Reliance on central vs. peripheral vision for visual search in younger and older adults

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Abstract

Older adults show declines performing visual search, but their nature is unclear. We propose that it is related to greater attentional reliance on central vision. To investigate this, we tested how occluding central vision would affect younger and older adults in visual search. Participants (14 younger, $M = 21.6$ years; 16 older, $M = 69.6$ years) performed pop-out and serial search tasks in full view and with different sized gaze-contingent artificial central scotomas (no scotoma, 3° , 5° or 7° diameter).

In pop-out search, older adults showed longer search times for peripheral targets during full viewing. Their reaction times, saccades and fixation durations also increased as a function of scotoma size, contrary to younger adults. These declines may reflect a relative impairment in peripheral visual attention for global processing in aging.

In serial search, despite older adults being generally slower, we found no difference between groups in reaction time increases for eccentric targets and for bigger scotomas. These results may come from the difficulty of serial search, in which both groups used centrally limited attentional windows.

We conclude that older adults allocate more attentional resources towards central vision compared to younger adults, impairing their peripheral processing primarily in pop-out visual search.

Keywords: visual search, aging, spatial attention, central and peripheral processing, artificial scotoma

Public significance statement

Older adults take longer to find specific objects when searching for them through their visual environment. We propose that this is related to how our visual attention is distributed: as we get older, we tend to focus more on central vision and have difficulty noticing things in the periphery. This has important implications for daily life, as we rely on visuospatial attention in many activities.

Word count: 8103 words

Introduction

Visual search requires scanning a visual scene to find a specific object (the target) among other objects (the distractors). It can measure two types of visual information processing with two different tasks: the pop-out version relies on bottom-up processing of the entire visual scene whereas the serial version requires top-down processing of each feature or group of features serially (Eckstein, 2011; Palmer, Fencsik, Flusberg, Horowitz, & Wolfe, 2011; Treisman & Gelade, 1980). 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 et al., 2011). Pop-out search has been proposed to be primarily based on bottom-up attentional processes that drive attention to the most salient items across the entire visual scene (Itti & Koch, 2000; Palmer et al., 2011). This type of searches tend to be highly efficient, in that increasing the number of distractors in the scene does not significantly affect the speed of target detection (Wolfe & Horowitz, 2004). In contrast, serial search involves top-down attentional processes to a much greater degree (Palmer et al., 2011). In this search, the target shares more features with the distractors, often requiring the conjunction of different features, and thus is more difficult to distinguish. In serial search, focus is restricted to each object or to a group of objects serially in time. Accordingly, an increase in the number of distractors increases the time needed to locate the target, requiring greater attentional resources and limiting performance (Treisman & Gelade, 1980; Wolfe & Horowitz, 2004).

Multiple neural and behavioral changes occur in aging, including a decrease in performance in visual search. In general, older adults show higher search times compared to younger adults (Hommel, Li, & Li, 2004; Humphrey & Kramer, 1997; Madden, Pierce, & Allen, 1996; Müller-Oehring, Schulte, Rohlfsing, Pfefferbaum, & Sullivan, 2013; Plude & Doussard-Roosevelt, 1989; Scialfa, Esau, & Joffe,

1998). However, the underlying cause of this impairment could be attributed to different processes, such as 1) sensory processing (basic visual detectability), 2) perceptual and cognitive processing (brain resources, e.g., attention and memory) or 3) motor processing. Specifically, the cause of these deficits found in normal aging was associated with motor and sensory processes (Irving, Steinbach, Lillakas, Babu, & Hutchings, 2006; Lindenberger & Baltes, 1994; Paquette & Fung, 2011), e.g. eye movement planning, while others have attributed it solely to perceptual processes (Madden, Gottlob, & Allen, 1999; Salthouse, Hancock, Mein, & Hambrick, 1996), e.g. target and motion detection. Cognitive functions such as attention (Greenwood & Parasuraman, 1999; Müller-Oehring et al., 2013; Wolfe, Cave, & Franzel, 1989) and working memory (Baddeley, 1996; Kramer, Hahn, & Gopher, 1999; Park & Reuter-Lorenz, 2009) were also hypothesized as the cause of these deficits. Further, there is much disagreement about whether all these deficits actually occur in aging or not (Beurskens & Bock, 2012; Coeckelbergh, Cornelissen, Brouwer, & Kooijman, 2004; Hommel et al., 2004; Sekuler, Bennett, & Mamelak, 2000). In summary, the underlying cause of the decline in aging for visual search performance remains unresolved.

