

Functional Field of View Determined by Crowding, Aging, or Glaucoma Under Divided Attention

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Purpose: Parafoveal or peripheral vision is important for various everyday activities. This is particularly relevant to those who suffer from visual field defects. Here we quantified the effect of visual crowding, normal aging, and glaucoma on the spatial extent of the functional field of view (FFV) under divided attention.

Methods: Unlike visual acuity measured by single-letter recognition or visual perimetry measured by light spot detection, we measured the FFV using a target letter presented either alone or in letter triplets appearing across the visual field. A subject's task was to report whether the target letter was the same as the letter displayed concurrently at the central fixation region (i.e., divided attention task). Over the trials, a plot of the proportion correct for letter recognition versus target location was constructed, resulting in a visual field map.

Results: The results obtained from three subject groups—normal young adults, normal older adults, and patients with glaucoma—showed that on average the central 20° visual field was relatively robust to uncrowded target recognition under divided attention. However, the FFV shrunk down to the central 10° visual field when the target appeared in clutter, suggesting a strong crowding effect on FFV. An additional shrinkage of the FFV occurred in the presence of aging and glaucoma.

Conclusions: Using a quantitative method, we demonstrate that crowding, aging, and glaucoma independently decrease the spatial extent of FFV under divided attention and that crowding seems to be the major contributor limiting FFV.

Translational Relevance: Our FFV test may complement standard clinical measurements by providing functionally relevant visual field information.

Introduction

Contrary to our perceptual impression, visual processing is not homogeneous across the visual field. For resolving fine spatial details, humans rely exclusively on the fovea, the small, central-most region of the retina, where light-sensitive cells are densely packed.¹ We move our eyes to direct the fovea to different parts of a scene, constructing a picture of the world around us. Outside the fovea, visibility progressively decreases with eccentricity. For this reason, most visual information necessary for daily visual tasks

is obtained through the foveal region of the retina. However, parafoveal (approximately 4°–5° eccentricity) and peripheral vision (beyond 5° eccentricity) are known to be also important for everyday tasks such as reading,^{2–6} visual search,^{7–9} navigation,⁷ scene recognition,¹⁰ maintaining postural balance,^{11,12} and driving.^{8,13–21}

For instance, it has been shown that skilled readers of alphabetic writing systems obtain useful letter information across the visual field that extends 3 to 4 letters to the left of fixation and 14 to 15 letters to the right of fixation.^{2,3} Accordingly, a number of studies showed that the visual span (i.e., the number of letters reliably

recognizable in a glance) is closely related to reading speed in both normal and clinical populations^{4–6,22–26}: the smaller the visual span, the slower the reading speed. Thus, the visual span can be viewed as the size of a window in the visual field within which letters can be recognized reliably. The visual span is typically measured using a trigram (i.e., a random string of three letters) letter recognition task in which an observer is asked to report a trigram flashed at varying letter positions on the horizon meridian while fixating at the center.²²

Studies on driving also pointed out the importance of the integration of the entire visual field in maintaining situational awareness while driving.⁸ Particularly, peripheral vision was shown to be critical for various driving tasks, including lane changing, avoiding obstacles, and crossing intersections.¹³ Thus, it was visual field defects that were closely associated with increased motor vehicle collision, but neither visual acuity nor contrast sensitivity.^{14–16} Moreover, the useful field of view (UFOV) test that measures the degree to which a person's detection or search performance is impaired under divided attention or in the presence of distractors across the visual field has been useful to predict driving ability and crash risk.^{6,9,20,21,27–30} Therefore, the findings of these studies underscore the significance of assessing the field of view under divided attention or in the presence of distractors that likely reflect the sensory and cognitive demand required for everyday activities.

It is, thus, important to quantify the spatial extent of the field of view relevant to everyday tasks (hereafter referred to as the functional field of view [FFV]). However, there is currently no test to map out the

spatial extent of the FFV across the visual field. Here, we developed a new method that allows us to map out the spatial extent of the FFV across the visual field. Unlike visual acuity measured by single-letter recognition or standard visual perimetry measured by light spot detection, our FFV test requires recognition of letter with and without distractors under divided attention across the visual field. This dual task (divided attention) was adopted because the ability to divide or split attention was shown to be closely related to real-life activities (i.e. paying attention to items occurring in the peripheral vision while processing centrally occurring visual inputs),^{18,19,31} and also because the deleterious effect of divided attention seemed to be even greater for older adults and visually impaired individuals.^{9,31,32} Thus, our FFV test was designed to estimate the spatial extent of the FFV across the visual field while representing the key principles captured by both the UFOV^{9,20,21,27,28} and the visual span task.^{4,6,25} The major differences between the UFOV and our FFV test lie in the fact that the UFOV primarily assesses a person's ability to process the information in the visual field under increased attentional demand by measuring reaction time for discriminating a target stimulus presented in the central vision either under divided attention or in the presence of peripheral distractors. In contrast, our FFV test estimates the visible boundaries across the visual field within which a person can reliably recognize a peripheral target while fixating at a central target by measuring the recognition accuracy of a target stimulus presented in the peripheral vision with or without nearby distractors for a given time limit (250 ms) under divided attention (see Fig. 1B).

