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Reduced spatial attentional distribution in older adults

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Older adults show decline in visual search performance, but the underlying cause remains unclear. It has been suggested that older adults' altered performance may be related to reduced spatial attention to peripheral visual information compared with younger adults. In this study, 18 younger (*M* = 21.6 years) and 16 older (*M* = 69.1 years) participants performed pop-out and serial visual search tasks with variously sized gaze-contingent artificial central scotomas (3°, 5°, or 7° diameter). By occluding central vision, we measured how attention to the periphery was contributing to the search performance. We also tested the effect of target eccentricity on search times and eye movements. We hypothesized that, if attention is reduced primarily in the periphery in older adults, we would observe longer search times for more eccentric targets and with central occlusion. During the pop-out search, older adults showed a steeper decline in search performance with increasing eccentricity and central scotoma size compared with younger adults. In contrast, during the serial search, older adults had longer search times than younger adults overall, independent of target eccentricity and scotoma size. Longer search times were attributed to higher cost-per-item slopes, indicating increased difficulty in simultaneously processing complex symbols made up of separable features in aging, possibly stemming from challenges in spatially binding individual features. Altogether, our findings point to fewer attentional resources of simultaneous visual processing to distribute over space or separable features of objects, consistent with decreased dorsal visual stream functioning in aging.

Introduction

Visual search involves actively scanning a visual scene to find a specific object among other objects, such as looking for a spoon among a drawer of cutlery. Older adults show a decline in visual search performance such that they tend to have longer search times compared with younger adults (Hommel, Li, & Li, 2004; Humphrey & Kramer, 1997; Madden, Pierce, & Allen, 1996; Müller-Oehring, Schulte, Rohlfing, Pfefferbaum, & Sullivan, 2013; Plude & Doussard-Roosevelt, 1989; Scialfa, Esau, & Joffe, 1998). This decline has been associated with general slowing of motor and sensory processes, affecting eye movement planning or peripheral vision, respectively (Irving, Steinbach, Lillakas, Babu, & Hutchings, 2006; Lindenberger & Baltes, 1994; Paquette & Fung, 2011; Rosenholtz, Huang, & Ehinger, 2012), as well as perceptual processes, such as target and motion detection (Madden, Gottlob, & Allen, 1999; Salthouse, Hancock, Meinz, & Hambrick, 1996). Changes in cognitive processes such as working memory (Baddeley, 1996; Kramer, Hahn, & Gopher, 1999; Park & Reuter-Lorenz, 2009) and attention (Greenwood & Parasuraman, 1999; Müller-Oehring et al., 2013; Russell, Malhotra, Deidda, & Husain, 2013; Wolfe, Cave, & Franzel, 1989) have also been hypothesized to contribute to this decline. More precisely, previous studies have suggested that peripheral attentional allocation may be reduced in aging (Astle, Blighe, Webb, & McGraw, 2014;

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Beurskens & Bock, 2012; Hommel et al., 2004; Muiños, Palmero, & Ballesteros, 2016; Plude & Doussard-Roosevelt, 1989; Yu, Cheung, Legge, & Chung, 2010). For example, in the context of visual search, peripheral visual span, or the spatial range of attention to the periphery, has been shown to decline with age (Yu et al., 2010). In the same vein, adding a secondary attentional central task to visual search affected the peripheral performance of older adults to a much greater extent than the younger adults' performance (Ball, Beard, Roenker, Miller, & Griggs, 1988; Russell et al., 2013; Sekuler, Bennett, & Mamelak, 2000). However, other studies have reported no decline in peripheral attention in aging (Astle et al., 2014; Hommel et al., 2004; Muiños et al., 2016). For example, Muiños et al. (2016) found that the cost of detecting eccentric targets compared with foveal targets did not differ between older and younger adults. Thus, it remains unclear whether peripheral attention is specifically reduced in older adults.

Previous studies have shown that different types of search (pop-out vs. serial) tend to differentially allocate attentional resources because spatial attention and object difficulty interact in visual search (Khan et al., 2016; Young & Hulleman, 2013). In pop-out, parallel, or efficient search, the target is defined by a prominent basic feature, easily distinguishable from distractors, and can be detected easily (Joseph, Chun, & Nakayama, 1997; Palmer, Fencsik, Flusberg, Horowitz, & Wolfe, 2011). In contrast, serial search involves top-down attentional processes to a much greater degree (Palmer et al., 2011) because the target shares more features with the distractors, often requiring the conjunction of different features. The target is thus more difficult to distinguish (Treisman & Gelade, 1980; Wolfe & Horowitz, 2004). It has been suggested that the pop-out search relies on bottom-up processing of the entire visual scene, whereas serial search requires top-down processing of a small group of features or items serially (Eckstein, 2011; Palmer et al., 2011; Treisman & Gelade, 1980). This leads to a small cost per item in pop-out search and a high cost per item in serial search. Using different-sized gaze-contingent visible windows, a recent study demonstrated that young adults performed visual search using different-sized attentional windows (i.e., peripheral visual spans) that depended on the difficulty of the visual search (Khan et al., 2016). The attentional window was defined as the attentional workspace around a single fixation within which all items are processed. The study by Khan et al. (2016) demonstrated that easy pop-out searches were performed using larger attentional windows, but more difficult serial searches tended to be performed with much smaller attentional windows. The authors concluded that for easy pop-out searches, attention was distributed further to the periphery (i.e., spans of 10°–20° eccentricity), whereas for more difficult serial searches attention tended to be directed closer toward the fovea (i.e., spans of 7°–10° eccentricity). Other studies have found that visual attention could also be directed to a limited number of objects when all distractors consisted of different spatial configurations of the same separable features (Vialatte, Salemme, Khan, & Pisella, 2021a).

To investigate the distribution of peripheral attention in older adults, we compared search performance and eye movements of younger and older adults during pop-out and serial visual search tasks while occluding foveal/parafoveal vision using different-sized gaze-contingent artificial central scotomas (Larson & Loshchky, 2009; Rayner & Bertera, 1979; Rayner & McConkie, 1976; van Diepen, Wampers, & d'Ydewalle, 1998). We reasoned that occluding foveal/parafoveal vision would force participants to perform the task with only peripheral attention; therefore, the impact of the central scotomas on search times and eye movements would reflect the efficiency of peripheral attentional distribution. Along these lines, we also investigated performance for targets that were closer to fixation compared with farther in the periphery in full-view control conditions. We predicted that older adults should take longer to find targets in the periphery than younger adults.

Methods

Participants

We recruited a total of 34 participants from the University of Montreal and the community: 18 young adults ($M = 21.6$ years; $SD = 1.4$ years; age range, 19–25 years; 12 females, including two authors AL and JO-E) and 16 older adults ($M = 69.1$ years; $SD = 6.5$ years; age range, 60–83 years; six females). This sample size was determined after a power analysis was conducted using G*Power (Erdfelder, Faul, & Buchner, 1996) based on a within-between repeated-measures analysis of variance (ANOVA) test, with two groups and two measurements per group. From a previous similar visual search study from our laboratory (Ouerfelli-Ethier et al., 2018), we calculated an effect size of 0.33 (based on a partial eta squared [η^2_p] value of 0.1 for pop-out search comparing older and younger groups). The calculated total sample size was 32.

All participants had normal or corrected-to-normal vision, had no neurological disorders, and were not taking any medication that could potentially influence their performance on the visual search tasks with respect to attention. They gave their free and informed consent before testing and received financial compensation upon participation completion. All experimental procedures were approved by the Health

Research Ethics Committee (CERES) of the University of Montreal.

Apparatus

Participants performed two types of visual search tasks (pop-out and serial) with and without scotomas. Tasks were designed and implemented using MATLAB R2016b (MathWorks, Natick, MA) with Psychophysics Toolbox (Brainard, 1997). Testing occurred in a dark room where participants sat in front of a VIEWPixx 3D display (20.5 × 11.5 inches, 1920 × 1080 pixels, 120 Hz; VPixx Technologies, Montreal, QC, Canada), with an eye–screen distance of 57 cm (Figure 1A). We recorded participants' eye movements at 1000 Hz with an EyeLink 1000 Plus eye tracker set in a binocular tower mount (SR Research, Ottawa, ON, Canada). To restrict head movements, the participant's forehead and chin were stabilized on a rest. We recorded button-press responses using a RESPONSEPixx handheld response box (VPixx Technologies).

We simulated an artificial circular invisible scotoma (i.e., invisible from the white background) (see Figure 1B) with a diameter of 3°, 5°, or 7°, corresponding to a radius of 1.5°, 2.5°, or 3.5°, respectively, of eccentricity from fixation. These sizes were used because they sample different foveal and parafoveal ranges determined from previous reading studies (Balota, Pollatsek, & Rayner, 1985; Pan, Frisson, & Jensen, 2021; Rayner & Bertera, 1979), as well as scene perception studies (Coletta & Williams, 1987; Larson & Loschky, 2009).

The scotoma was aligned on the participant's central vision based on a two-step calibration process at the beginning of each experimental block. We first calibrated the participant's right eye with a standard nine-point EyeLink calibration/validation procedure, according to the manufacturer instructions; an acceptable calibration is coded green. A second 15-point calibration (custom MATLAB script) was then performed to precisely align the scotoma on the participant's fovea. Participants were asked to fixate each of the 15 fixation dots, which were presented in random order equally spaced across a grid spanning 4/5 of the screen, and then to press a button. To enhance fixation stability and precision, fixation dots were a combination of a bullseye and a cross-hair (Thaler, Schütz, Goodale, & Gegenfurtner, 2013). A custom MATLAB script mapped the eye positions to the fixation dot locations using a polynomial fit with six parameters. These parameters were then used to adjust eye position from the parameters of the EyeLink for accurate scotoma presentation and eye position recording; according to the analysis, the standard EyeLink calibration resulted in a mean error of 2.21° in absolute distance (distance between the recorded position and the actual target positions), but the second calibration reduced this error to 0.53°.