One hypothesis is that this may be related to older adults distributing their attention differently to central and peripheral vision. In this study, we have defined central vision as the area encompassing foveal and parafoveal regions as extending to approximately 5 deg from center (Coletta & Williams, 1987; Larson & Loschky, 2009); this has been defined as the area that contains the highest density of cones. Peripheral vision, outside of approximately 5 deg of center (Coletta & Williams, 1987; Larson & Loschky, 2009) is important in visual search as information in the periphery can guide eye movements towards the target among distractors. Indeed, the target is more likely to be localized in a peripheral area, and a peripheral encoding can determine if a region contains specific features that we are looking for (Levi, 2008; Rosenholtz et al., 2012). Peripheral visual processing amounts to

processing the gist of the scene, while central vision processes more detailed information about objects. Compared to central vision, perception in peripheral vision is much less accurate, with less acuity, subject to crowding effects and covers a much larger area (Balas, Nakano, & Rosenholtz, 2009). In this part of our vision, we perceive texture characteristics of the objects surrounding us and can perceive spatial information about our surroundings, but we cannot organize all perceptual elements to their respective objects and their precise localization (Balas, Nakano, & Rosenholtz, 2009; Pelli & Tillman, 2008; Rosenholtz et al., 2012; Rosenholtz, Huang, & Ehinger, 2012). In visual search, when a target has a distinct texture characteristic, distractors do not impair an observer's ability to locate it and that target is said to 'pop out'. The task can then be undertaken using only peripheral vision fairly easily. When the target is more easily confused with distractors, as in serial search, the task compels the observer to average more local estimates for its identification (Balas et al., 2009; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001).

A decline in peripheral attentional processing was demonstrated in older adults compared to younger adults (Beurskens & Bock, 2012; Plude & Doussard-Roosevelt, 1989; Yu, Cheung, Legge, & Chung, 2010). For example, peripheral reading becomes slower and peripheral visual span declines with age, and perceptual training in the periphery was also less effective among older adults compared to younger (Yu et al., 2010). More specifically, the spatial range of attention to the periphery, in the context of visual search, has also been suggested to decrease with age. Adding a secondary central task to visual search affects peripheral performance of older adults to a much greater extent than the younger adults' performance (Ball et al., 1988; Sekuler et al., 2000), which could be due to said decrease in peripheral attention but also to impaired divided attention abilities in older adults. On the other hand, other studies have shown no decline in peripheral visual function (Astle, Blighe, Webb, & McGraw, 2014; Hommel et al., 2004; Muiños, Palmero, & Ballesteros, 2016). While the allocation of

covert attention to the periphery (a cognitive process) is likely to be decreased in older adults, it seems that sensory phenomena, such as crowding in the peripheral visual field, remain unchanged in aging (Astle et al., 2014). Similarly, Muiños et al. (2016) found that the cost of detecting eccentric targets compared to foveal targets was not different for older and younger adults. The difference between (most of) these studies appears to be whether a central task and a peripheral task are competing with one another. Taken together, it appears that when solely a peripheral task is required, there is no decline in performance in older adults, whereas when both a central and peripheral task are required at the same time, peripheral performance declines. This suggests that there may instead be an attentional over-reliance on processing stimuli in the central visual field, at the expense of peripheral processing, in older adults.

One means of testing reliance on central vision is to determine the cost of occluding central vision. This can be done using a gaze-contingent display presenting an artificial central scotoma (Rayner & Bertera, 1979; Rayner & McConkie, 1976). The artificial central scotoma is a circular blanked region in the central visual field of participants which follows their gaze and keeps them from using their central vision during the experiment. Some researchers have investigated the effects of central scotomas on search tasks in younger adults (Bertera, 1988; Cornelissen, Bruin, & Kooijman, 2005; Murphy & Foley-Fisher, 1988). Overall, they observed that central scotomas significantly delayed reaction time (RT) in serial and pop-out search tasks (Bertera, 1988; Cornelissen et al., 2005; Murphy & Foley-Fisher, 1988). Accordingly, we measured how central vision occlusion influences visual search performance in older adults compared to younger participants. Both groups performed pop-out and serial search tasks in the absence or presence of different sized artificial central scotomas. We surmised that if older adults rely more on central vision and less on peripheral vision for processing, then occluding central vision should affect older adults more than younger adults when peripheral

processing is required, such as during easy pop-out visual search tasks where the entire visual scene is processed. In contrast, during more difficult serial search, central visual processing is used predominantly. Therefore, we should see no differences between younger and older adults in terms of the cost of central vision occlusion.

