Majaj (2004) and Petrov, Popple, and McKee (2007), crowding has been documented using stimuli as diverse as Landolt Cs, letters, gratings, and Vernier targets (Flom et al., 1963; Levi, Klein, & Aitsebaomo, 1985; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001). Crowding effects are related to target-flanker similarity in the spatial frequency domain (Chung, Levi, & Legge, 2001; Hess, Dakin, & Kapoor, 2000; Levi & Waugh, 1994; Nazir, 1992; Polat & Sagi, 1993) and are also selective for orientation (Levi & Waugh, 1994; Polat & Sagi, 1993).

Because crowding effects are much greater than would be predicted from foveal acuity (Chung et al., 2001) and occur under dichoptic viewing (Flom et al., 1963), it has been suggested that they result from pooled responses or spatial interactions occurring in visual cortex (Chung et al., 2001; Levi, Hariharan, & Klein, 2002; Livne & Sagi, 2007; Parkes et al., 2001). This makes crowding a good model for assessing human aging where age-dependent changes...
in function may be due to optical changes like lens opacity (see Scialfa & Kline, 2007).

Aside from clinical studies of visual fields (e.g., Johnson, 1986; Rowe, 2006), peripheral visual function in older adults has received relatively little experimental interest. The research suggests that information outside of central vision suffers disproportionate loss in healthy older adults. Visual fields for simple luminance detection are reduced by approximately 25% (Johnson, 1986). Peripheral acuity and contrast sensitivity declines are of larger magnitude in older adults (Collins, Brown, & Bowman, 1989; Crassini, Brown, & Bowman, 1988). These losses are not due to greater refractive error (Scialfa, Leibowitz, & Gish, 1989) or spatial summation (Brown, Peterken, & Bowman, 1989) in the periphery.

Are older adults more susceptible to visual crowding? There are robust age differences in the Useful Field of View (Ball, Beard, Roenker, Miller, & Riggs, 1988; Scialfa & Kline, 1988; Scialfa, Kline, & Lyman, 1987; Scialfa, Thomas, & Joffe, 1994; Sekuler, Bennett, & Mamela, 2000), often obtained when peripheral targets are embedded in distractors. In a study resembling the present research, Cerella (1985, Experiment 1) asked younger and older adults to indicate which of several letters were presented briefly at 1°–3° from fixation. Letters were presented alone or embedded within a string of non-letter stimuli. Older adults showed a relatively larger increase in reaction time when non-foveal letters were surrounded by other information, an effect Cerella attributed, in part, to lateral masking. As well, he reported that older adults could not perform the task accurately when small letters (0.4°) were crowded. In Experiment 2, Cerella determined the maximum eccentricity allowing letter identification in isolated and embedded conditions. In the isolated condition there were small age differences. In the embedded condition, whereas younger adults’ thresholds averaged 12°, those of older adults were approximately 6°. Experiment 3 showed that age differences in foveal flanker effects could be eliminated when distractors were separated from the target by at least 3.8° (see also Zeef, Sonke, Kok, Buiten, & Kenemans, 1996).

Although Cerella’s results are consistent with the hypothesis that older adults exhibit greater crowding, other explanations cannot be eliminated. Foremost among them is that in his Experiments 1 and 2, visual search demands added a selective attention component to the task. In Experiment 3, the displays consisted of letter triplets centered on fixation that were more similar to those used in crowding studies. However, flanking letters were either congruent (G-G-G) or incongruent (R-G-R) with the correct response. Accuracy was quite high (e.g., approximately 97%) for both age groups, suggesting that the age effects seen were not related to resolution, but instead to difficulties in focused attention or response competition. As well, neither Cerella (1985, Experiment 3) nor Zeef and colleagues (1996) examined flanker effects outside of foveal vision.

In this experiment, we examined age differences in crowding effects on visual acuity at 3° and 6° using a protocol that eliminated response compatibility effects (Cerella, 1985; Zeef et al. 1996), as well the need for search (e.g., Ball et al., 1988; Scialfa et al., 1994). If, as expected, older adults display greater crowding effects, this may have important implications for complex tasks such as reading (Pelli et al., 2007) and the Usefield of View (Scialfa, Thomas, & Joffe, 1994; Sekuler et al., 2000). Additionally, by reducing retinal illumination in a group of younger adults and comparing their data to those of older adults, we can determine whether it is likely that age differences obtained may be overcome rather simply by increasing ambient light levels. Finally, because older adults experience greater losses in peripheral acuity (Collins, Brown, & Bowman, 1989; Crassini, Brown, & Bowman, 1988) and crowding may be proportional to acuity at that retinal location (Petrov, Popple, & McKee 2007), we were able to determine if this proportional change in resolution differed between younger and older adults.