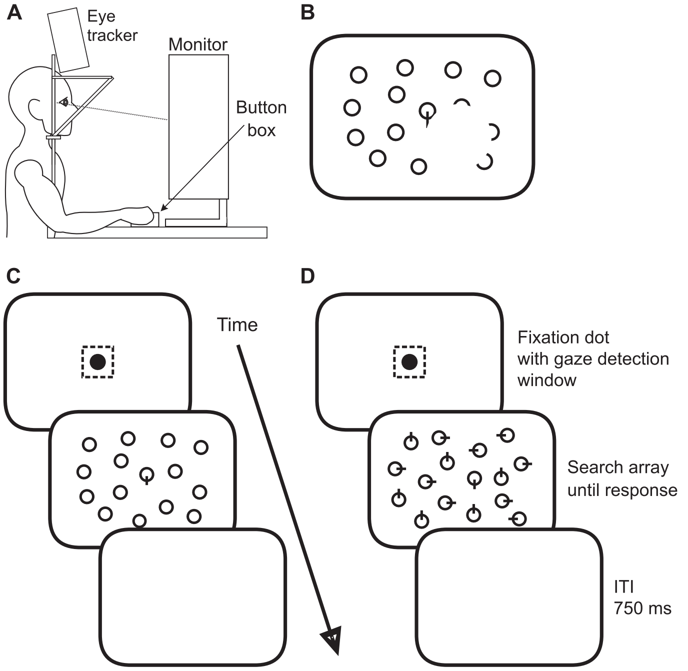

Figure 1. Experimental setup and cognitive tasks. (**A**) Apparatus. Participants sat in front of a computer screen with their head stabilized. Their eye movements were recorded with an infrared camera. (**B**) Artificial invisible gaze-contingent scotoma. A white scotoma invisible from the white background masked participants' central vision. Possible scotoma diameters were 3°, 5°, and 7° of visual angle. (**C**) Pop-out visual search task experimental sequence. Participants fixated the center of the screen (dotted lines represent the gaze-detection window), then searched for a circle with a vertical line crossing the bottom half target among circular distractors (feature-present visual search). With a button box, they reported as quickly as possible whether or not the target was present within the search array. (**D**) Serial visual search. Participants searched for the same circle with a vertical line crossing the bottom-half target among distractors, which were the same symbol as the target but rotated at 90°, 180°, and 270°. Participants indicated as quickly as possible whether or not the target was present using the button box.

To prevent the scotoma from following the eye downward during blinks, we froze the scotoma in place whenever the velocity in the vertical direction exceeded 900°/s. In addition, the entire search array blurred so that participants could not distinguish distractors and target. In terms of timing, the minimum delay between the position of the eye and the scotoma was approximately 3 ms. The end-to-end sample delay for eye recording at 1000 Hz was 1.95 ms (SR Research). There was approximately 1 ms between the time at which the eye position was determined and the rendering of the scotoma (Psychophysics Toolbox; Brainard, 1997). The maximum time was determined by the screen refresh rate of 8.3 ms.

Stimuli and procedure

Overall, participants completed the tasks in two or three sessions of approximately 1 hour, each spanning over 1 to 2 weeks. The experimental procedures differed between groups to prevent fatigue in the older adults. Younger adults performed eight blocks of 75 trials in a randomized order with four different conditions: full view without scotoma and 3°, 5°, and 7° diameter scotomas for each of the two visual search types. Older adults performed 16 blocks of 45 trials each, representing two blocks per condition and per search type. The first two blocks were full-view blocks randomized across search types, followed by the remaining six blocks also in a randomized order. The order of the eight blocks was then counterbalanced to control for fatigue and order effects.

We instructed participants that they were to indicate whether the target was present or absent as quickly and accurately as possible. We also informed them that they would perform the task in full view, with central scotomas occluding their central vision to varying degrees, and that the target would not be present some of the time. Participants were given 10 practice trials, with feedback, each for the pop-out and serial tasks. Finally, they were reminded of the total number of blocks and of the approximate duration of the experiment.

Across both tasks, the target was present in 80% of trials within each block. We focused on target-present trials rather than target-absent trials because of task difficulty. Through pilot testing, we determined that the task with the scotoma present was very difficult to undertake, particularly for older adults. Initial testing with 50% target-absent trials resulted in extremely long trial durations and frustration. Therefore, we decided to decrease target-absent trials to 20%, enough to be able to determine compliance to task instructions but not to overly tax participants. Participants were not informed of the target-present/target-absent distribution. We did not analyze target-absent trials in the subsequent analysis; they were catch trials used to ensure participants were performing the task correctly.

The number of items (set size of 16, 32, or 64) was equally and randomly presented among the trials. Among target-present trials, target location was randomly distributed evenly across each of the four quadrants of the search array space and eccentricity from the center of the array.

Pop-out visual search

Each trial began with a black fixation dot (1° diameter) set against a white background (Figure 1C). Gaze detection was applied within a window of 2° × 2° around the fixation dot. When gaze was detected within this window, the fixation dot was replaced with a square search array (24° × 24°), centered on the screen, composed of 16, 32, or 64 items, comprised of distractors and the target, if present. Distractors were circles (1.1° diameter), and the target, when present, was the same circle except with a vertical line (0.75°) crossing the bottom half (also known as a feature-present visual search) (Treisman & Souther, 1985). The target was presented at different positions and eccentricities in each trial within the search array.

Participants pressed one of two buttons to indicate whether the target was present or absent. Upon their response, the search array disappeared, and a blank screen appeared for an intertrial interval of 750 ms. At the end of each block, participants received feedback about their performance in terms of percent correct responses.

Serial visual search

The search task trial sequence was identical to the pop-out version, except for the appearance of the target and distractors (Figure 1D). The target, when present, consisted of a circle with a vertical line crossing the bottom half. Distractors, in contrast, were the same symbol as the target but rotated at 90°, 180°, or 270°.

Data analysis

We collected a total of 22,631 trials. We visually verified eye movements in each trial using a custom-made MATLAB analysis code. Saccades were automatically detected using a saccade detection algorithm with a velocity criterion of 15°/s and verified visually. We manually removed trials in which the camera lost the position of the eye or the eye movement recording was too noisy. This resulted in 21,017 remaining trials.

We calculated (a) response times (RTs), the time of the button press from the time of the search array onset; (b) total number of saccades made; (c) mean saccade amplitude, the average of the amplitudes of each saccade calculated as absolute distance from beginning and end of the saccade; and (d) mean fixation duration, the average duration of each fixation, calculated between consecutive saccades, from the first saccade to the last. We verified that participants performed the task correctly by calculating the percentage of correct button presses in target-absent and target-present trials. To further validate the tasks, we compared the participants' RTs for target-absent and target-present trials as a function of set size, separately for each group and search type.

For subsequent analyses, we only considered target-present correct trials, of which there was a total of 15,870. We removed all trials with outlier RTs, which were defined as those in which the RT was outside of 3 *SD* of the mean RT for each participant and condition (341 trials, 164 for older adults and 177 for younger adults). To obtain the means for each condition, we calculated the means of all measures for each set size (16, 32, and 64 items) and then averaged across the three set sizes (to consider uneven number of trials for each set size for each participant).

For the full-view conditions, we compared mean RTs, accuracy (i.e., correct button presses) and eye movement parameters for the two groups and the two search types. We also calculated cost per item to ascertain task difficulty. The cost per item was calculated by fitting a slope to the RTs across the three set sizes.

We additionally analyzed RTs, accuracy, and eye movement parameters as a function of target eccentricity for the full-view conditions, separately for the pop-out and serial search conditions. Target eccentricity from the center of the search array was divided into four groups: E1 (<3.5°), E2 (3.5° to <7°), E3 (≥7° to <10.5°), and E4 (≥10.5°). Finally, we analyzed RTs, accuracy, and eye movement parameters for each scotoma condition compared with the full-view condition for the two search tasks comparing across groups.

Separately for each task, we compared the search RT, accuracy, and eye movement parameters using mixed ANOVAs, with group as a between-subject factor and condition (search type, eccentricity, and scotoma size) as the within-subject factor, as well as paired-sample *t*-tests. We adjusted any results with Greenhouse–Geisser and Welch corrections when necessary and followed up any significant results with the appropriate post hoc tests, with Holm–Bonferroni family-wise corrections. We also estimated the extent to which performance differences could be explained by our manipulations with effect sizes. We used partial eta squared ($\eta^2{}_p$) to calculate effect sizes for ANOVAs (Lakens, 2013).

We verified that performance for the two authors (AL and JO-E) was not different from the performance of the rest of the younger group; their RT *z*-scores ranged from −1.41 to 0.4 for AL and from −1.12 and −0.07 for JO-E across all conditions. We also wanted to further verify whether any learning effects could influence participants' performances across scotoma conditions. To do this, we proceeded differently for younger and older participants, as their condition blocks were arranged differently.

Older adults performed each condition twice in a randomized counterbalanced order (the second time in the reverse order than the first time, randomized), starting and ending with control conditions. Thus, for this group, we compared their RTs across their block order, separately for each control condition. More precisely, we used paired-sample *t*-tests to verify whether their performance was different when they performed the pop-out and serial conditions as their first blocks compared with when they performed it as their last blocks. We found no evidence of learning in pop-out search, $t(15) = 1.48$, $p = 0.159$), but there was a learning effect in serial search, $t(14) = 3.7$, $p = 0.002$. For this group, because we averaged their performance across first (i.e., non-trained) and last (trained) blocks, this minimized any confounding effect, if any, due to learning.

For younger adults, because their block order was not counterbalanced, we re-examined each significant main condition effect according to the chronological order in which participants completed the tasks. To do this, we examined the percentage of times across participants in which the more difficult conditions, with longer response times, were performed before the easier conditions, with shorter response times. If the percentage of times for the more difficult conditions first was 50% or less, then a learning effect was unlikely because learning would have resulted in shorter response times for the more difficult conditions later on, thus reducing the likelihood of observing an effect of the condition. However, if the percentage of times was much higher than 50%, then we would consider that the effect might have been amplified by trial order.

Results

Full-view conditions

Effect of target presence, set size, and group

In order to validate our tasks, we first investigated search RTs in the full-view conditions for target-present and target-absent conditions. In each search type, shown in Figure 2, we conducted repeated-measures ANOVAs with target presence, group, and set size (16, 32, or 64 items) as factors.