Methods

Participants

We recruited a total of 30 participants from the University of Montreal and the community: 14 young adults ($M = 21.6$ y, $SD = 1.5$ y, age range = 19-25 y, 10 women, including two authors AL and JOE) and 16 older adults ($M = 69.6$ y, $SD = 7.3$ y, age range = 61-83 y, 4 women). This sample size was decided after a power analysis was conducted using G*Power (Erdfeiler, Faul, & Buchner, 1996). Based on effect sizes from a previous study in our laboratory (Ouerfelli-Ethier et al., 2018), it concluded that the minimum number of total participants needed was $N = 6$. This was based on a partial eta squared value of 0.395 (resulting in a large effect size of 0.8) obtained from visual search conditions comparing older and younger adults. 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. They gave their free and informed consent before testing and received financial compensation upon participation completion. All experimental procedures were pre-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 of various sizes. Tasks were designed and implemented using MatLab R2016b (The MathWorks, Inc.,

Natick, Massachusetts, United States) with Psychophysics toolbox (Brainard, 1997). Testing occurred in a dark room where participants sat in front of a VIEWpixx 3D computer screen (VPixx Technologies, Montreal, Canada; 20.5*11.5 inches, 1920*1080 pixels, 120 Hz), with an eye-screen distance of 57cm (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, Mississauga, ON, Canada). To restrict head movements, participants' forehead and chin were stabilized on rests. We recorded button-press responses using a RESPONSEpixx handheld response box (VPixx Technologies, Montreal, Canada).

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 masked participants' central vision. Possible scotoma diameters were 3°, 5° and 7° of visual angle. (C) Pop-out visual search task experimental sequence. Participants 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 the target was present or not 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°. They indicated as quickly as possible whether the target was present or not using the button box.

We simulated an artificial circular invisible scotoma (i.e. invisible from the white background; see Figure 1B) with a diameter of either 3, 5 or 7°. It was aligned on participants' central vision based on a two-step calibration process at the beginning of each experimental block. We first calibrated participants' right eye with a standard nine-point EyeLink calibration/validation procedure. A second fifteen-point calibration (custom Matlab script) was then performed to precisely align the scotoma on participants' fovea. Participants were asked to fixate each of the 15 fixation dots which were presented in random order equally spaced across a grid spanning 4/5th of the screen, then 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 6 parameters. These parameters were then used to adjust eye position from the EyeLink's parameters for accurate scotoma presentation and eye position recording; the standard EyeLink calibration resulted in a mean error of 2.21° in absolute distance (distance between recorded position and the actual target positions), while the 2nd calibration reduced this error to 0.53°.

To prevent the scotoma from following the eye downwards during blinks, we froze the scotoma in place whenever the velocity in the vertical direction exceeded 900°/sec. In addition, the entire search array blurred so that participants could not distinguish distractors and target when blinking. In terms of timing, the minimum delay between the position of the eye and the scotoma was approximately 3ms. The end-to-end sample delay for eye recording at 1000 Hz was 1.95ms (SR Research, Kanata, Canada). In addition, there was approximately 1ms between the time at which the eye position was

determined and the rendering of the scotoma (Psychophysics toolbox). The maximum time was determined by the screen refresh rate, 8.3ms.

Stimuli and procedure

Overall, participants completed the tasks in 2-3 sessions of approximately 1 hour each spanning one to two weeks.

Pop-out visual search. Participants were asked to indicate whether a target was present or absent within a search array as quickly as possible. Each trial began with a black fixation dot (1° diameter) set against a white background (Figure 1C). Gaze verification was applied within a window of $2^\circ \times 2^\circ$ around the fixation dot. Once gaze was detected within this window, the fixation dot was replaced with a square search array ($24^\circ \times 24^\circ$), centered on the screen, composed of either 16, 32 or 64 items, comprising 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 present in 80% of trials within each block. The number of items (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 4 quadrants of the search array space and eccentricity from the center of the array.

Participants pressed one of two buttons to indicate whether the target was present or absent. Upon response, the search array disappeared, and a blank screen appeared for an inter-trial 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 and instructions were identical to the pop-out version, except for the appearance of the target and distractors (Figure 1D). In this case, 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° and 270°.