Method

Participants

Participants were 66, predominantly female adults divided into three groups. Twenty-five older adults (M = 70.3 years, standard deviation [SD] = 7.6 years) served as paid volunteers and were tested under relatively high luminance conditions. One group of 20 younger adults (M = 20.61 years, SD = 1.9 years) was given partial course credit for their involvement and was tested under these same luminance conditions. In order to evaluate the contribution of age-related differences in retinal illumination (Weale, 1961), a second group of 21 younger adults (M = 21.28 years, SD = 4.2 years), also receiving partial course credit, was given the task under reduced luminance conditions. Demographic and self-reported health characteristics of the three groups are presented in Table 1. The University of Calgary Conjoint Faculties Research Ethics Board approved this study.

All participants indicated that they were in good overall physical health. None of the younger adults reported the presence of visual diseases or disorders. Among the older adults, by self-report, one had glaucoma, one had macular degeneration, one was color deficient, and one reported a loss of peripheral vision. Four older adults had cataracts removed and five others were diagnosed with cataract, but had not had surgery. Thus, the researchers’ older adult sample had a diversity of visual health problems that are seen in the general population.

Binocular Landolt C acuity was assessed at 45 cm for all participants. For the younger participants at 45 cm acuity was M = 0.91 min arc (SD = 0.22) and for the older participants it was M = 1.60 min arc (SD = 0.58). Because of the
age differences in near acuity, at the 120 cm test distance some older participants wore trial frames (Burton 100 TLS) with their distance correction and a 0.75 D addition for the viewing distance. This improved the acuity of the older group to an average of 1.18 min arc (SD = 0.34).

Visual acuity was measured for high-contrast stimuli using Postscript-generated Landolt Cs with five optotypes per level of minimum angle of resolution (steps of 0.25 min arc). The gap and stroke width of each optotype were one fifth of the diameter. Threshold was defined as the smallest line producing no more than one error.

Contrast sensitivity was measured using the VISTECH Contrast Test System—VCTS 6500 from a 3 m distance under photopic lighting. As shown in Table 1, participants were in the normal range for their age (Scialfa, Adams, & Giovanetto, 1991).

### Stimulus and Procedures

The detail to be resolved was the gap in a Landolt C. It was presented alone (C) or with two flanking bars (I/C) of the same luminance, size, and stroke width as the target on a given trial. Target-flanker separation and gap size were also equal to stroke width. The Landolt C was rotated to have the gap and flankers “up” or “down,” that is at 0° or 180°, creating a two-alternative, forced-choice task.

The critical detail of the positive contrast Landolt C stimuli ranged from 0.024° to 0.156°. At the highest luminance level, the background luminance (Minolta LS100 photometer) was 53 cd/m² and the target luminance was 112 cd/m². This yielded a target with a Weber contrast of 1.11.

Weale (1961) has estimated that retinal illumiance for older adults is reduced to between 10% and 33% that of younger adults, an effect due to miosis of the pupil and opacification of the lens. Therefore, when younger participants were tested under low luminance conditions, the target luminance was 19.5 cd/m² and the background luminance was 8.8 cd/m², which yielded a target contrast of 1.21.

The target was presented at 3° and 6° (left and right of fixation) along the horizontal meridian, with eccentricity randomly determined on trial-wise basis. The exposure duration was 150 ms to eliminate the possible effect of eye movements, but eye movements were not monitored.

Thresholds were determined using the method of constant stimuli with 20 trials for both the uncrowded and crowded conditions at each of 12 levels of target size, and therefore, gap size in the Landolt C. The dependent measure was percentage correct.

Each session lasted approximately 50 min. Each participant completed an initial practice block of 50 trials, in which stimulus duration was slowly decreased from 500 ms to the experimental level of 150 ms. After the practice, participants dark-adapted for 10 min and then began the experimental trials. In the experiment proper, there were 1,920 trials per session (5 blocks × 2 repetitions × 2 orientations × 2 levels of crowding × 4 locations × 12 sizes). Head position and distance were maintained with a chin and forehead rest. Self-directed, brief rest periods followed each block. During each break, participants were shown an instruction page to reiterate the task instructions for the next block. Responses were made with a left- or right-handed mouse, depending on the participant’s preference.

## Results

We identified two younger and two older participants as “outliers,” defined as being more than 2.5 SDs from the group average in 25% or more of the 48 conditions in which they were tested. Three more outliers (one younger and two older) were also identified because their data were not well described by the psychometric function used in some analyses. Analyses were conducted both with and without these outliers. Because the significance tests for the analyses did not differ, we report subsequently only results of those analyses that include all participants.