For pop-out search, we found main effects of set size, $F(1.76, 56.43) = 35.10$, $p < 0.001$, $\eta^2{}_p = 0.52$; target presence, $F(1, 32) = 225.08$, $p < 0.001$, $\eta^2{}_p = 0.88$; and group, $F(1, 32) = 59.31$, $p < 0.001$, $\eta^2{}_p = 0.65$. We also found interaction effects between target presence and group, $F(1, 32) = 26.26$, $p < 0.001$, $\eta^2{}_p = 0.45$, and between set size and target presence, $F(1.49, 47.54) = 8.81$, $p = 0.002$, $\eta^2{}_p = 0.22$.

In serial search, we also found main effects of set size, $F(1.10, 35.26) = 74.67$, $p < 0.001$, $\eta^2{}_p = 0.70$; target presence, $F(1, 32) = 98.55$, $p < 0.001$, $\eta^2{}_p = 0.76$;

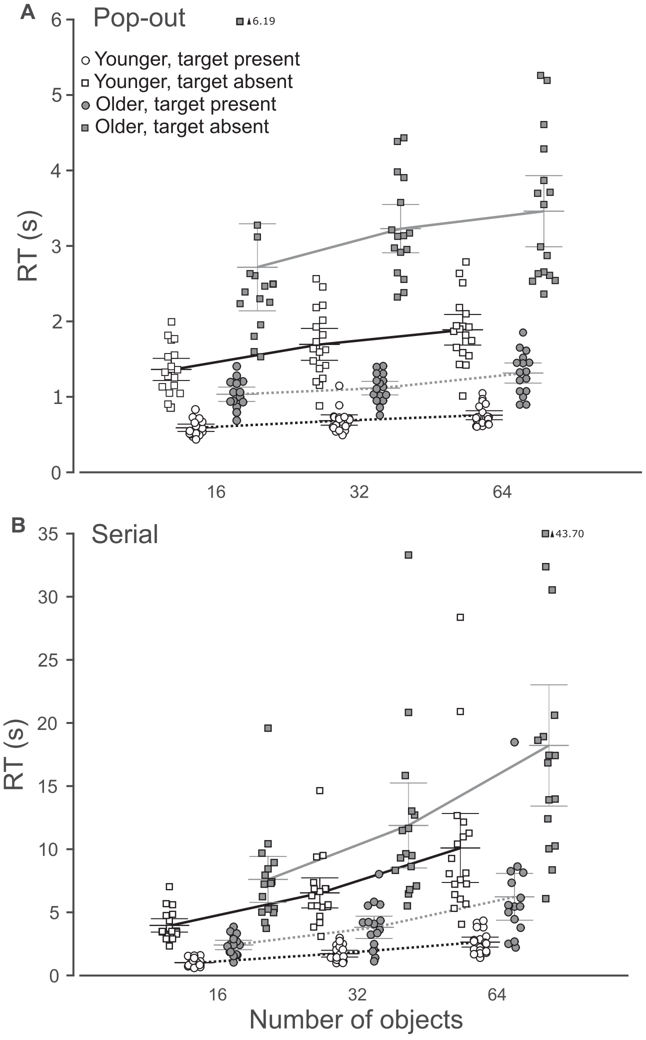

Figure 2. Response times as a function of set size (number of objects) and target presence across full viewing pop-out and serial search tasks. Mean RTs plus *SEM* (in seconds) and individual RTs are shown for target-present (circles) and target-absent (squares) conditions and for younger (black dots and squares) and older (gray dots and squares) adults across three set sizes (16, 32, and 64 items). (**A**) Pop-out search RTs. The upward arrow represents data not shown for an older adult with a high mean RT of 6.19 seconds in the set size of 64 items. (**B**) Serial search RTs. The upward arrow represents data not shown for an older adult with a high mean RT of 43.7 seconds in the set size of 64 items.

and group, $F(1, 32) = 13.12$, $p < 0.001$, $\eta^2_p = 0.29$. We also identified interactions between set size and group, $F(1.10, 35.26) = 6.86$, $p = 0.011$, $\eta^2_p = 0.18$, and between target presence and group, $F(1, 32) = 6.06$, $p = 0.019$, $\eta^2_p = 0.16$.

In sum, both participant groups took longer to respond when the target was absent compared with when it was present, for both search types, which validated our method (Humphrey & Kramer, 1997; Madden et al., 1996). Both participant groups also had longer RTs with larger set size for both search types, indicating that feature-present search was not fully parallel. This pattern replicated previous findings indicating that pop-out and serial searches occur along a gradient of cost per item rather than clear-cut dissociated categories (Khan et al., 2016).

To further validate our method, we computed response accuracy for target-present and target-absent trials. We confirmed that across all conditions both younger and older adults were accurate and pressed the target-absent button when no target was presented ($M_{younger\ adults} = 97.8\%$, range 95.2%–100%; $M_{older\ adults} = 96.8\%$, range 91.6%–100%) rather than automatically pressing the same button at every trial. As for target-present trials, both younger and older adults were also accurate and pressed the target-present button in target-present trials ($M_{younger\ adults} = 95.5\%$, range 91.9%–98.1%; $M_{older\ adults} = 91\%$, range 81.7%–97.2%), indicating that they actively searched for the target.

Effect of search type and group

Accuracy

We examined error rates in target-present trials with repeated-measures ANOVAs with search type and group as factors. Our analyses revealed only a main effect of search type, $F(1, 32) = 31.48$, $p < 0.001$, $\eta^2_p = 0.50$, in which pop-out search was performed more accurately. The difference between pop-out and serial search performance was 5.96% ($t = 5.61$, $p < 0.001$). In pop-out search, mean accuracy was 97.44% for younger adults ($SD = 1.73\%$) and 96.99% for older adults ($SD = 1.91\%$). In serial search, mean accuracy was 93.17% for younger adults ($SD = 6.06\%$) and 89.33% for older adults ($SD = 6.47\%$).

Response Times

As can be seen in Figure 3, RTs were higher for older adults overall compared with younger adults and for the serial search task compared with the pop-out search task. A two-way mixed ANOVA with group (younger and older) and search task (pop-out and serial) as factors revealed a significant main effect for group, $F(1, 32) = 27.32$, $p < 0.001$, $\eta^2_p = 0.46$, and search task, $F(1, 32) = 68.37$, $p < 0.001$, $\eta^2_p = 0.68$, as well as a significant interaction effect, $F(1, 32) = 15.02$, $p < 0.001$, $\eta^2_p = 0.32$.

Post hoc Holm–Bonferroni corrected *t*-tests indicated that both younger adults ($p_{holm} = 0.009$) and older adults ($p_{holm} < 0.001$) had longer RTs in serial search (younger = 1638 ms, older = 3810 ms) compared with pop-out search (younger = 658 ms, older = 1103 ms). In addition, comparing within condition, the two

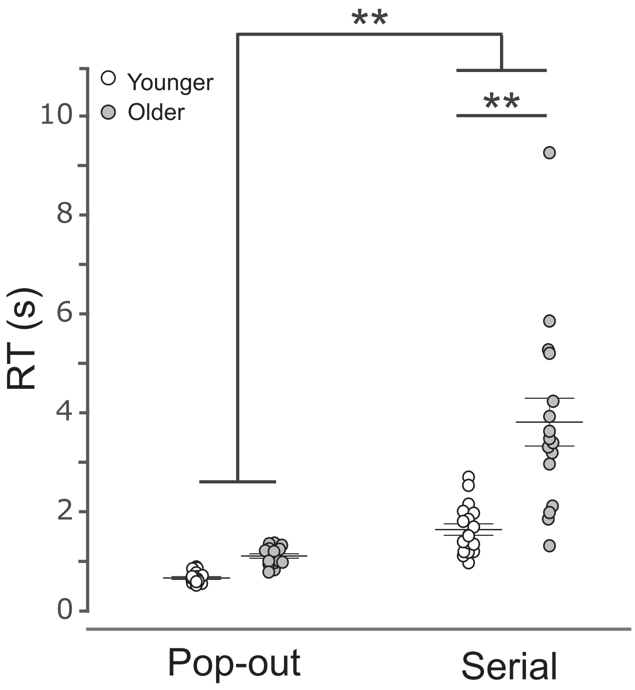

Figure 3. Younger and older adults’ mean RTs across full-viewing pop-out and serial search tasks. Mean RTs (in seconds) are shown for the two tasks for younger adults (open circles) and older adults (gray filled circles). The error bars represent *SEM*.

groups were not different for the pop-out search (p_{holm} = 0.23) but they were for the serial condition ($p_{holm} <$ 0.001). This suggests that RTs increased for serial search compared with pop-out search to a much greater degree for older adults as shown by the significant interaction effect.

Cost per item

We also observed that the mean cost per item for the pop-out condition was 3.04 ($SD = 1.56$) for the younger group and 5.27 ($SD = 3.97$) for the older group. For the serial condition, the mean cost per item was 24.43 ($SD = 13.3$) for the younger group and 58.6 ($SD = 58.31$) for the older group. A two-way mixed ANOVA with group (younger and older) and search type (pop-out and serial) as factors revealed significant main effects for group, $F(1,32) = 6.74$, $p = 0.014$, $\eta^2_p = 0.17$, and search task, $F(1, 32) = 27.37$, $p < 0.001$, $\eta^2_p = 0.46$. We also found a significant interaction effect, $F(1, 32) = 5$, $p = 0.032$, $\eta^2_p = 0.14$. Post hoc *t*-tests performed separately for each group revealed that the younger group’s mean costs per item were not different across the two tasks ($p_{holm} = 0.11$), but the older group’s were different, ($p_{holm} < 0.001$). In addition, in the pop-out task, the costs per item did not differ between the two groups ($p_{holm} = 0.824$), but they did for the serial task ($p_{holm} = 0.004$).

In summary, consistent with previous studies (Cornelissen, Bruin, & Kooijman, 2005; Hommel et al., 2004; Madden et al., 1996; Plude & Doussard-Roosevelt, 1989; Treisman & Gelade, 1980), we observed that (a) the cost per item was greater for serial search than for pop-out for older participants only, (b) older participants had longer RTs and higher costs per item overall compared with the younger participants for the serial task only, and (c) the increase in RTs and costs per item for serial compared with pop-out was greater overall for older participants.