The experimental procedures differed between groups to prevent fatigue in older adults. Younger adults performed eight blocks of 75 trials in a randomized order, i.e. 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 were then counterbalanced to control for fatigue and order effects. For both groups, the first 10 trials of the first pop-out and serial tasks were considered practice trials and were not included in the analysis.

Data analysis

The data of two older participants were removed because they showed abnormal patterns of results; one participant's reaction times for the no scotoma conditions were at least two-fold longer than those with the scotoma, and the other participant's mean reaction times were several times longer than the rest of the participants.

We established an accuracy threshold of 80% correct responses for both target-absent and target-present trials to verify that participants performed the task correctly (i.e., pressing the target present button when they detected the target rather than automatically pressing the same response at every trial). In total, two additional participants (1 younger and 1 older adult) were excluded from the dataset

because of low performance, likely because the task was very difficult in the presence of central scotomas.

From the remaining 26 participants, we collected a total of 15, 445 target-present trials. Analyses focused on measures of task performance such as reaction times (RTs) and cost-per-item (CPI). The CPI (also known as the set-size effect) is a slope which indicates the increase in reaction time associated with the addition of each item to the search display (Wolfe & Horowitz, 2004). Stated otherwise, the reaction time x set size linear function indexes the performance decline with the increasing number of objects in the display, an indicator of the attentional demand (Eckstein, 2011; Plude & Doussard-Roosevelt, 1989). RTs were calculated by subtracting button press time from the time of the search array onset. CPI was calculated as the slope fitted to RTs as a function of the number of items, which shows the cost in time associated with finding each item displayed on the visual array. CPI was analysed per search type; we performed a linear fit per participant using the polyfit function in Matlab over mean RT per number of item conditions (i.e., 16, 32 and 64 items). We also performed separate analyses for RTs as a function of target eccentricity. Target eccentricity was grouped into one of two eccentricities that split our work space equally; near – which we defined as target eccentricities of less than 6° approximately comprising foveal and para-foveal visual regions (Coletta & Williams, 1987; Larson & Loschky, 2009) and far – defined as target eccentricities of 6° or greater comprising peripheral vision (when fixating at the centre).

For each visual search task, we compared performance (i.e., RT, CPI, mean number of saccades and mean fixation duration) across groups, scotoma conditions and target eccentricities using mixed ANOVAs (with groups as between-subject factor and condition as within-subject factors) and paired-sample *t*-tests. We adjusted any results with Greenhouse-Geisser 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 (η^2_p) to calculate effect sizes for ANOVAs (Lakens, 2013).

Results

We first compared baseline visual search performance (i.e., overall RTs and CPI) without the presence of a scotoma between visual search tasks and across groups. This provided an overview of differences related to aging when no scotoma was present. Next, we assessed the effect of target eccentricity on performance and the effect of scotoma conditions across groups for each visual search type. These two analyses aimed to determine the role of central visual information relative to periphery in older adults compared to younger.

Baseline performance: Overall reaction times (RTs) and cost-per-item (CPI)

We first compared overall RTs across groups and between search tasks for the full view condition to replicate previous findings and validate our tasks. Consistent with previous studies (Hommel et al., 2004; Madden et al., 1996; Plude & Doussard-Roosevelt, 1989; Treisman & Gelade, 1980), we observed that 1) RTs for the serial search task were longer than those for pop-out, 2) that older participants had longer RTs overall compared to younger and 3) that the increase in RTs for serial compared to pop-out was greater for older participants (Figure 2A).

Figure 2. Younger and older adults' performances across full viewing pop-out and serial search tasks. Younger adults' performance is shown in white and older adults' in grey. (A) Mean reaction time (RT) in seconds (s), according to search type and group. (B) Mean cost-per-item (CPI slope) according to search type and group. ** = $p < .001$.

Repeated-measures ANOVAs with group (younger and older) and search task (pop-out and serial) as factors revealed a main effect of search task where serial RTs were significantly longer than pop-out RTs, $F(1, 24) = 89.1, p < .001, \eta^2_p = .788$. We also found a main effect of group, $F(1, 24) = 29.3, p < .001, \eta^2_p = .550$, as well as a significant interaction effect between search task and group, $F(1, 24) = 12.5, p = 0.002, \eta^2_p = .342$. Post-hoc t -tests with Holm-Bonferroni corrections performed separately for each group revealed that the younger group had longer RTs in the serial condition ($M = 1739.1$ ms) compared to pop-out ($M = 672.5$ ms, $t(12) = 8.6, p < .001$). Similarly, older adults' RTs were also longer in serial search ($M = 3498.9$ ms) compared to pop-out ($M = 1155$ ms, $t(12) = 6.9, p < .001$).