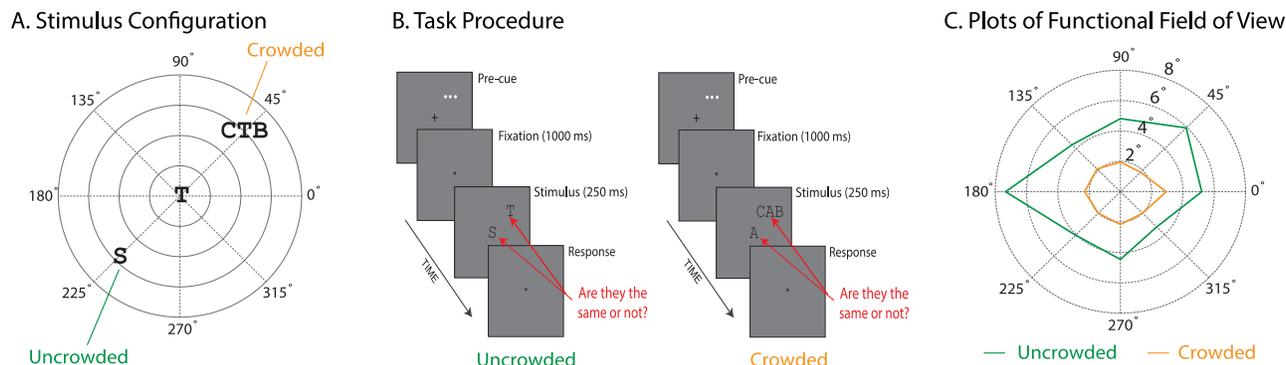


Figure 1. Schematic diagram of stimuli, task procedure, and FFV map. (A) An illustration of the stimulus configuration. There is a single letter displayed at the central fixation region. For the uncrowded condition, a single target appears in the peripheral visual field, whereas a target is presented with nearby flankers for the uncrowded condition. (B) Task procedure for crowded and uncrowded conditions. Before the presentation of target stimuli, a visual cue (white dot) appears to indicate the target location. A subject's task is to recognize the single letter or the middle letter in letter triplets and report whether the target letter is the same as the letter displayed at the central fixation region concurrently. (C) The spatial extent of FFV is plotted on the polar coordinate plane for the crowded (orange solid line) and uncrowded (green solid line) conditions.

Previous studies have reported a significant shrinkage of the visual span in both older adults with healthy vision and patients with glaucoma.^{26,33} As shown in UFOV studies, visual crowding—the inability to recognize a target when presented in clutter³⁴—was reported to play a limiting role in the visual span^{35,36} as well. Thus, in the current study, we are particularly interested in evaluating the effect of crowding, aging, and ocular pathology such as glaucoma on the spatial extent of the FFV. To this end, we compared the spatial extent of the FFV of three groups of subjects: normal young adults, normal old adults, and patients with glaucoma under either crowded (i.e., in the presence of nearby distractors) or uncrowded (i.e., in the absence of distractors) condition.

Methods

Participants

A total of 76 subjects participated in the current study: 30 patients with primary open-angle glaucoma (mean age, 64 ± 9 years), 27 age-matched normally sighted older adults (mean age, 60 ± 8 years), and 19 normally sighted young adults (mean age, 25 ± 7 years). The study participants were recruited from either Callahan Eye Hospital Clinics at the University of Alabama at Birmingham (UAB) or the UAB campus. Patients with glaucoma, whose diagnosis was validated through medical records, met the following inclusion criteria. (i) There were glaucoma-specific changes of optic nerve or nerve fiber layer defect. The presence of the glaucomatous optic nerve was defined by masked review of optic nerve head photos by glaucoma specialists using previously published criteria.³⁷ (ii) There was a glaucoma-specific visual field defect: a value of Glaucoma Hemifield Test from the Humphrey Field Analyzer (HFA) must be outside normal limits. (iii) There was no history of other ocular or neurological disease or surgery that caused visual field loss.

Table summarizes characteristics of study participants. The average mean deviation obtained from the HFA (SAP 24-2 test) in patients with glaucoma was -5.84 ± 6.79 dB for the better eye and -10.17 ± 9.80 dB for the worse eye. According to the Hodapp–Anderson–Parish glaucoma grading system,³⁸ the majority of our patients with glaucoma were in either early or moderate stages of glaucoma (21 of 30). The mean binocular visual acuity (Early Treatment Diabetic Retinopathy Study charts) for patients with glaucoma was 0.02 ± 0.11 logarithm of the minimum

angle of resolution (logMAR) (or 20/20 Snellen equivalent). The mean binocular log contrast sensitivity (Pelli–Robson charts) was 1.70 ± 0.22 .

Normal vision was defined as better than or equal to 0.2 logMAR best-corrected visual acuity in each eye with normal binocular vision and with no history of ocular or neurological disease other than cataract surgery. The mean binocular visual acuity for normal control subjects was -0.08 ± 0.09 logMAR (or 20/20 Snellen equivalent). The mean binocular log contrast sensitivity for normal controls was 1.92 ± 0.11 . The mean binocular visual acuity for normal young subjects was -0.12 ± 0.08 logMAR (or 20/20 Snellen equivalent). The mean binocular log contrast sensitivity for normal controls was 1.94 ± 0.11 .

All participants were native or fluent English speakers without known cognitive or neurological impairments, confirmed by the Mini Mental State Examination (score of ≥ 25 for those aged ≥ 65 years). The main experiments were conducted with binocular viewing. This was done to assess the amount of crowding relevant to real-life visual tasks. Proper refractive correction for the viewing distance was used. The experimental protocols followed the tenets of the Declaration of Helsinki and were approved by the Internal Review Board at UAB. Written informed consents were obtained from all participants before the experiment, after an explanation of the nature of the study.

Measuring the FFV

Stimulus and Apparatus

The 26 lowercase Courier font letters of the English alphabet—a serif font with fixed width and normal spacing—were used. For the crowded condition, trigrams—random strings of three letters—were used. All letters were black and had a letter size of 0.8° (in x-height) at the 57-cm viewing distance and were presented on a uniform gray background with a contrast of 99%.

All stimuli were generated and controlled using a computing environment (MATLAB version 8.3 and Psychophysics Toolbox extensions^{39,40}; MathWorks, Inc., Natick, MA) for a commercial operating system (Windows 7; Microsoft Corp., Redmond, WA) running on a PC desktop computer (Dell Precision Tower 5810; Dell, Inc., Round Rock, TX). Stimuli were presented on a liquid crystal display monitor (model: Asus VG278HE; refresh rate: 144 Hz; resolution: 1920×1080 , subtending $60^\circ \times 34^\circ$ visual angle at a viewing distance of 57 cm) with the mean luminance of the monitor at 159 cd/m^2 . The luminance of the display monitor was made linear using an 8-bit