Number of saccades

As shown in Figure 4A, a repeated-measures ANOVA examining the mean number of saccades with search type and group as factors revealed main effects of search type, $F(1,31) = 91.69$, $p < 0.001$, $\eta^2_p = 0.75$, and group, $F(1,31) = 15.47$, $p < 0.001$, $\eta^2_p = 0.33$, as well as an interaction effect, $F(1,31) = 8.53$, $p = 0.006$, $\eta^2_p = 0.22$. The two groups did not differ significantly in pop-out condition ($p_{holm} = 0.26$) but had a mean difference of 4.77 saccades in the serial condition ($t = 4.89$, $p_{holm} < 0.001$). There were differences between search types for both groups (younger: $t = 4.94$, $p_{holm} < 0.001$; older: $t = 8.46$, $p_{holm} < 0.001$). Thus, although similar to younger adults in the pop-out search, older adults made increasingly more saccades in the serial search.

Saccade amplitude

We also compared mean saccade amplitude using repeated-measures ANOVA with search type and group as factors (Figure 4B). We observed main effects of search type, $F(1, 32) = 25.24$, $p < 0.001$, $\eta^2_p = 0.44$, and group, $F(1, 32) = 8.17$, $p = 0.007$, $\eta^2_p = 0.20$. Post hoc *t*-tests revealed main differences of 0.64° between search types ($t = 5.02$; $p_{holm} < 0.001$) and 0.56° between groups ($t = 2.86$; $p = 0.007$). Older adults thus generally made shorter saccades than younger adults, and saccade amplitude decreased in a similar manner for both groups in serial search compared with pop-out search.

Fixation duration

Using a repeated-measures ANOVA with search type and group as factors, we found main effects of search type, $F(1, 32) = 115.68$, $p < 0.001$, $\eta^2_p = 0.78$, and group, $F(1, 32) = 14.97$, $p < 0.001$, $\eta^2_p = 0.32$, as shown in Figure 4C. Mean differences were 71.90 ms between search types ($t = 10.76$, $p_{holm} < 0.001$) and 43.66 ms between groups ($t = 3.89$, $p_{holm} < 0.001$). Average fixation duration was longer in older adults, and both

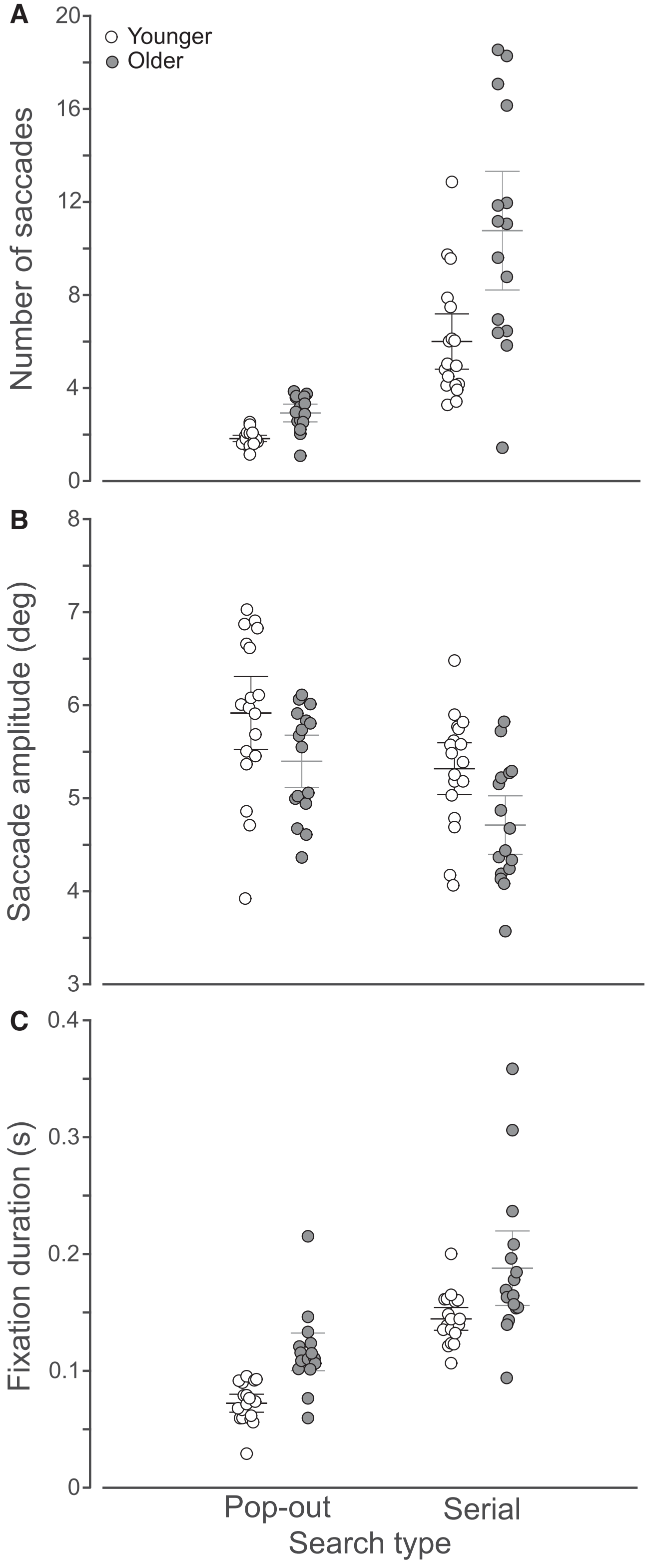

Figure 4. Younger and older adults' eye movement parameters across full-viewing pop-out and serial search tasks. Mean number of saccades, saccade amplitude in visual degrees, and fixation duration in seconds, as well as individual data, are shown for younger (black dots) and older (gray dots) adults across pop-out and serial search. The error bars represent *SEM*. (**A**) Mean number of saccades. (**B**) Mean saccade amplitude. (C) Mean fixation duration.

groups fixated longer in serial search compared with pop-out search.

Effect of target eccentricity and group

It has been shown that target eccentricity exerts an influence on target detection in visual search tasks, leading to increased target detection times as eccentricity increases (Carrasco, Evert, Chang, & Katz, 1995). We hypothesized that this is related to peripheral attention, in that less attention to the periphery around current fixation decreases the likelihood of detecting an eccentric target. With reduced peripheral attention, participants would have to look around more for the target using central attention, particularly when it was further from the center of the screen, where search begins. Therefore, if older participants allocated fewer attentional resources to the periphery, it should take them longer to find a more eccentric target compared with younger adults. To investigate this, we performed two-way repeated measures ANOVAs on error rate, RT, and eye movement parameters with group and eccentricity as factors separately for the pop-out and serial search tasks. As such, we divided target eccentricity from the center of the search array into four distances: E1 ($<3.5°$), E2 ($3.5°$ to $<7°$), E3 ($\geq 7°$ to $<10.5°$), and E4 ($\geq 10.5°$).

Accuracy

In pop-out search, a repeated-measures ANOVA with eccentricity (E1–E4) and group as factors revealed a main effect of eccentricity only, $F(1.90, 60.74) = 41.31$, $p < 0.001$, $\eta^2{}_p = 0.56$. Post hoc *t*-tests revealed differences between the farthest location from center compared with all others (all $t \geq 7.84$; all $p_{holm} < 0.001$). In serial search, with the same analysis, we also found a main effect of eccentricity, $F(2.27, 72.60) = 5.98$, $p = 0.003$, $\eta^2{}_p = 0.16$. Post hoc comparisons revealed differences between the second closest distance from center (E2) and all others (all $t \geq 2.56$; all $p_{holm} \leq 0.049$). The non-significant effect of group on accuracy in both search types attests that both group participants searched for the target until they detected it, despite the search difficulties of older adults that are therefore rather reflected in RTs.

Response times

Figure 5A shows overall RTs for four different target eccentricities in the full-view pop-out search task. As can be observed, older participants' RTs appeared to increase to a greater extent compared with younger participants as target eccentricity increased. This was confirmed through a repeated-measures ANOVA with eccentricity (E1–E4) and group as factors. The analysis

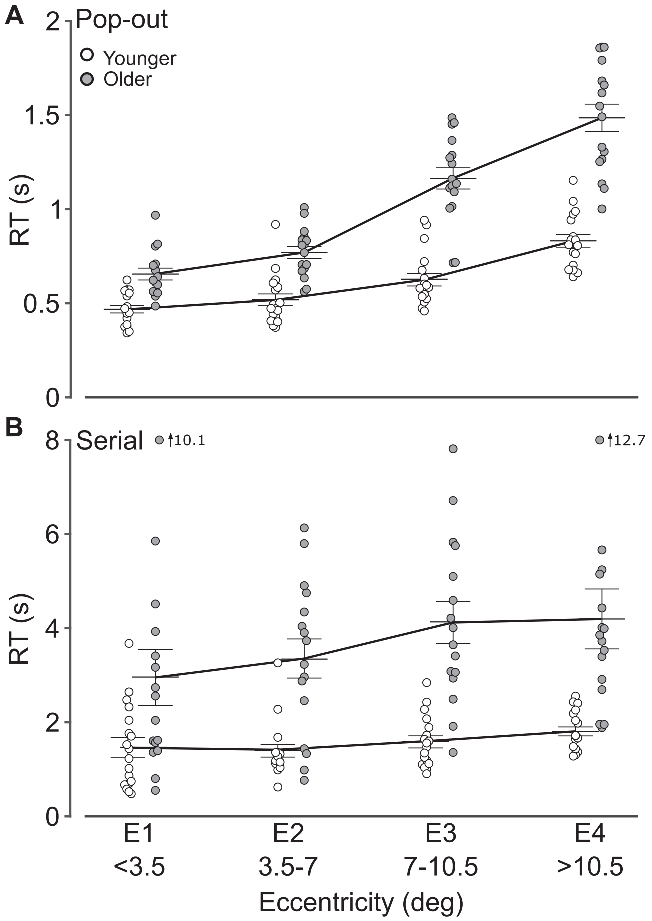

Figure 5. Response times as a function of eccentricity across full-viewing pop-out and serial search tasks. Mean response times plus *SEM* (in seconds), as well as individual RTs, are shown for younger (white filled circles) and older (gray filled circles) adults for four eccentricities: E1, the target was within 3.5° eccentricity of the center of the array (initial fixation); E2, the target was between 3.5° and 7° eccentricity; E3, the target was between 7° and 10.5° eccentricity; and E4, the target was outside of 10.5°. (**A**) Pop-out search RT. (**B**) Serial search RT. The two upward arrows represent data not shown for an older adult with high RTs; the participant had a mean RT of 10.1 seconds in the E1 category and a mean RT of 12.7 seconds in the E4 category.

revealed significant main effects of eccentricity, $F(1.38, 44.29) = 60.57$, $p < 0.001$, $\eta^2_p = 0.65$, and group, $F(1, 32) = 32.19$, $p < 0.001$, $\eta^2_p = 0.5$, as well as an interaction effect, $F(1.38, 44.29) = 5.55$, $p = 0.014$, $\eta^2_p = 0.15$.