Post-hoc Holm-Bonferroni corrected t -tests comparing the two groups indicated that older adults had significantly longer RTs in both pop-out, $t(24) = 6.8, p < .001$, and serial, $t(15.3) = 4.6, p < .001$, visual search tasks compared to younger adults.

The significant interaction effect between group and visual search tasks suggests that the difference between pop-out and serial RTs is greater in older adults than in younger adults. We confirmed this effect with a difference analysis in which we subtracted the pop-out RT from the serial RT for each participant. We then compared the two groups on the difference score, which revealed that RTs for the older group increased to a much larger extent than the younger group ($\text{Diff}_{\text{younger}} = 1066.7$ ms, $\text{Diff}_{\text{older}} = 2343.9$ ms, $t(15.1) = 3.5, p = 0.003$). In sum, both groups took longer to find the target in serial trials compared to pop-out trials, but older adults took even longer.

In addition to overall RTs, we investigated potential differences in cost-per-item (CPI). CPI analyses complement overall RTs as they measure the slope of the RT as a function of set size (number of items; Wolfe & Horowitz, 2004). CPI thus reflects the efficiency of the search: in a very efficient search, RTs should remain constant regardless of the number of distractors on the screen, whereas in a less efficient search, an additional amount of time should be associated with the scan of each item. To validate our search tasks, we investigated whether the cost in RTs with increasing number of objects varied according to the search type and the subject group. In serial search, where the attentional demand is higher, it is expected that the set size effect (i.e. the CPI) should be larger compared to pop-out, where the target can be distinguished from distractors at a pre-attentive stage (Treisman & Gelade, 1980; Treisman & Souther, 1985).

We found similar results for CPI as we did for RTs (Figure 2B). We conducted a repeated-measures ANOVA with group and visual search task as factors and found a main effect of visual search task, $F(1, 24) = 50.3, p < .001, \eta^2_p = .677$, of group, $F(1, 24) = 6.8, p = 0.015, \eta^2_p = .221$, as well as an interaction effect, $F(1, 24) = 5.6, p = 0.026, \eta^2_p = .189$.

Post-hoc t -tests, Holm-Bonferroni corrected, performed separately for each group revealed that the younger group had a higher CPI in the serial condition ($M = 29.8$ ms) compared to the pop-out condition ($M = 3.2$ ms, $t(12) = 6.7, p < .001$). The same pattern was found in older adults ($M_{pop-out} = 6.3$ ms, $M_{serial} = 59.7$ ms, $t(12) = 5.1, p < .001$). For both groups, RTs increased to a much larger extent in relation to the increasing number of items in the serial condition compared to pop-out. Further, to investigate if the present pop-out search was performed completely in parallel, we conducted one sample t -tests in which we compared each group's CPI to zero, separately. We found that the slope was different from zero for both younger, $t(12) = 7.9, p < .001$, and older adults, $t(12) = 3.3, p = 0.006$. These results indicate that, although the pop-out task was much more efficient than serial, it was not completely performed in parallel.

Post-hoc Holm-Bonferroni corrected t -tests comparing the two groups revealed that older adults had a higher CPI than younger adults in the serial condition only, $t(14.8) = 2.5, p = 0.023$. No difference between the groups was found in pop-out search, $t(13) = 1.6, p = 0.128$. The number of items seems to affect the two groups in a similar way in pop-out search when measured overall across the entire workspace. In contrast, the cost to search for each item was higher for older adults in serial search.

To test the interaction effect, we conducted a difference analysis in which we subtracted the pop-out CPI from the serial CPI of each participant and set the difference as a factor. The test revealed that

the CPI increased to a greater extent in the serial search for the older adults (Diff. = 53.4 ms) compared to younger adults (Diff. = 26.7 ms, $t(15.4) = 2.4, p = 0.031$). In sum, an increase in number of items caused longer RTs in the serial task compared to pop-out for both groups, and the cost of each item was found to be bigger for older adults than younger adults in serial search only.

In summary, we observed longer overall RTs for older adults as well as decreased search performance in serial search, similarly to what was found in previous studies.