Table. Characteristics of the Study Participants

SubID	Diagnosis	Sex	Age (Years)	Binocular Visual Acuity (logMAR)	Binocular log Contrast Sensitivity	Mean Deviation (dB)	
						OD	OS
G01	POAG	m	62	0.02	1.65	-0.61	-2.39
G02	POAG	f	56	-0.1	1.8	-19.15	-12.87
G03	POAG	f	65	-0.1	1.65	-5.9	-3.47
G04	POAG	f	86	0	1.5	-1.51	-6.94
G05	POAG	f	66	-0.08	1.65	2.25	-4.07
G06	POAG	f	47	0.24	1.35	-32.3	-15.14
G07	POAG	m	55	-0.04	1.65	-20.91	-27.88
G08	POAG	f	74	0.2	1.65	-16.34	-15.98
G09	POAG	m	53	0.2	1.65	N/A	-4.31
G10	POAG	m	62	0.12	1.65	-9.55	-10.63
G11	POAG	m	65	0.18	1.8	-0.7	-8.42
G12	POAG	f	62	0.02	1.5	-15.58	-6.51
G13	POAG	f	59	0.04	2.1	-0.3	1.01
G14	POAG	f	61	-0.08	2	-1.32	-5.15
G15	POAG	f	64	-0.1	1.9	-4.52	-7.01
G16	POAG	m	62	-0.1	1.9	-2.42	-4.64
G17	POAG	f	61	-0.12	1.9	1.16	-0.55
G18	POAG	f	52	-0.1	1.95	-0.16	0.01
G19	POAG	f	55	-0.06	1.75	-4.25	-7.7
G20	POAG	m	68	-0.04	1.95	-0.93	-0.93
G21	POAG	m	58	0.08	1.75	0.09	-2.73
G22	POAG	m	68	0.1	1.95	-2.48	-1.24
G23	POAG	m	72	0.04	1.65	-4.52	-2.49
G24	POAG	f	64	0.04	1.9	-2.37	-1.34
G25	POAG	m	68	-0.06	1.8	-1.57	-3.17
G26	POAG	f	67	0.22	1.45	-17.26	-12.07
G27	POAG	f	70	0.1	1.35	-9.46	-6.74
G28	POAG	m	75	0.04	1.4	-19.16	-29.44
G29	POAG	m	81	0.06	1.6	-28.01	-16.74
G30	POAG	f	52	-0.02	1.15	-25.19	-11.77
POAG (n = 30)		f:m = 17:13	63.67 (±8.66)	0.02 (±0.11)	1.70 (±0.22)	-8.38 (±9.84)	-7.71 (±7.51)
Old normal vision (n = 27)		f:m = 12:15	59.81 (±7.63)	-0.08 (±0.09)	1.92 (±0.11)	0.10 (±1.67)	-0.21 (±1.94)
Young normal vision (n = 19)		f:m:nr = 12:6:1	24.89 (±7.14)	-0.12 (±0.08)	1.94 (±0.11)	-0.09 (±0.80)	-0.95 (±1.77)

Note that the numbers in parenthesis are standard deviations (SD). OD, right eye; OS, left eye; POAG, primary open-angle glaucoma; f, female; m, male; nr, no reply; N/A, not available.

lookup table in conjunction with photometric readings from a luminance meter (MINOLTA LS-110; Konica Minolta, Inc., Tokyo, Japan).

Task Procedure

As shown in Figure 1A, the FFV was assessed with either single letters or letter triplets presented in each testing location across the visual field, spanning approximately 36° horizontally and vertically. The single letter or letter triplets flashed on the screen for 250 ms along one of the eight predetermined meridians as a subject fixated on a central fixation region of the visual display. The subject’s task was to recognize the single letter or the middle letter in letter triplets and report whether the target letter was the same as the letter displayed at the central fixation region concurrently (Fig. 1B). For each radial direction

($\theta = 0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ, 225^\circ, 270^\circ,$ and 315°), the presentation of the target letter always started at the farthest location from the central fixation point (i.e., at 18° eccentricity) and moved toward or away from the fixation point along the meridian depending on the subject’s recognition performance. This was done to estimate the spatial extent of FFV by estimating the maximum distance between the central fixation and target (i.e., threshold distance or eccentricity) that allows for reliable recognition performance. The threshold distance (eccentricity) between the central fixation and target location was measured using a three-down-one-up staircase procedure, which yields a target identification accuracy of 79.4%.⁴¹ The step size of the staircase was 1dB. Auditory feedback was given for correct answers. The total number of staircase reversals were set to eight. The final threshold distance

was determined by taking the geometric average of the last seven staircase reversals. The test session consisted of 40 to 60 blocks, with 15 trials per block. One of the eight predetermined radial directions was randomly selected for each block. Over the trials, a plot of threshold distance versus target location was constructed, resulting in a visual field map tracing out the visible boundary (Fig. 1C). For data analysis, the mean FFV (area, deg²) was computed. Before testing, a practice round was conducted to determine initial contrast of the letters and to familiarize subjects with the task procedure. Before data collection, all subjects had practice trials. A chinrest was used to minimize head movements maintain a fixed viewing distance.

For each participant, binocular visual acuity (Early Treatment Diabetic Retinopathy Study charts), binocular contrast sensitivity (Pelli-Robson charts), stereoacuity (Titmus Fly SO-001 StereoTest), and monocular visual field tests were also measured. Visual field test was performed with standard automatic perimetry using a SITA Standard 24–2 test with a HFA (Carl Zeiss Meditec, Inc.). Goldmann size III targets with a diameter of 0.43° were presented for 200 ms at one of 54 test locations in a grid on a white background (10 cd/m²). All functional measurements except for the Humphrey visual field test were made under binocular viewing. Statistical analyses were performed using SPSS (version 27) in combination with MATLAB (R2014b; MathWorks, Inc.).

Results

To evaluate the effects of crowding, normal aging, and glaucoma on the FFV, we performed two separate two-way analysis of variance (ANOVA) on the area under the FFV (deg²) in a log unit: (1) a 2 (age group: normal young, normal old) × 2 (crowding condition: crowded and uncrowded) ANOVA with age group as a between-subject factor and crowding condition as a within-subject factor; (2) a 2 (diagnosis group: normal old and glaucoma) × 2 (crowding condition: crowded and uncrowded) ANOVA with diagnosis group as a between-subject factor and crowding condition as a within-subject factor. From the first ANOVA, we found a significant main effect of crowding condition, $F_{(1, 44)} = 808.86$, $P < 0.001$, and aging, $F_{(1, 44)} = 5.08$, $P = 0.03$, on the area under the FFV. The interaction between crowding and aging was also significant, $F_{(1, 44)} = 5.09$, $P = 0.03$. From the second ANOVA, we also found a significant main effect of crowding condition, $F_{(1, 55)} = 334.68$, $P < 0.001$, and diagnosis, $F_{(1, 55)} = 17.38$, $P < 0.001$, on the area under the

FFV. The interaction between crowding and diagnosis was also significant, $F_{(1, 55)} = 18.87$, $P < 0.001$. We will be reporting the results of the effects of crowding, normal aging, and glaucoma separately in the following sections.