Post hoc *t*-tests with Holm–Bonferroni corrections comparing the two groups showed that RTs were shorter for the younger group compared with the older group for every eccentricity ($p_{holm} \leq 0.024$) except E1 ($p_{holm} = 0.19$). In addition, tests indicated that the younger group had longer RTs when the target was farthest in the periphery (E4; $p_{holm} < 0.001$) compared with the other three eccentricities, which were not different from one another ($p_{holm} \geq 0.19$). In contrast, older adults had longer RTs when the target was in the farthest two eccentricities from center (E3 and E4) compared with the nearest two eccentricities from center (E1 and E2; $p_{holm} < 0.001$).

We performed the same analysis for the serial condition (Figure 5B) and found a main effect of group, $F(1, 32) = 22.24$, $p < 0.001$, $\eta^2_p = 0.41$, but no main effect of eccentricity, $F(1.55, 49.52) = 2.31$, $p = 0.12$, nor a significant interaction, $F(1.54, 49.52) = 1.82$, $p = 0.18$.

In sum, in the pop-out condition, when the target was more eccentric, both groups took longer to detect it, and this increase was even greater for older adults. In contrast, target eccentricity did not affect search times for either younger or older adults in serial search, even though older adults took overall more time to detect the target.

Number of saccades

For pop-out search (Figure 6A), we found main effects of eccentricity, $F(1.85, 57.18) = 155.92$, $p < 0.001$, $\eta^2_p = 0.83$, and group, $F(1, 31) = 31.26$, $p < 0.001$, $\eta^2_p = 0.50$, as well as an interaction effect, $F(1.85, 57.18) = 18.49$, $p < 0.001$, $\eta^2_p = 0.37$, for the mean number of saccades. There were no differences between groups at E1, but groups were different at all farther eccentricities (all $t \geq 2.96$; all $p_{holm} \leq 0.030$). For younger adults, there were differences between all levels (all $t \geq 3.26$; all $p_{holm} \leq 0.016$) except E1 and E2 ($p_{holm} = 1.0$). In this instance, the relationship between target eccentricity and the number of saccades was not linear; instead, it seems to indicate that younger adults were affected to a greater degree by similar increases in eccentricity the farther away the target was from the center. For older adults, there were differences between all eccentricities (all $t \geq 3.18$; all $p_{holm} \leq 0.018$).

For serial search (Figure 6B), we also found main effects of eccentricity, $F(2.61, 80.77) = 9.52$, $p < 0.001$, $\eta^2_p = 0.24$, and group, $F(1, 31) = 11.06$, $p = 0.002$, $\eta^2_p = 0.26$, as well as an interaction effect, $F(2.61, 80.77) = 3.51$, $p = 0.024$, $\eta^2_p = 0.10$. For younger adults, there were no significant differences among any eccentricity level. For older adults, there were differences between E1 and both E3 ($t = 5.02$; $p_{holm} < 0.001$) and E4 ($t = 4.20$; $p_{holm} = 0.002$).

Saccade amplitude

Conducting repeated-measures ANOVA with eccentricity and group as factors for pop-out search, we observed main effects of eccentricity, $F(2.23, 71.32) = 263.87$, $p < 0.001$, $\eta^2_p = 0.89$, and group, $F(1, 32) = 5.09$, $p = 0.031$, $\eta^2_p = 0.14$ (Figure 6C). Post hoc

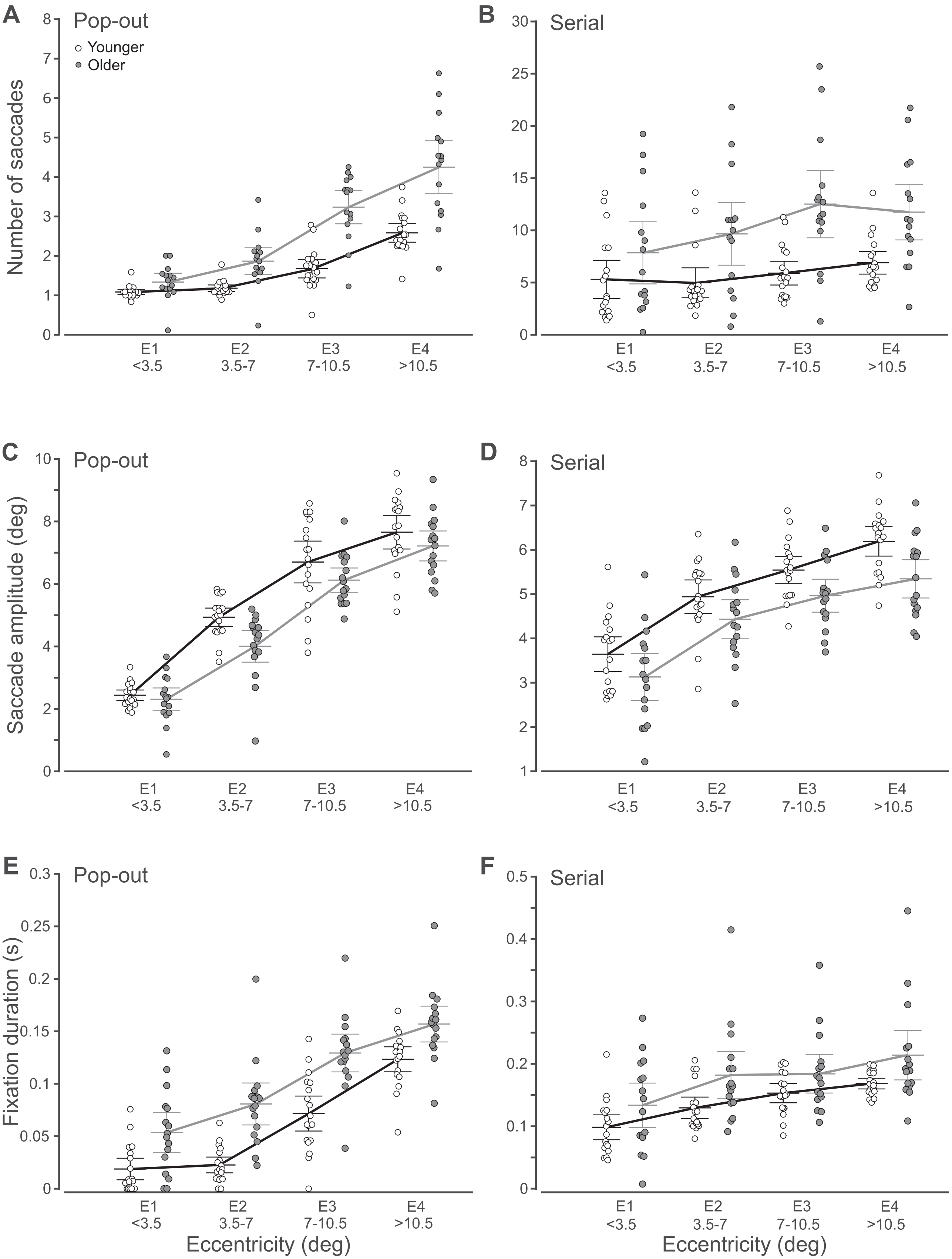

Figure 6. Eye movement parameters as a function of eccentricity across full-viewing pop-out and serial search tasks. Mean number of saccades, saccade amplitude in visual degrees, and fixation duration (in seconds), as well as individual data, are shown for younger (black dots) and older (gray dots) adults for the four eccentricities: E1, the target was within 3.5° eccentricity of the center of the

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←
array (initial fixation); E2, the target was between 3.5° and 7° eccentricity; E3, the target was between 7° and 10.5° eccentricity; and E4, the target was outside of 10.5°. (**A**) Pop-out search number of saccades. (**B**) Serial search number of saccades. (**C**) Pop-out search saccade amplitude. (**D**) Serial search saccade amplitude. (**E**) Pop-out fixation duration. (**F**) Serial search fixation duration. Across all panels, error bars represent *SEM*.

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analyses revealed a main difference of 0.52° between groups ($t = 2.26$; $p_{holm} = 0.031$). There were differences between all eccentricity categories (all $t \geq 5.26$; all $p_{holm} < 0.001$).

For serial search (Figure 6D), we also found main effects of eccentricity, $F(2.21, 70.61) = 78.65$, $p < 0.001$, $\eta^2_p = 0.71$, and group, $F(1, 32) = 8.35$, $p = 0.007$, $\eta^2_p = 0.21$. Post hoc analyses showed a main difference of 0.61° between groups ($t = 2.89$; $p_{holm} = 0.007$). There were differences between all eccentricity categories (all $t \geq 3.15$; all $p_{holm} \leq 0.002$). Overall, for both search types, older adults generally made saccades of smaller amplitude, and both groups made bigger saccades as the target was farther in the periphery.