Effect of target eccentricity on search times

Target eccentricity was shown to influence target detection in visual search tasks, where target detection times increase with eccentricity (Carrasco, Evert, Chang, & Katz, 1995). We hypothesized that if older participants indeed tend to be biased in processing central vision compared to peripheral, they should show larger increases in RTs compared to younger adults as target eccentricity increases. We did not follow these analyses with CPI due to insufficient number of trials.

Figure 3A shows overall RTs for two different target eccentricities in the full view pop-out search task (near = less than 6°, far = 6° or greater). As can be observed, older participants' RTs increased to a greater extent compared to younger participants for the far eccentric targets. A repeated-measures ANOVA with eccentricity (near and far) and group as factors revealed significant main effects of eccentricity, $F(1, 24) = 212, p < .001, \eta^2_p = .898$, and group, $F(1, 24) = 45.2, p < .001, \eta^2_p = .653$, and an interaction effect, $F(1, 24) = 44.8, p < .001, \eta^2_p = .651$.

Figure 3. Reaction times in relation to eccentricity across full viewing pop-out and serial search tasks. Younger adults' performance is shown in white and older adults' in grey. (A) Pop-out search RT. Mean reaction time (RT) in seconds (s) according to eccentricity category (near and far, threshold established at 6° of visual angle). (B) Serial search RT. Mean reaction time (RT) in seconds (s) according to eccentricity category (near and far, threshold established at 6° of visual angle).

Post-hoc t -tests with Holm-Bonferroni correction, performed separately for groups, indicated that the younger group had longer RTs when the target was further in the periphery ($M = 777.7$ ms) compared to when it was nearer to center ($M = 508.3$ ms, $t(12) = 11$, $p < .001$). The same pattern was found in older adults ($M_{near} = 710.8$ ms, $M_{far} = 1439$ ms, $t(12) = 11.4$, $p < .001$). RTs were also shorter for the younger group compared to the older group both when the target was near, $t(24) = 4.4$, $p < .001$, and far, $t(18) = 7.2$, $p < .001$.

We tested this interaction with a difference analysis, which revealed that the older group's RTs increased to a greater degree (Diff. = 728.2 ms) than the younger group's (Diff. = 269.4 ms) for far target eccentricities, $t(15.4) = 6.7$, $p < .001$.

We next performed the same analysis for the serial condition (Figure 3B). We found main effects of eccentricity, $F(1, 24) = 10.8, p = .003, \eta^2_p = .310$, and group, $F(1, 24) = 18.7, p < .001, \eta^2_p = .438$, but no significant interaction, $F(1, 24) = 0.4, p = .542$.

In sum, in the pop-out, full viewing condition, when the target was more eccentric, both groups took longer to detect it, and older adults showed larger increases in RTs associated with the distance from the center. In serial search, eccentric targets also took longer to be detected compared to more central targets. Although older adults took overall more time to detect the target, both groups' RTs increased in a similar manner for peripheral targets.

Effect of scotoma size on pop-out search

The eccentricity results from the full viewing search tasks with no scotoma suggest that peripheral visual processes are decreased in older adults for pop-out search. Older adults' performance was also lower for serial search, where peripheral visual processing appears to be less relevant, but this may be due to the nature of the task. Thus, we predict that when central vision is occluded by a scotoma, there should be greater impairments for older adults in the pop-out condition compared to younger adults. We expect less of a difference between the two groups for the serial search task.

Figure 4 shows RTs as a function of scotoma size for the pop-out search task. Following a repeated-measures ANOVA with scotoma size (full view condition, 3° scotoma, 5° scotoma and 7° scotoma) and group as factors, we observed significant main effects of scotoma size, $F(1.6, 37.9) = 24.4, p < .001, \eta^2_p = .504$, group, $F(1, 24) = 31.4, p < .001, \eta^2_p = .567$, and an interaction effect, $F(1.6, 37.9) =$

5.4, $p = 0.013$, $\eta^2_p = .183$. These results show that the scotoma did not have the same effect on the two groups; the increase in RTs was bigger for older adults.

Figure 4. *Reaction time in relation to scotoma size in pop-out search.* Reaction times (RT) in seconds (s) according to scotoma conditions (full-viewing condition, scotomas of 3°, 5° and 7° of visual angle). Younger adults' performance is shown in white and older adults' in grey.