The Effect of Crowding on the FFV

In Figure 2A, the spatial extent of the FFV averaged across all subjects was plotted in polar coordinates for the crowded and uncrowded conditions. The green line outlines the spatial extent of the FFV measured under the uncrowded condition and the orange line encompasses the spatial extent of FFV measured under the crowded condition. Each polar plot represents the visual field and the dotted widening circles represent the retinal eccentricity. It is evident that the spatial extent of the FFV of the uncrowded condition is considerably larger than that of the crowded condition. On average, the spatial extent of the FFV of the crowded condition was reduced by more than 50% across all the radial directions compared with that of the uncrowded condition, that is, the spatial extent of the FFV spanning over the central 20° visual field for the uncrowded condition as opposed to the central 10° visual field for the crowded condition. This pattern of results remained consistent across all subject groups as shown in Figures 2B, 2C, and 2D. These findings suggest that crowding is a major factor limiting the FFV regardless of whether a person is healthy young, old, or a patient with glaucoma, $F_{(1, 44)} = 808.86$, $P < 0.001$; $F_{(1, 55)} = 334.68$, $P < 0.001$.

The bar graphs in Figure 2E represent the mean values of the log area under the FFV (deg²) comparing between the uncrowded and crowded condition for all the subjects (2.64 vs 1.87, $t_{(75)} = 23.40$, $P < 0.001$), for normal young adults (2.80 vs 2.03, $t_{(18)} = 16.61$, $P < 0.001$), for normal older adults (2.71 vs 1.90, $t_{(26)} = 16.15$, $P < 0.001$), and for patients with glaucoma (2.46 vs 1.74, $t_{(29)} = 11.43$, $P < 0.001$).

Figure 3 shows examples of individual subjects' FFV from each subject group. Consistent with the group average data, all individual subjects exhibited a significant shrinkage of the FFV due to crowding.

The Effect of Normal Aging on the FFV

To evaluate the effect of normal aging on the FFV, we compared the FFV between normal young and normal older adults for both crowded and uncrowded conditions. Our two-way ANOVA showed a significant main effect of aging ($F_{(1, 44)} = 5.08$, $P = 0.03$) and a significant interaction between crowding condition and aging ($F_{(1, 44)} = 5.09$, $P = 0.03$) on the area under the

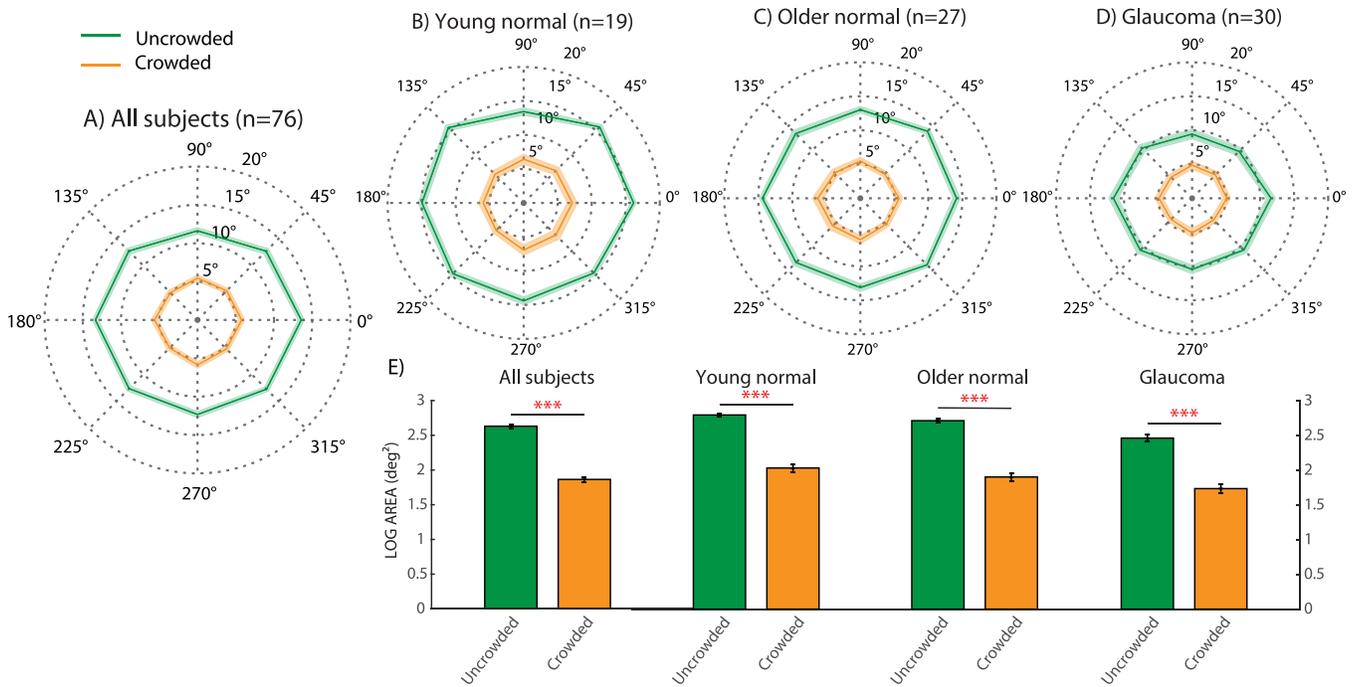


Figure 2. The effect of crowding on the spatial extent of the FFV. The solid lines map the average spatial extent of the FFV across subjects. The shaded area represents ± 1 standard error of mean (SEM). Each polar plot represents the visual field. (A) The spatial extent of the FFV averaged across all subjects for the crowded and uncrowded conditions. (B) The spatial extent of the FFV averaged across all normal young subjects for the crowded and uncrowded conditions. (C) The spatial extent of the FFV averaged across all normal older subjects for the crowded and uncrowded conditions. (D) The spatial extent of the FFV averaged across all glaucoma subjects for the crowded and uncrowded conditions. (E) Bar graphs represent the mean values of the log area under the FFV (deg²). Error bars represent ± 1 SEM. Green color indicates the data from the uncrowded condition and orange color indicates the data from the crowded condition. *** $P < 0.001$.

FFV. Figure 4A shows the spatial extent of the FFV of older normal subjects (dark purple lines) and young normal subjects (light purple lines) in both crowded and uncrowded conditions. As shown in the bar graphs (Fig. 4C), there was a small, yet statistically significant difference in the FFV between the two age groups for the uncrowded condition (2.80 vs 2.71, $t_{(44)} = 2.57$, $P = 0.014$). However, in the crowded condition, no significant difference was found between the two age groups (2.03 vs 1.90, $t_{(44)} = 1.58$, $P = 0.122$).