Fixation duration

For pop-out search, we conducted a repeated-measures ANOVA with eccentricity and group as factors (Figure 6E) and found main effects of eccentricity, $F(2.77, 88.54) = 121.41$, $p < 0.001$, $\eta^2_p = 0.79$, and group, $F(1, 32) = 30.60$, $p < 0.001$, $\eta^2_p =0.49$. The main difference between groups was 46.03 ms ($t = 5.53$; $p_{holm} < 0.001$), and there were differences between all eccentricities (all $t \geq 2.55$; all $p_{holm} \leq 0.012$). For serial search (Figure 6F), we also found main effects of eccentricity, $F(2.18, 69.86) = 23.24$, $p < 0.001$, $\eta^2_p = 0.42$, and group, $F(1,32) = 6.63$, $p = 0.015$, $\eta^2_p = 0.17$. The main difference between groups was 41.09 ms, and we observed differences between E1 compared with all others (all $t \geq 4.30$; all $p_{holm} < 0.001$), as well as between E2 and E4 ($t = 3.82$; $p_{holm} < 0.001$), and E3 and E4 ($t = 2.45$; $p_{holm} = 0.032$). Overall, older adults fixated longer than younger adults, and both groups' fixation times increased with target eccentricity.

Effect of scotoma size

The eccentricity results from the full-viewing search tasks suggest that peripheral visual processes are decreased in older adults for pop-out search but not for serial search, where both younger and older groups presumably use more central/focused attention. Based on these findings, we expected that the presence of the central scotoma would not decrease performance in the younger adults as much as the older adults in the pop-out condition. For serial search, because younger and older adults both use more central attention, we expected that occluding central vision would cost both groups similarly.

Accuracy

For pop-out search, when we compared response accuracy using a repeated-measures ANOVA with condition (full-view condition, 3° scotoma, 5° scotoma, and 7° scotoma) and group as factors, we found a main effect of group, $F(1, 32) = 7.59$, $p = 0.010$, $\eta^2_p = 0.19$, and an interaction effect between group and condition, $F(16.67, 364.96) = 4.70$, $p = 0.009$, $\eta^2_p = 0.13$. The mean difference between groups was 1.84% ($t = 2.76$; $p_{holm} = 0.010$). For younger adults, no significant differences were found between conditions. For older adults, a difference was found between the control condition and the 7° scotoma ($t = 3.25$; $p_{holm} = 0.042$). In short, older adults generally had more incorrect responses than younger adults, and their performance decreased with increased scotoma size compared with the control condition, in contrast to the younger adults, who maintained a stable accuracy across conditions. For serial search, the same analysis revealed only a main effect of group, $F(1, 32) = 12.62$, $p = 0.001$, $\eta^2_p = 0.28$. The mean difference in accuracy between groups was 7.35% ($t = 3.55$; $p_{holm} = 0.001$).

Response Times

Figure 7A shows RTs as a function of scotoma size for the pop-out search task. Using a repeated-measures ANOVA with scotoma size (full-view condition, 3° scotoma, 5° scotoma, and 7° scotoma) and group as factors, we obtained significant main effects of scotoma, $F(1.39, 44.37) = 26.49$, $p < 0.001$, $\eta^2_p = 0.13$, and group, $F(1, 32) = 37.3$, $p < 0.001$, $\eta^2_p = 0.54$, as well as an interaction effect, $F(1.39, 44.37) = 8.7$, $p = 0.002$, $\eta^2_p = 0.22$. These results show that the scotoma did not have the same effect on the two groups; the increase in RTs as a function of scotoma size was bigger for older adults. Post hoc t-tests with Holm–Bonferroni corrections comparing the two groups showed that RTs were shorter for the younger group compared with the older group for all scotoma sizes ($p < 0.034$). In addition, separated by groups, tests indicated that RTs were not significantly different across any of the scotoma conditions ($p_{holm} > 0.088$; $M_{full} = 659$ ms, $M_3 = 737$ ms, $M_5 = 767$ ms, $M_7 = 913$ ms). In contrast, older adults' RTs were significantly longer than the

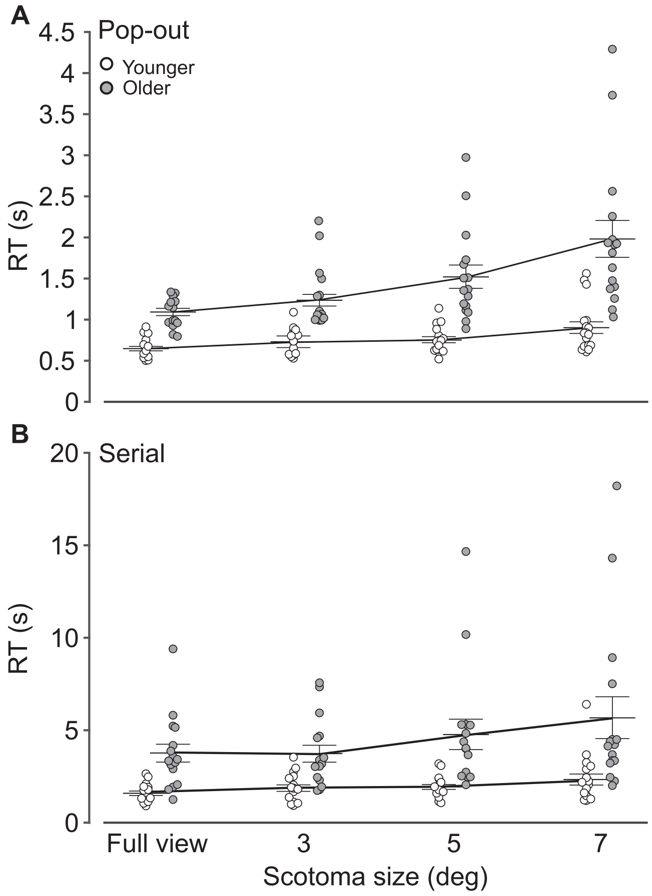

Figure 7. Response times in relation to scotoma in pop-out and serial searches. RTs (in seconds) according to scotoma conditions (full-viewing and 3°, 5°, and 7° diameter scotomas, corresponding to eccentricities of 1.5°, 2.5°, and 3.5°, respectively) for the pop-out (**A**) and the serial (**B**) searches. Younger adults' performance is shown in white and older adults' in gray.

full-view condition (M_{full} = 1103 ms) for the 5° (M = 1532 ms; $p_{holm} < 0.001$) and the 7° (M = 1991 ms; $p_{holm} < 0.001$), but not the 3° (M = 1268 ms; $p_{holm} = 0.58$) scotoma conditions. However, there was also a difference between 5° and 7° scotomas ($t = 4.65$; $p_{holm} < 0.001$), indicating another nonlinear relationship between variables, where a 2° increase in scotoma size impacted performance for larger scotoma sizes more than smaller ones. In summary, these findings show that in the pop-out search condition, scotoma size was increasingly detrimental for older adults but it did not affect younger adults.

For serial visual search, we analyzed the effect of scotoma on RT in the same manner outlined in the pop-out task above (Figure 7B). We observed a main effect of scotoma, $F(1.8, 58) = 7.78$, $p = 0.001$, $\eta^2_p = 0.2$, and group, $F(1, 32) = 15.19$, $p < 0.001$, $\eta^2_p = 0.32$. However, there was no significant interaction effect, $F(1.8, 58) = 22.34$, $p = 0.11$. These results show that, overall, older adults had longer RTs than younger adults ($t = 3.90$; $p_{holm} < 0.001$). In addition, for both groups together, the presence of bigger scotomas increased RTs (control vs. 7° scotoma: $t = 4.32$, $p_{holm} < 0.001$; 3° vs. 7° scotomas: $t = 3.91$, $p_{holm} < 0.001$). However, the increase was not greater for older adults; the scotoma influenced both groups in the same manner. Examining any potential learning effects for younger adults, we observed that the most difficult condition (7° scotoma) was presented first for six participants (33% of cases) in comparison with the easier, control condition. Comparing it with the 3° scotoma, we found that eight participants (44%) performed it first. Thus, in both instances, we can conclude with confidence that these results can not be due to any learning effects.

Cost per item

Additionally, we tested the cost per item as a function of scotoma size in both search types. In pop-out search, conducting a repeated-measures ANOVA with scotoma size and group as factors, we found a main effect of group, $F(1, 32) = 11.74$, $p = 0.002$, $\eta^2_p = 0.27$, but no effect of scotoma size ($p = 0.378$) nor an interaction ($p = 0.572$). Thus, although older adults were overall slower in trials with more distractors, the cost per item did not get higher with bigger scotomas for either group. Examining cost per item with a repeated-measures ANOVA for the serial search, we observed a main effect of scotoma size, $F(2.05, 65.66) = 5.95$, $p = 0.004$, $\eta^2_p = 0.16$, and a main effect of group, $F(1, 32) = 9.97$, $p = 0.003$, $\eta^2_p = 0.24$, but no interaction effect ($p = 0.077$). Thus, older adults had longer search times according to the number of distractors, but both groups showed similar RT increases as the scotoma got bigger.