Mean proportion correct for the crowded and uncrowded conditions is plotted as a function of stimulus size, eccentricity, and group in Figure 1. For all groups, accuracy improved with stimulus size, declined under crowded conditions, and was more sensitive to eccentricity for the older group than the younger group.
conditions and was worse at 6° than at 3°. Additionally, the crowding effect was more pronounced at 6°. There were few differences between the two young groups; that is, reduced luminance did not affect the magnitude of the crowding effect in younger adults. Of greater importance, older adults exhibited a larger crowding effect, particularly at 6°.

The researchers carried out an Age (2) × Size (12) × Crowding (2) × Eccentricity (2) mixed-model analysis of variance comparing younger high luminance and older high luminance performance. Summary statistics are shown in Table 2. As expected, there was a main effect of Size, Crowding, and Eccentricity. A Crowding × Size interaction was obtained, wherein larger stimulus sizes were needed to reach any given level of accuracy in the crowded, relative to uncrowded condition. In other words, acuity was worse under crowded conditions. The Crowding × Eccentricity interaction showed that the crowding effect was greater at 6° than at 3°. As expected, the Size × Eccentricity interaction was also significant; larger stimulus sizes were needed at 6° than at 3° to achieve a given level of accuracy. Finally, the Crowding × Size × Eccentricity interaction was significant because acuity was more strongly affected by crowding at 6° than at 3°.

Older adults had worse accuracy generally and worse visual acuity as evidenced by an Age × Size interaction. The crowding effect was larger for older adults, as seen in a significant Age × Crowding × Size interaction. Older adults also had more difficulty resolving detail when it was presented further from fixation, resulting in a Size × Eccentricity × Age interaction. Finally, a Crowding × Size × Eccentricity × Age effect demonstrated that older adults exhibited a larger crowding effect on acuity at 6° compared with 3°. No other effects involving age were significant.

Because older adults are known to experience reduced retinal illuminance (Weale, 1961), we also compared younger low luminance and older high luminance data (See Figure 1). The results were similar to those found in the comparisons of younger and older participants who viewed displays under the same, higher luminance conditions. Older adults had worse performance when compared with younger adults. In the Age × Size interaction, there was significantly worse acuity in older adults and the Age × Crowding × Size interaction indicated a larger effect of crowding on acuity for them. Older adults had more difficulty identifying the stimulus at 6° than at 3°, as seen in the Size × Eccentricity × Age interaction. Finally, as before, older adults had a larger crowding effect at 6° than at 3°, as shown in the Crowding × Size × Eccentricity × Age interaction. All other effects involving age were non-significant.

One would expect the crowding effect to be related to acuity at a given retinal location. In fact, correlations between crowded and uncrowded acuity were substantial at both 3° (r = .88) and 6° (r = .70). In order to assess this hypothesis we fitted the individual psychometric functions to estimate the visual angle corresponding to 75% accuracy in both crowded and uncrowded displays. We then operationalized the crowding effect as the ratio of crowded to uncrowded visual angle. The ratios, shown in Table 3, average approximately 1.5 and do not differ across the three groups at either 3° or 6° (p > .34). Thus, although older adults exhibit greater differences in crowded versus uncrowded acuity, crowding effects were proportional to uncrowded acuity in both younger and older adults and at both retinal locations. Additionally, after controlling for uncrowded acuity at both 3° and 6°, the age effects on crowding were non-significant at either retinal location (p = .08 at 3° and p = .79 at 6°).

Table 3. Average Crowding Ratios (SDs) for Each Age Group and Retinal Location

<table>
<thead>
<tr>
<th>Group</th>
<th>Young high luminance</th>
<th>Young low luminance</th>
<th>Old high luminance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3°</td>
<td>1.48 (0.19)</td>
<td>1.44 (0.17)</td>
<td>1.39 (0.18)</td>
</tr>
<tr>
<td>6°</td>
<td>1.46 (0.50)</td>
<td>1.84 (1.91)</td>
<td>1.50 (0.16)</td>
</tr>
</tbody>
</table>

Note. SD = standard deviation.
**Discussion**

This experiment was conducted to determine if crowding effects seen previously in young observers would also be seen in older adults, if any observed age differences in visual crowding could be explained by declines in retinal illuminance, and if the crowding effect is larger in older adults, particularly in the periphery. In brief, our conclusions are "yes," "no," and "it depends."

Robust crowding effects were seen in both younger and older adults and these effects were larger in absolute magnitude in the periphery. Thus, we replicated results seen for letter identification, hyperacuity, and other resolution tasks (Bouma, 1970; Levi et al., 1985; Parkes et al., 2001) but with a much larger and more diverse group of observers than is usually employed in crowding studies.

The age differences we observed do not appear to be due to age-related declines in retinal illuminance. Data from the two younger groups were essentially identical (see Figure 1), even though one group viewed the displays at about 17% the luminance of the other. As well, age differences in crowding that were obtained when observers were tested under equivalent luminance persisted when older adults were compared with the younger adults tested under reduced luminance. Thus, reduced retinal illuminance is an unlikely explanation of the present results, although ideally one would incorporate the technically difficult task of matching observers on the amount of light reaching the retina.