Additionally, to investigate how aging deviates the extent of FFV from what is expected from young normal group, we computed the difference in the log area under the FFV between old normal subjects and the mean log area under the FFV value of the normal young group for both uncrowded and crowded conditions as follows:

$$D_i = \log AUFFV_{\text{sub}_i} - \mu_{\text{normal young}}, \text{ sub}_i \in \text{normal older group},$$

where D_i and $\log AUFFV_{\text{sub}_i}$ are the deviation and log area under the FFV for i^{th} subject, respectively, and $\mu_{\text{normal young}}$ is the mean log area under the FFV across normal young subjects. The deviation values of individual subjects were plotted in Figure 4E (dark purple

circles) for uncrowded and crowded conditions. The gaussian distributions of the deviations for uncrowded (green curve) and crowded (orange curve) conditions are also shown in Figure 4E. Note that zero value (light purple dotted line) means no deviation and the negative and positive values denote smaller and larger FFV compared with the normative group (i.e., the young normal group), respectively. As shown in Figure 4E, the average deviation values for uncrowded (green dashed line) and crowded (orange dashed line) conditions are -0.08 and -0.13 , respectively. Moreover, the spread (σ) of the distribution for crowded condition (orange gaussian curve) is noticeably larger than that of the uncrowded condition (green gaussian curve) ($\sigma = 0.12$ for the uncrowded vs. $\sigma = 0.29$ for the crowded), indicating greater intersubject variability for the crowded condition.

The Effect of Glaucomatous Damage on the FFV

To evaluate the effect of glaucoma on the FFV, the FFV was compared between normal older adults

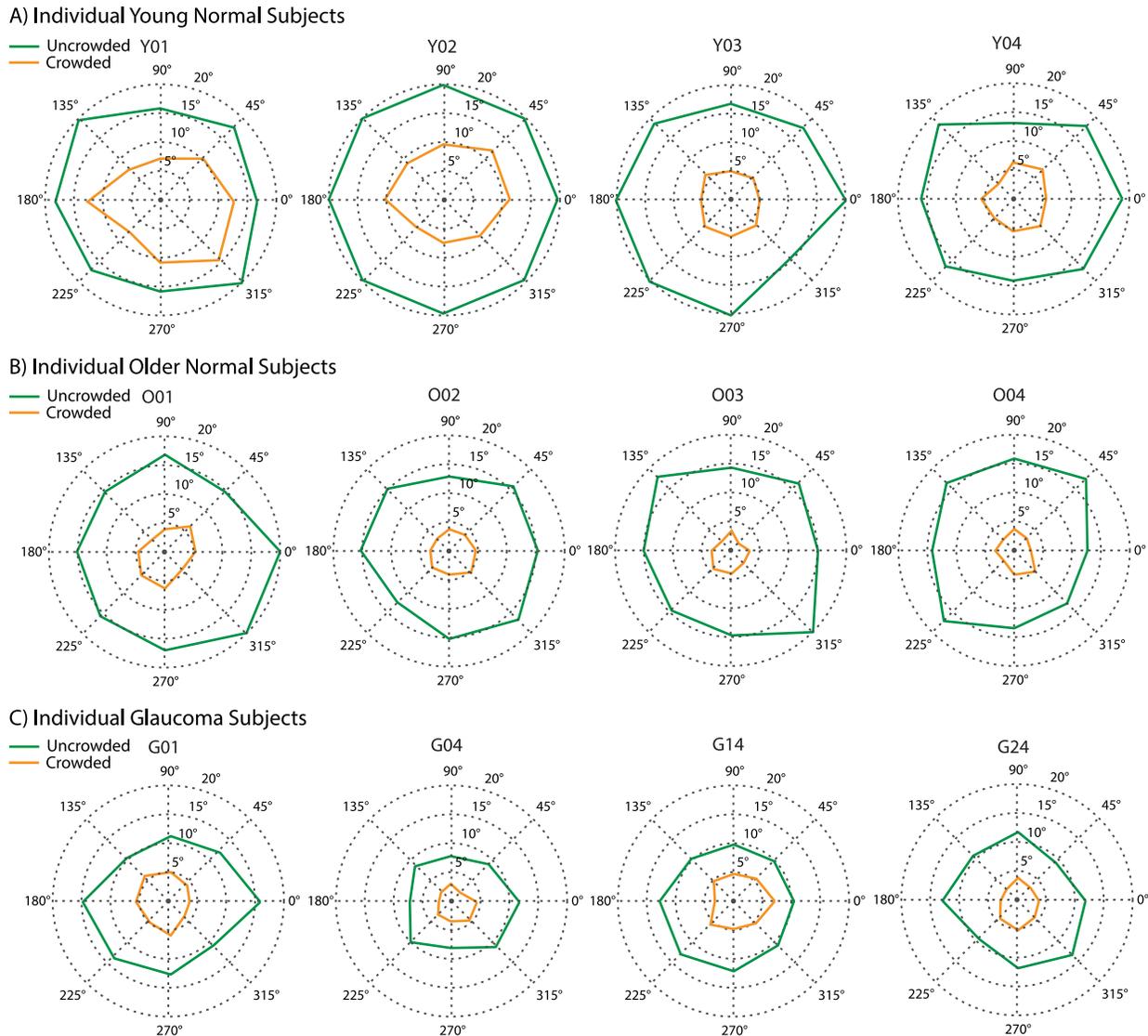


Figure 3. Examples of individual subject's FFV from each subject group. An individual subject's spatial extent of the FFV was plotted on the polar coordinate plane for the crowded (orange solid line) and uncrowded (green solid line) conditions. Each polar plot represents the visual field. (A) Young normal subjects. (B) Older normal subjects. (C) Glaucoma subjects.

and patients with glaucoma for both the crowded and uncrowded condition. Our two-way ANOVA showed a significant main effect of diagnosis ($F_{(1, 55)} = 17.38, P < 0.001$) and a significant interaction effect between crowding condition and diagnosis ($F_{(1, 55)} = 18.87, P < 0.001$) on the FFV. **Figure 4B** summarizes the spatial extent of the FFV of older normal subjects (dark purple lines) and glaucoma subjects (black lines) in both crowded and uncrowded conditions. As shown in the bar graphs (**Fig. 4D**), there was a statistically significant difference in the log area under FFV between older normal subjects and patients with glaucoma for the uncrowded condition (2.71 vs 2.46, $t_{(55)} = 4.36, P < 0.001$), whereas there was a marginally significant difference for the crowded condition (1.90 vs

1.74, $t_{(55)} = 1.92, P = 0.059$). Similar to the previous section, we also computed the deviations of glaucoma subjects with respect to the mean area under FFV value of normal older group for both uncrowded and crowded conditions. As shown in **Figure 4F**, the average deviation values for uncrowded (green dashed line) and crowded (orange dashed line) conditions are -0.25 and -0.17 , respectively. Moreover, the spread of the distribution for crowded condition ($\sigma = 0.35$) is larger than that of the uncrowded condition ($\sigma = 0.28$), indicating greater intersubject variability for the crowded condition.