Number of saccades

For pop-out search, we conducted repeated-measures ANOVAs comparing the mean number of saccades with scotoma condition (control and 3°, 5°, and 7° scotoma) and group as factors (Figure 8A), and we found main effects of condition, $F(1.53, 47.45) = 22.37$, $p < 0.001$, $\eta^2_p = 0.42$, and group, $F(1, 31) = 29.19$, $p < 0.001$, $\eta^2_p = 0.49$, as well as an interaction effect, $F(1.53, 47.45) = 4.81$, $p = 0.020$, $\eta^2_p = 0.13$. Post hoc t-tests revealed differences between groups for all conditions (all $t \geq 3.47$; all $p_{holm} \leq 0.015$). For younger adults, the only difference was between the full-view control condition and the 7° scotoma ($t = 2.91$; $p = 0.049$). In the same manner as with RTs, we ensured that this difference could not be explained by a learning effect, as only seven participants (39%) performed the 7° scotoma before the control condition. For older adults, there were differences between the 7° scotoma and all other conditions (all $t \geq 4.49$; all $p_{holm} < 0.001$). Converging

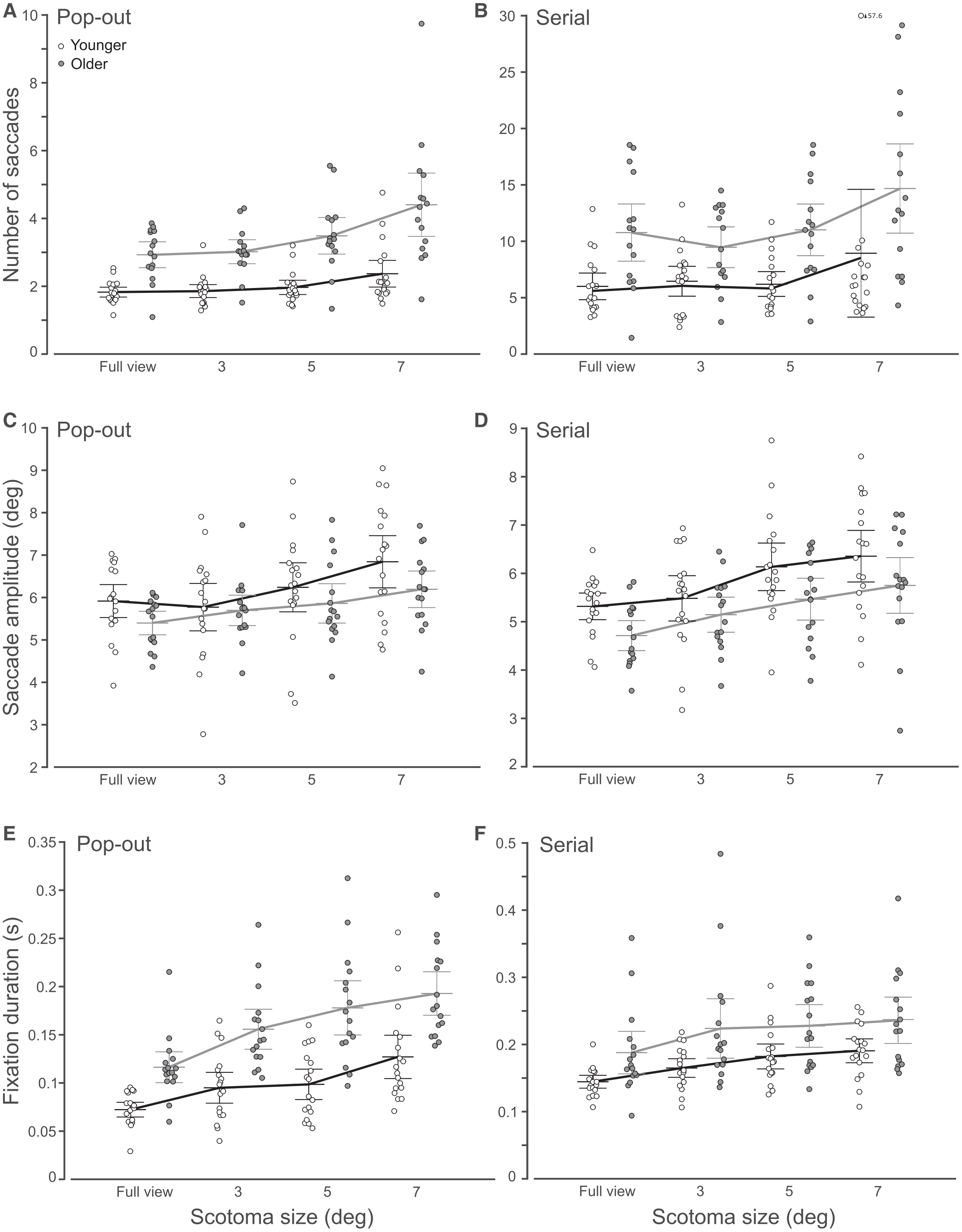

Figure 8. Eye movement parameters as a function of scotoma across pop-out and serial search tasks. Mean number of saccades, saccade amplitude in visual degrees, and fixation duration (in seconds) with individual data are shown for younger (black dots) and older (grey dots) adults across scotoma conditions (full-viewing and 3°, 5°, and 7° diameter scotomas, corresponding to eccentricities of 1.5°, 2.5°, and 3.5°, respectively). (**A**) Pop-out search number of saccades. (**B**) Serial search number of saccades. (**C**) Pop-out search saccade amplitude. (**D**) Serial search saccade amplitude. (**E**) Pop-out fixation duration. (**F**) Serial search fixation duration. Across all panels, error bars represent *SEM*.

with findings related to RTs, increases in scotoma size had an impact on performance only in the most difficult conditions. As for the serial condition (Figure 8B), the same analyses showed a main effect of group, $F(1, 31) = 9.99$, $p = 0.004$, $\eta^2_p = 0.24$, and a tendency toward a main effect of condition, $F(1.18, 36.45) = 3.81$, $p = 0.053$. The mean difference between groups was 4.58 saccades, $t = 3.16$, $p_{holm} = 0.004$. Thus, older adults made increasingly more saccades than younger adults with scotoma conditions in pop-out search and made globally more saccades in serial search.

Saccade amplitude

Using the same analysis comparing mean saccade amplitude, we found only a main effect of condition, $F(2.34, 75.03) = 15.05$, $p < 0.001$, $\eta^2_p = 0.32$ (Figure 8C). Post hoc *t*-tests revealed differences between the 7° scotoma and all other conditions (all $t \geq 3.28$; all $p_{holm} \leq 0.006$), as well as between the control condition and the 5° scotoma ($t = 2.76$; $p_{holm} = 0.021$). For these conditions in younger adults, any learning effect could not have influenced performance, as ≤ ten participants (≤ 56%) completed a more difficult condition before an easier condition. For serial search (Figure 8D), we found a main effect of condition, $F(2.53, 80.80) = 22.31$, $p < 0.001$, $\eta^2_p = 0.41$, and a tendency toward a group effect, $F(1, 32) = 4.05$, $p = 0.053$, $\eta^2_p = 0.11$. Post hoc analyses revealed differences between the control condition and both the 7° scotoma ($t = 7.40$; $p_{holm} < 0.001$) and the 5° scotoma ($t = 5.61$; $p_{holm} < 0.001$). For this search type in younger adults, performance could also not have been influenced by trial order, as ≤ seven participants (≤ 39%) completed a more difficult condition before an easier condition.

Fixation duration

As shown in Figure 8E, when we compared the mean fixation duration with scotoma condition and group as factors, we found main effects of condition, $F(2.84, 90.83) = 37.51$, $p < 0.001$, $\eta^2_p = 0.54$, and group, $F(1, 32) = 28.33$, $p < 0.001$, $\eta^2_p = 0.47$, as well as a tendency toward an interaction effect, $F(2.84, 90.83) = 2.66$, $p = 0.056$, $\eta^2_p = 0.08$. Post hoc *t*-tests revealed a mean difference of 62.40 ms between groups ($t = 5.32$, $p_{holm} < 0.001$), and there were differences between all conditions (all $t \geq 2.03$; all $p_{holm} \leq 0.045$). For younger adults, any learning effects could not have biased results, as ≤ ten participants (≤56%) completed a more difficult condition before an easier condition. For serial search (Figure 8E), we found significant main effects of condition, $F(2.14, 68.52) = 11.73$, $p < 0.001$, $\eta^2_p = 0.27$, and group, $F(1, 32) = 8.70$, $p = 0.006$, $\eta^2_p = 0.21$. The main difference between groups was 48.29 ms ($t = 2.95$; $p_{holm} = 0.006$), and there were significant differences between control condition and all scotoma sizes (all $t \geq 3.33$; all $p_{holm} \leq 0.007$). For this condition in younger adults, these results could also not have been influenced by learning effects, as ≤ seven participants (≤39%) completed a more difficult condition before an easier condition.

Discussion

It has been suggested that older adults may have reduced attention to the periphery compared with younger adults. To investigate this, we tested younger and older adults' strategies of exploration during pop-out and serial visual search to determine how quickly they located peripheral targets during full-view conditions. We observed that older adults were significantly slower to find targets than younger adults, and specifically for more eccentric targets only in pop-out search. In serial search, older adults had longer RTs as well as higher cost per item slopes, even for central targets, indicating greater difficulty in performing the serial task as the number of items increased, irrespective of target eccentricity.

We also compared their eye movement parameters, such as their mean saccade number, fixation duration, and saccade amplitude, related to eccentricity for both search types. In pop-out search in the full-view condition, we observed that older adults made increasingly more saccades than younger adults as target eccentricity increased. This may suggest a reduced attentional spotlight that older adults would have to displace using additional saccades to find objects situated farther in the periphery. In serial search, younger adults did not make more saccades as target eccentricity increased, but older adults' number of saccades increased when the target was situated farther from the center. Regarding saccade amplitude, we found that, overall, for both search types, older adults generally made smaller saccades, and both groups made larger saccades the farther the target was in the periphery. Older adults also generally fixated longer than younger adults for both search types. Both groups' fixation times increased similarly with target eccentricity, indicating an increase in the effort required to locate the target in older adults compared with younger irrespective of target eccentricity, and a similar increase of difficulty for targets at greater eccentricities in both groups. Overall, older adults made shorter saccades, fixated the search array longer, and made more saccades than younger adults; furthermore, their average saccade number increased more with target eccentricity compared with that for the younger adults.

Further, we investigated the impact of occluding central vision to different degrees on response times and eye movement patterns. We observed that older adults were more negatively impacted when the central scotoma size increased in pop-out search but not in serial search. During scotoma conditions, they also made more saccades than younger adults in pop-out search, and their mean saccade number increased even more with the size of the scotoma in pop-out search. Mean saccade amplitude was similar for both groups for pop-out and serial search and increased with the presence of the scotoma and for the biggest scotoma sizes. In pop-out and serial search, older adults also fixated longer than younger adults, but both groups' fixating times increased in a similar manner with the presence and size of the scotoma.