Do older adults show greater crowding effects? In absolute angular size, crowding effects were larger for older adults at both retinal locations, but were particularly apparent at 6°. However, the ratio of crowded to uncrowded acuity was essentially the same across all three groups of observers at both retinal locations and the correlation between crowded and uncrowded acuity was quite strong. Thus, the proportional increase in stimulus size needed to compensate for flanking contours was equivalent for older and younger adults. Still, older adults needed a larger increase in visual angle to reach resolution threshold under crowded conditions. Thus, whether older adults exhibited greater visual crowding depends on one’s definition of a crowding effect.

This is not a trivial distinction. Imagine, for example, that one wanted to format displays to allow good visual resolution outside of central vision. Relative to younger observers, older adults would require the to-be-resolved detail to be larger when it was embedded in other contours. Even though the increase required for them is proportional to their uncrowded acuity at that location, the costs of manufacturing a larger display would be affected and other display capabilities might well be impacted. To our knowledge, no studies of age differences in peripheral visual function adjust image size or separation on an individual basis.

The observed pattern of age differences in crowding effects could account for some diverse effects in the aging literature. For example, Cerella (1985) reported that flanking distractors interfered with identification latencies.
and accuracy of older adults more than young adults and that this age deficit could be eliminated with sufficiently large separations of flanking contours. Age differences in search latencies are greater for conjunction search than for feature search (Plude & Doussard-Roosevelt, 1989). In conjunction search through spatially extensive arrays, coarse integration of separable features will compel more eye movements to reduce errors, thus increasing the time to respond (Scialfa & Joffe, 1997; Scialfa et al., 1994).

Relatedly, older adults have difficulty processing peripheral information, that is, they demonstrate a reduced Usef Field of View, when the to-be-resolved detail is presented in nearby contours (e.g., Scialfa et al., 1994; Sekuler et al., 2000). Older adults exhibit greater saccadic averaging under some conditions (Scialfa, Hamaluk, Skaloud, & Pratt, 1999), an effect attributed to coarse spatial pooling of low-level information that guides oculomotor behavior. Reading rates decline with age (Stine-Morrow, Miller, & Hertzog, 2006) and reading rates in young adults can be predicted by a combination of crowding and retinal eccentricity (Pelli et al., 2007). Rayner and colleagues (2009) recently reported that perceptual span was reduced in healthy, older readers relative to their younger counterparts. They hypothesized that this may result from less efficient processing in the periphery. Our results are consistent with this suggestion. In short, an apparently heterogeneous picture of age differences in task performance could be explained, in part, by greater visual crowding in older observers.

There are two limitations to the present investigation. First, several of our older adults reported that they had some visual health problems that could affect spatial resolution and the magnitude of their crowding effect. Presumably this would influence both uncrowded and crowded acuity. Perhaps, then, the greater age differences are attributable to these individuals. Post hoc analysis comparing those older adults with and without self-reported visual health problems revealed no group differences on measures of foveal acuity or contrast sensitivity or, for that matter, on crowding ratios. Thus, although additional research that more rigorously controls for visual health problems that could affect spatial resolution and contrast properties of crowding.

The second issue concerns age differences in the spatial extent of crowding, consistently found to be approximately one half the eccentricity of the to-be-resolved detail (e.g., Bouma, 1970). It is possible that the crowding effects persist over greater spatial separations in older observers. Although this possibility is certainly worth investigation, Brown and colleagues (1989) did not find older adults to demonstrate any greater peripheral spatial summation at 10° from fixation.

The findings of this study raise three additional questions. First, are age differences in crowding effects specific to the resolution task used here, or do they generalize to other and more complex stimuli and stimulus properties (e.g., contrast thresholds or letter identification)? Second, is the spatial extent of crowding larger for older adults and does it increase more rapidly with eccentricity? Finally, can measures of crowding be used to account for age-related differences in complex tasks such as reading, visual search, and hazard perception in driving? These questions will be addressed in future research.

In summary, we have found that older adults demonstrate greater visual crowding in the near periphery, manifested as difficulty resolving critical detail. In both younger and older adults, however, crowding effects were of the same proportion relative to uncrowded acuity at a given retinal location. This pattern is consistent with the view that crowding is the result of spatial pooling of information that is coarser in the periphery and in older adults. These results may have implications for a variety of tasks including visual search and some aspects of driving performance.

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**Correspondence**

Correspondence should be addressed to Charles T. (Chip) Scialfa, Ph.D., Department of Psychology, University of Calgary, Calgary, Alberta T2N 1N4, Canada. E-mail: scialfa@ucalgary.ca

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**References**


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