Next, we compared the light sensitivity data measured by the HFA 24-2 test with the results obtained from our FFV test for both uncrowded and

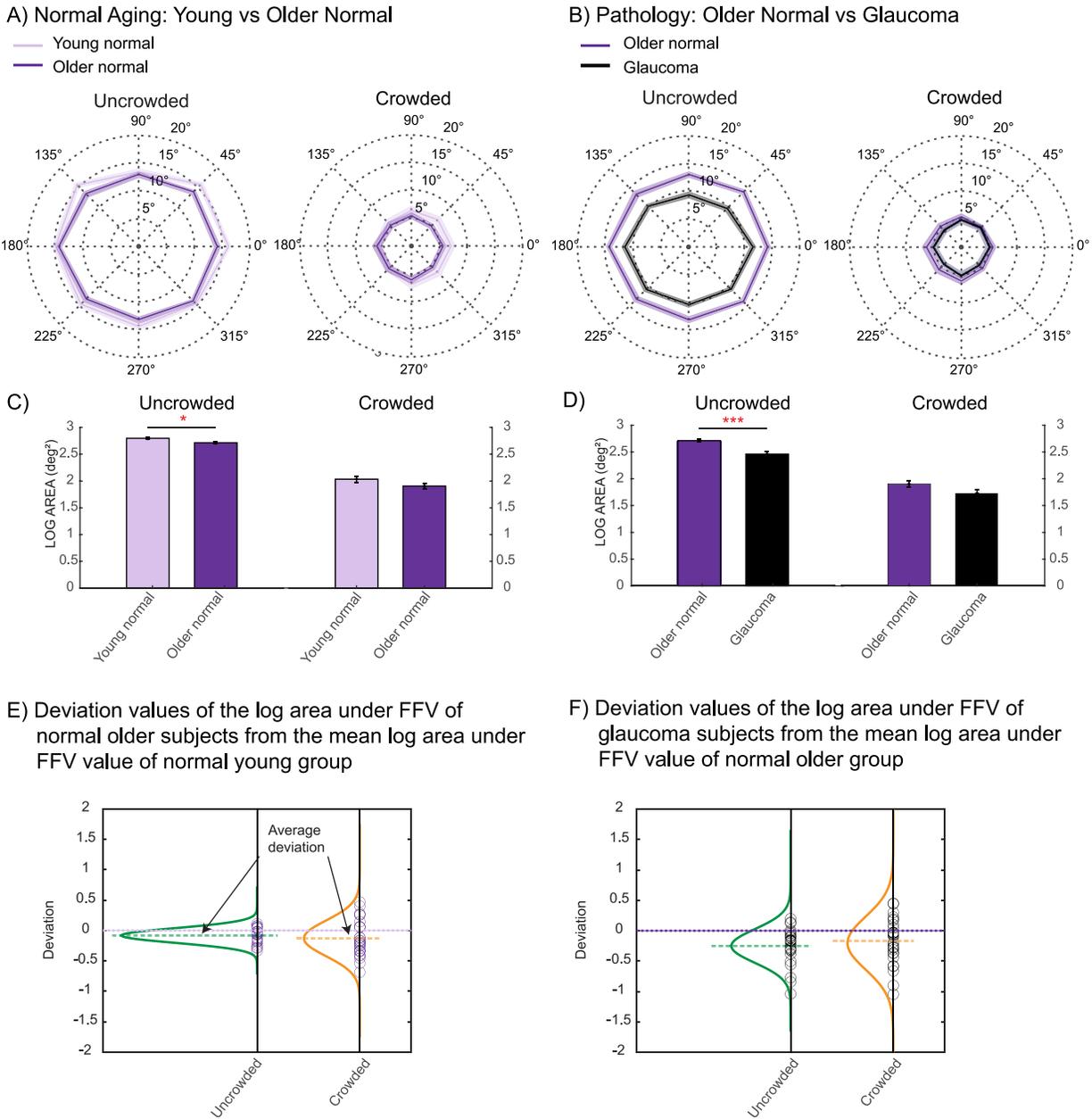


Figure 4. The effect of normal aging and glaucoma on the spatial extent of the FFV. (A and B) The solid lines map the average spatial extent of the FFV across subjects. The shaded area represents ± 1 SEM. Each polar plot represents the visual field. (A) The spatial extent of the FFV averaged across young vs older normal subjects for the crowded and uncrowded conditions. Plots visualize the difference between the older normal (dark purple lines) and young normal (light purple lines) FFV under crowded and uncrowded conditions. (B) The spatial extent of the FFV averaged across older normal vs glaucoma subjects for the crowded and uncrowded conditions. Plots visualize the difference between the older normal (dark purple lines) and glaucoma (black lines) FFV under crowded and uncrowded conditions. Bar graphs (C and D) indicate the mean values of log area under the FFV (deg²). Error bars represent ± 1 SEM. * $P < 0.05$, *** $P < 0.001$. (C) Light purple color indicates the data from the normal young group and dark purple color represents the data from the normal older group. (D) Dark purple color shows the data from the normal older group and the black color denotes the data from the glaucoma group. (E) Deviation values of the log area under FFV of normal older subjects from the mean log area under FFV value of normal young group. Dark purple circles indicate the individual data points. Note that zero value (light purple dotted line) indicates no deviation while negative and positive values denote smaller and larger FFV compared with the normative group, respectively. Gaussian distribution (solid lines) of the deviation data for uncrowded and crowded conditions and their corresponding mean values (dashed lines) are shown in green and orange, respectively. (F) Deviation values of the log area under FFV of glaucoma subjects with respect to the mean log area under FFV value of normal older group. Black circles show the individual data points.