Our study supports the cognitive hypothesis that older adults experience visuospatial attentional decline, resulting in different difficulties depending on visual search type. In the full-view condition, both groups took longer to find eccentric targets in both visual search tasks, suggesting that visual information is processed consecutively from the fovea to the periphery, with greater attentional allocation to central information (Larson, Freeman, Ringer, & Loschky, 2014). In pop-out visual search, we found that older adults had a more pronounced bias toward central vision than younger adults, as reflected by higher RTs as target eccentricity increased. The different patterns between participant groups during pop-out search is specifically associated with item location with respect to eccentricity, whereas the cost per item was similar between younger and older adults. We also examined the performance of younger and older adults on visual search tasks with various central scotoma sizes. Our results confirmed that older adults have difficulty attending to peripheral targets in pop-out search, as evidenced by increased search times in the presence of central scotomas with a diameter of 5° and 7°. In contrast, younger adults were not significantly affected by the presence or size of central scotomas, suggesting efficient use of peripheral attention during pop-out search. Previous studies have demonstrated that the distribution of attentional allocation around fixation depends on the degree of difficulty of the search task, ranging from the entire visual field, as in efficient pop-out search, to a much smaller area in very inefficient serial searches (Geisler & Chou, 1995; Khan et al., 2016; Motter & Simoni, 2008; Pomplun, Reingold, & Shen, 2001; Young & Hulleman, 2013).

During visual search, distribution of attention on a smaller area would result in more saccades of smaller amplitude and thus in longer RTs, as it takes more time to shift smaller attentional "windows" to find a target located in the periphery; as target eccentricity increases, a more systematic exploration of the display would be needed to locate the target. This was indeed what we observed in our older adult group. The difficulties found in older adults when the central scotoma was present could also be explained by a smaller attentional window as the scotoma would leave only a small remaining attentional ring where the target can be detected. In contrast, younger adults, given their large attentional window sizes in pop-out search (Khan et al., 2016), would require much less exploration time to find the eccentric targets and would be minimally hindered by the central scotoma.

In serial search, although we did observe overall longer RTs for the older adults, increases in RT were not different from younger adults in terms of target eccentricity or central scotoma size. We surmise that this may be due to the reliance on more central attentional distribution required in serial search for both younger and older adults; the size of the attentional window is smaller for serial search compared with pop-out search in younger adults (Khan et al., 2016). The small attentional window during serial search means that items are processed within a smaller area than the search array, which makes the eccentricity of the target less important. Consequently, a central scotoma would be equally detrimental to younger and older adults, as it occludes objects within the same restricted attentional window, thus requiring more time to find the target for both groups. However, it is worth noting that we did not directly measure the attentional window of our participants, which limits our interpretation.

The behavioral comparison of older and younger adults in serial search full-view conditions suggests that aging is also associated with difficulties in spatial binding—that is, in the ability to process relative positions (relations in space) between different parts of an object to bind them into a single object unit. In our feature-absent serial search task, participants had to distinguish the target (circle without associated line) from distractors (circle and line bound) by identifying the location of each circle relative to each line. The requirement of spatial binding thus increases with the number of items in the visual display (i.e., the set size), increasing the cost per item. Slowing in spatial binding in older adults would explain their greater cost per item in addition to their longer RTs in the control full-view condition compared with younger adults for the serial search, which was not the case for the pop-out search, a condition not requiring spatial binding. Previous aging studies have also reported increased RTs but no difference in cost per item for pop-out searches, whereas both RTs and cost per item were increased in serial search (Greenwood & Parasuraman, 2004; Hommel et al., 2004; Müller-Oehring et al., 2013; Plude & Doussard-Roosevelt, 1989). Such a pattern of visual search impairment has also been observed after visual dorsal stream damage (Khan et al., 2016; Vialatte, Yeshurun, Khan, Rosenholtz, & Pisella, 2021b) and are thought to result from a specific deficit in spatial attention, affecting simultaneous visual processing (Valdois, Roulin, & Bosse, 2019; Vialatte et al., 2021b). Common attentional resources for simultaneous visual processing would be shared for extending the attentional spotlight across space over numerous objects, but also across separable features of complex objects (Vialatte et al., 2021a). Consequently, reduced spatial attentional resource affects only the periphery when visual complexity is low (pop-out search) but the entire space when spatial binding is required (serial search).

It has been suggested that the dorsal stream is subject to decline in aging (Müller-Oehring et al., 2013; Sciberras-Lim & Lambert, 2017). Overall, our findings for pop-out and serial search are consistent with this hypothesis, in that we observed difficulties processing the spatial location of objects, as well as the spatial relationships between features in older participants. Scanning different areas in the visual environment to locate a target is a task that is spatial in nature and relies notably on different parietal regions, including the posterior parietal cortex and the intraparietal sulcus (Ptak, 2012; Rolls & Webb, 2014). These regions are part of the dorsal visual stream, also known as the “where” visual pathway, theorized as one of the two main networks enabling visual perception. The dorsal stream is associated with encoding objects’ spatial locations and orienting visual attention in space (Lambert & Shin, 2010; Siegel, Donner, Oostenveld, Fries, & Engel, 2008). Taken together, our results suggest that a decline in the dorsal stream in older adults results in decreased efficiency in the “where” aspect of visual search, leading to poorer performance in conditions that require more reliance on the spatial selection of the target.

There are some limitations to this study that constrain our interpretations. First, older participants were not systematically screened on their cognitive abilities and therefore we cannot exclude the possibility of some participants being affected by an undiagnosed cognitive pathology. However, we excluded participants with diagnoses or medication that could influence cognitive performance. We also obtained the Montreal Cognitive Assessments (MoCA) scores of three participants from previous studies, which were all 30. We compared control response times between those with MoCA scores and those without and observed that they were not statistically different. Finally, we ensured that all participants performed the task correctly and verified that older adults performed the task with the same accuracy as younger adults.

Moreover, sensorimotor declines affecting eye movements, visual crowding (Levi, 2008), and visual acuity—or, alternatively, declines in executive functions, including visual working memory—can also at least partly contribute to the group differences found in visual search. For example, some researchers have associated lower target detectability with decreased performance in older adults due to sensory decline (Madden et al., 1999), as well as changes in saccade parameters and general slowing in aging (Bono et al., 1996; Irving et al., 2006; Moschner & Baloh, 1994; Paquette & Fung, 2011; Salthouse et al., 1996). Consistent with these previous findings, in full-viewing conditions, we observed increased RTs and more numerous and smaller saccades in older adults for both search types. However, more detailed analysis of older adults’ performance showed specific decreases in certain conditions, a differential pattern that cannot be accounted for by general age-related sensorimotor changes or slowing alone, which would produce a homogeneous increase in RTs in both pop-out and serial search tasks. The decreases in pop-out search performance in older adults could also be due to reduced peripheral visual acuity in aging. In this easier search, peripheral vision is used to a greater extent compared with serial search; such sensory declines, specific to the peripheral visual field, could have affected RTs and eye movement patterns in older adults in pop-out search. However, they cannot explain the lower performance in the full-view condition of serial search in terms of cost per item in the whole visual field.

Another low-level mechanism that could explain older adults’ decreased performance is visual crowding. Visual crowding is a phenomenon specific to peripheral vision in which clusters of different visual elements at one place impair performance in visual cognitive tasks. Age differences in crowding effects have been reported to be larger in serial search compared with pop-out search (Plude & Doussard-Roosevelt, 1989), although such differences were also shown to increase with target eccentricity (Scialfa, Cordazzo, Bubric, & Lyon, 2013), which we did not find in the present study. Nevertheless, it is possible that the difficulty of the serial search task required all participants to adopt strategies less reliant on peripheral vision. Thus, visual crowding and/or visual acuity could contribute to the decreased performance that we found in older adults in pop-out search, specific to visual periphery. Note that it is also possible that slow spatial binding in older adults increased visual crowding for low visual eccentricities for serial searches involving complex shapes made up of separable features. However, we are limited in this interpretation, as we did not specifically measure visual crowding in this study, and it is not clear whether or not visual crowding increases with aging (Astle et al., 2014, Malavita, Vidyasagar, & McKendrick, 2017). Alternatively, the cognitive hypothesis posits that aging decreases the top-down attentional control required for serial searches with many distractors, leading to longer response times (Eckstein, 2011; Hommel et al., 2004;

Scialfa et al., 1998; Treisman & Gelade, 1980; Treisman & Souther, 1985; Wolfe, Cave, & Franzel, 1989; Wolfe & Horowitz, 2004). This could explain the older adults' performance in terms of cost per item in the serial task but not the specific decline in visual periphery in the pop-out task.

Finally, decreased working memory capacity has been associated with poorer visual search performance (Greenwood & Parasuraman, 1999; Kramer et al., 1999; Van der Linden, Brédart, & Beerten, 1994). However, the pattern of results we observed here, specific to either large target eccentricity in pop-out search or to large set size in serial search, is inconsistent with working memory difficulties.

With respect to visual search in aging, future studies could include measures of sensory processing in the periphery, such as contrast detection. Another limitation to the attentional distribution hypothesis is that we did not directly measure the attentional window (i.e., the perimeter around each fixation to which participants could direct their covert attention to locate the target). By occluding participants' peripheral vision to different degrees during a visual search task, instead of central vision, to directly measure the size of the attentional window (Dalrymple, Barton, & Kingstone, 2013; Khan et al., 2016), future studies could further deepen our understanding of the impact of aging on spatial distribution. Moreover, our results indicate that pop-out search was not performed entirely in parallel, and that serial search likely induced a smaller attentional window for both younger and older participants. Thus, it would also be relevant to investigate how the distribution of spatial attention can be influenced in other types of search designs, such as parallel visual search, easier serial search, or more ecologically valid search arrays, in which semantic guidance might occur. Finally, future studies could also aim to better understand the attentional window in visual search in pathological conditions such as mild cognitive impairment, in relation to other attentional deficits.

We showed that, compared with younger adults, in pop-out search older adults had difficulties locating peripheral targets in full viewing conditions and their search was less efficient with a central scotoma obstructing their central vision. These findings suggest that there is a decrease in peripheral attention in older adults. In serial search, we surmise that a difficulty in processing the spatial relations between the features of each object could explain older adults' increasingly longer RTs associated with larger set sizes. Our findings are most consistent with decreased attentional and spatial processing, as well as decreased functioning of the dorsal visual stream.

Keywords: visual search, aging, feature binding, artificial scotoma, dorsal stream

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