A) Comparison between FFV and binocular HFA visual field

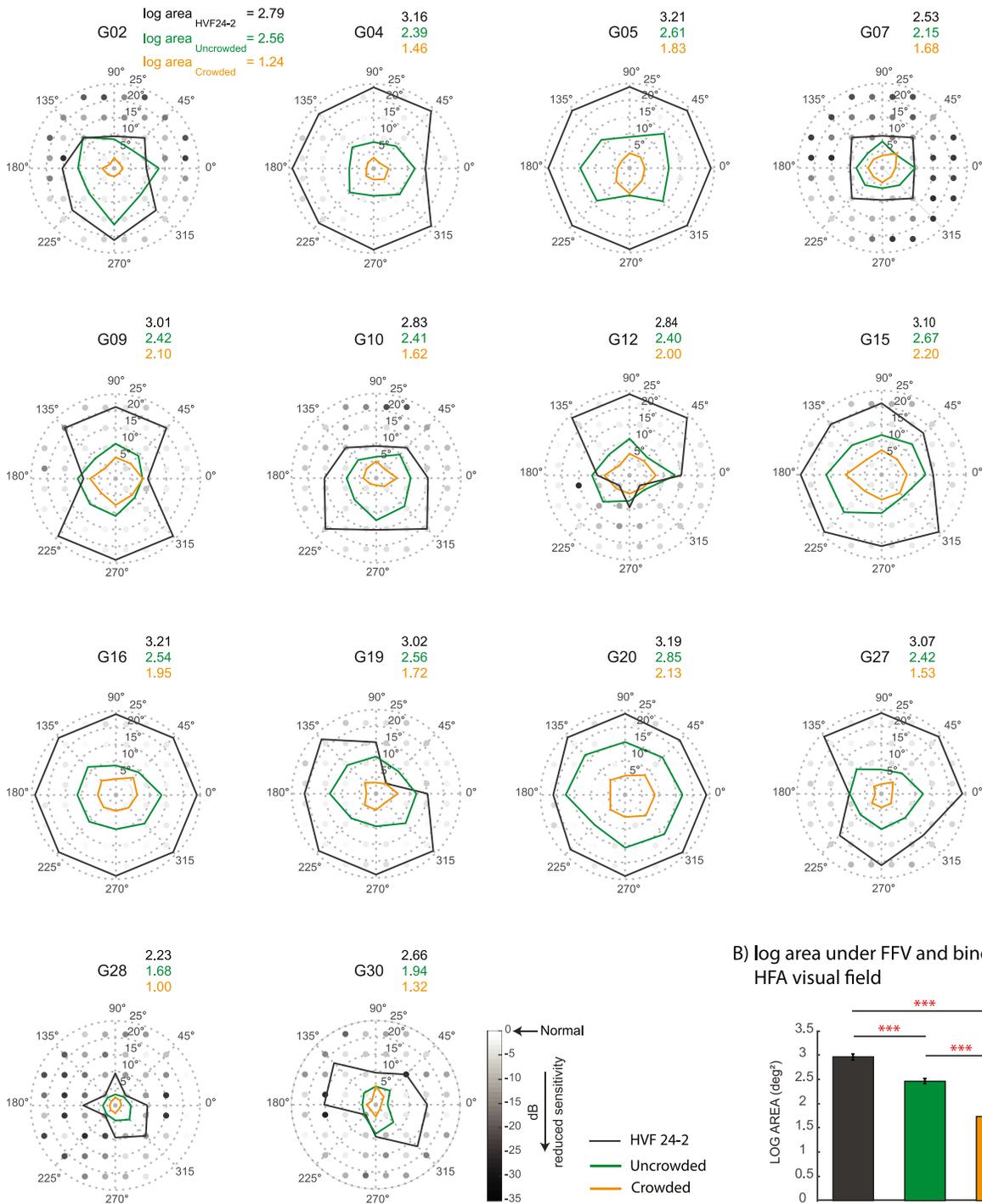


Figure 5. Comparisons between the binocular HFA visual field constructed from Humphrey Visual Field 24-2 test and uncrowded and crowded FFV. (A) The spatial extent of the FFV for a subset of glaucoma subjects for the crowded (orange line) and uncrowded (green line) conditions and spatial extent of the binocular HFA visual field (black line). The log area under the binocular HFA visual field and FFV (deg²) for uncrowded and crowded conditions are presented at the upper right corner of each polar map. (B) The bar graph visualizes the mean of log area under the binocular HFA visual field (black) and FFV (deg²) for uncrowded (green) and crowded (orange) conditions. Error bars represent ± 1 SEM. *** $P < 0.001$.

crowded conditions. To this end, we first constructed the binocular (integrated) visual field sensitivity map (hereafter we call it the binocular HFA visual field) using the monocular total deviation values (i.e., age-adjusted sensitivity values) where the binocular sensitivity value was set to the value of the more sensitive eye at each visual field location. Then, by tracing out the sensitivity values of -6 dB in the binocular visual field map, we determined visible boundaries for light detection. The value of -6 dB was chosen because it is usually considered to be mild sensitivity loss.³⁸

This comparison revealed that, for most subjects, the extent of field of view predicted by the binocular HFA visual field was noticeably larger than that of our FFV test in uncrowded and crowded conditions. Figure 5A visualizes the extent of the binocular HFA visual field (black lines) and the uncrowded (green lines) and crowded (orange lines) FFV for a subset of glaucoma subjects. The circles indicate binocular sensitivity values in the binocular HFA visual field where the darker colors indicate more sensitivity loss. The log area under the binocular HFA visual field (black) and uncrowded (green) and crowded (orange) FFV for each subject are shown in the upper right corner of the corresponding visual field map. Bar graphs in Figure 5B represent the mean values of log area under the binocular HFA visual field and our FFV under uncrowded and crowded conditions (deg^2). One-way ANOVA and pairwise comparisons were conducted on the mean values of log area under the field of views. The results showed that significant differences among the mean of the log area under the field of view between the three conditions ($F_{(2, 87)} = 114.46$, $P < 0.001$). More importantly, the binocular HFA visual field was significantly larger than that of the uncrowded (2.97 vs 2.46) and crowded (2.97 vs 1.74) FFV.

Another noteworthy point that was reported in previous findings^{42–45} is the asymmetry between the upper and lower field of view, with the lower visual field being larger than the upper visual field. Thus, we also examined the lower and upper visual field asymmetries in our FFV data. To this end, we calculated the area under the upper FFV (from 45° to 135° radial direction) and lower FFV (from 225° to 315° radial direction) for all subjects and both uncrowded and crowded conditions. Then, for each subject, the mean value of upper/lower FFV was obtained by taking the average of the upper/lower FFV over uncrowded and crowded conditions. Finally, we performed the pairwise t-test on the mean upper vs lower FFV for all subjects. Consistent with previous findings, we also observed a moderate yet statistically significant difference between

the lower vs upper FFV (1.34 vs 1.32, $t_{(75)} = 2.54$, $P = 0.013$).

Discussion and Conclusions

Although most visual information is obtained through central vision, parafoveal or peripheral vision is also important for various everyday activities such as reading,^{2–6,25,46,47} visual search,^{7–9} navigation,⁷ and driving.^{8,13–21} This is particularly relevant to those who suffer from visual field loss such as glaucoma. Because visual field loss comes in varying forms in terms of its shape and location, it is important to determine the spatial extent of a person's remaining vision relevant to everyday tasks. In this study, we investigated how crowding, aging, or glaucoma determines the spatial extent of the FFV. We adopted a new method that allows us to map out the spatial extent of the FFV across the visual field under divided attention. This divided attention task (i.e., dual task) in combination with the short stimulus duration (250 ms) was chosen because it is likely to reflect the difficulty that older or visually impaired individuals may experience in everyday tasks.^{12,18,19,29,31,32}

We found that, under divided attention, observers were fairly good at recognizing the peripheral target when it was presented alone within the central 20° visual field. However, when the target was presented in clutter, observers had great difficulty recognizing the target beyond the central 10° visual field considered as parafoveal vision (approximately 4° or 5° eccentricities). Regardless of age or ocular pathology, crowding shrunk the spatial extent of the FFV by about 50% on average (from about central 20° visual field for uncrowded condition to central 10° visual field for the crowded condition). Thus, as expected from previous studies on crowding,^{4,5,25,26,46,48–51} our results further confirmed that crowding indeed limits the spatial extent of the visual field within which target can be recognized reliably at one fixation.

Importantly, we also observed a relatively small yet statistically significant decrease in the FFV due to either normal aging or glaucoma. These results are consistent with previous findings showing that both aging and visual disorders impair the ability to exclude task-irrelevant information,^{52–54} to split attention across different targets or visual field,^{19,53,55} or to process visual information rapidly.^{9,56} For example, Gazzaley et al.⁵² investigated the relationship between inhibitory deficits and processing speed in aging populations. Their results suggested a selective deficit in suppressing task-irrelevant information in the early

stages of visual processing, in older adults compared with young adults during the encoding phase of a visual working memory task. In their study, participants were asked to view two types of stimuli, namely, faces and scenes, and to respond whether the third image matched the previous images. Specifically, they showed that the use of suppressive mechanisms is delayed in time with aging, thereby causing a decrease in processing speed. Interestingly, the electrophysiological results suggested that delayed suppressive mechanisms are originated from excessive attention to early distracting information. Furthermore, Rubin et al.¹⁵ administered vision (visual acuity, contrast sensitivity, glare sensitivity, stereoacuity, and visual fields) and attention (UFOV score, a composite of processing speed, divided attention, and selective attention) tests in older adults to investigate the risk of crash involvements. Their results showed that older age and visual impairment were associated with a decrease in divided attention measured by the UFOV test. Moreover, they showed that glare sensitivity, visual fields, and UFOV, especially the divided attention, were significant predictors of crash involvement, suggesting the adverse effect of visual impairment on driving. In addition, Dive et al.,⁵⁷ after administering a familiar sandwich making task and a less familiar model-building to both patients with glaucoma and normally sighted controls, showed that patients with glaucoma were slower in performing the unfamiliar model-building task and exhibited longer fixation and more saccades for both relevant and irrelevant objects compared with normal controls, suggesting a slower processing of visual information in patients.

As shown in Figure 4, this detrimental effect of aging or glaucoma was more pronounced in the uncrowded condition (statistically significant) compared with the crowded condition (not significant). However, previous studies²⁶ showed that both aging and crowding resulted in increased crowding. One possible explanation for this discrepancy might have to do with the obvious methodological differences between our previous studies and the current one. For example, in previous work, the crowding zone (i.e., a minimum spacing between the target and flankers yielding a criterion recognition accuracy) was estimated using a peripheral target recognition task where a subject paid their full attention to the peripheral target appearing in clutter. In contrast, the task in the current study required a subject to judge whether the target appearing in the central fixation point is identical to the concomitant peripheral target appearing in clutter (i.e., target matching task under divided attention and under crowded condition). We believe that the task difficulty imposed by the current study

might have reached its maximum capacity, thereby leaving very little room for any further decrease by aging or glaucoma for the crowded condition. Alternatively, it might also have to do with the age range and the severity of glaucoma used in the current study. The majority of our patients with glaucoma fall under either mild or moderate glaucoma. And all of our older adults are in their 60s. Therefore, future studies may need to evaluate the FFV in patients with more severe glaucoma to determine the impact of severity or progression of the disease and its impact on the FFV. Also, a larger range of older subjects (ages of ≥ 70 years) may need to be tested to better characterize the effect of aging on the FFV. Additionally, the greater intersubject variability observed under crowded condition might have contributed to weakening the power for us to detect a signal, if any. Indeed, when we examined the effect of aging and glaucoma on the deviation of the spatial extent of the FFV shown in Figure 4E and 4F, we found that both aging and glaucoma resulted in higher intersubject variability under crowded condition compared with uncrowded one.

It is also noteworthy that our FFV test requires letter recognition in which observers have to recognize the target letters concurrently appearing in the fovea and peripheral vision. However, the spatial extent of the FFV is likely to depend on the nature of task (e.g., detection vs. recognition) and the properties of target stimulus (e.g., face, objects, light spot). For example, Strasburger et al.⁵⁸ showed that the spatial extent of the visual field defined by single letter recognition is much smaller than the visual field defined by light spot detection (static perimetry). Consistent with these previous findings, we also found that on average, the extent of visual field predicted from the HVF 24-2 test was significantly larger than that of our FFV under uncrowded and crowded conditions (Fig. 5). These results suggested that although the visual field perimetry measured with light detection may provide valuable information about visual field loss, it may not reflect the FFV relevant to everyday visual activities (i.e., object recognition under divided attention and in clutter). Thus, the FFV test can be used as a complementary method to assess visual field loss in real world context.

In summary, using a novel quantitative method, the spatial extent of the FFV was measured under divided attention. We showed that crowding, aging, and glaucoma independently reduce the spatial extent of the FFV under divided attention, while crowding seems to be the major contributor limiting the FFV. Our findings further suggest that our FFV test may complement standard clinical measurements such as visual acuity or perimetry by providing functionally relevant visual field information.

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