ANOVAs performed separately for each group revealed a main effect of scotoma size for both groups, younger: $F(1.6, 19.5) = 9.1$, $p = .003$, $\eta^2_p = .431$; older: $F(1.5, 18.5) = 16.3$, $p < .001$, $\eta^2_p = .576$. For the younger group, family-wise Holm-Bonferroni corrected post-hoc t -tests revealed significant differences between the full view condition ($M = 672.5$ ms) and the 3° scotoma ($M = 792.8$ ms, $t(12) = 3.4$, $p = .006$), full view and 5° scotoma ($M = 815.6$ ms, $t(12) = 4$, $p = .002$) and full view and 7° scotoma ($M = 1010.9$ ms, $t(12) = 3.8$, $p = .002$), but no significant differences between the different scotoma sizes ($p > .023$).

For the older group, we observed differences between every condition except full view and 3° scotoma. There were differences between the full view condition ($M = 1155$ ms) and 5° scotoma ($M = 1523.6$ ms, $t(12) = 3.3$, $p = .006$), between full view condition and 7° scotoma ($M = 2012.9$ ms, $t(12) = 4.6$, $p = .001$), between 3° ($M = 1294.2$ ms) and 5° scotomas, $t(12) = 3.1$, $p = .009$, between 3° and 7° scotomas, $t(12) = 4.2$, $p = .001$, and between 5° and 7° scotomas, $t(12) = 3.6$, $p = .004$. Only a tendency was found between the full view condition and 3° scotoma, $t(12) = 2.1$, $p = .062$.

In summary, younger adults did not show an effect of scotoma size other than an increase in RT in all scotoma conditions compared to full view, suggesting a limited disruptive effect of the presence of the scotoma. For older adults, we observed a relationship between scotoma size RTs: the bigger the scotoma, the longer the RTs. This implies that the central/para-foveal field plays an important role in visual scene processing during pop-out search for this group.

Influence of scotoma size on saccade number and fixation duration in pop-out search

We next investigated whether the relationship between scotoma size and RTs could be explained by different eye movements in younger and older adults. We aimed to determine whether the increase in RTs was related to an increase in the number of saccades, an increase of the duration of each fixation or both. The former would suggest a decreased attentional window size while the latter would suggest increased processing time during peripheral viewing (Khan et al., 2016; Young & Hulleman, 2013; Cornelissen et al., 2005). If older adults had small attentional windows, then they would need to shift their eyes more often compared to younger adults to compensate for deficits in visual processing at a single fixation. Moreover, with increasing central occlusion, more of their attentional window would be obstructed requiring additional saccades. On the other hand, increased fixation durations as a

function of increased central occlusion would suggest difficulties in visual processing in peripheral vision.

We first looked at mean saccade number per trial as a function of the presence and size of the scotoma (full view condition, 3° scotoma, 5° scotoma and 7° scotoma), separately for each group (Figure 5). For younger adults, a repeated-measures ANOVA revealed a significant scotoma size effect, $F(2.4, 29.9) = 6.3$, $p = .003$, $\eta^2_p = .344$. After family-wise Holm-Bonferroni corrections, however, no significant difference was found between conditions ($p > .008$, threshold for significance).

Figure 5. Mean saccade number in relation to scotoma size in pop-out search. (A) Younger adults' mean saccade number according to scotoma conditions (full-viewing condition, scotomas of 3°, 5° and 7° of visual angle). (B) Older adults' mean saccade number according to scotoma conditions (full-viewing condition, scotomas of 3°, 5° and 7° of visual angle).

For older adults, a repeated-measures ANOVA showed an effect of scotoma size, $F(1.4, 17.3) = 9.6$, $p = .003$, $\eta^2_p = .445$. Post-hoc Holm-Bonferroni corrected t -tests revealed differences between the full view condition ($M = 3$ saccades) and 7° scotoma ($M = 4.2$ saccades; $t(12) = 3.3$, $p = .007$), between

3° ($M = 3$ saccades) and 5° scotoma conditions ($M = 3.4$ saccades, $t(12) = 5.1, p < .001$), and between 3° and 7° scotoma conditions ($M = 4.2$ saccades, $t(12) = 3.6, p = .004$). No difference was found between other conditions ($p > .017$, Holm-Bonferroni corrected). Generally, older adults made more saccades as the scotoma got bigger, contrary to younger adults. In addition, correlational analyses performed for each group revealed strong relationships between saccade number and RTs for both younger, $r(12) = .824, p = .001$, and older adults, $r(12) = 0.744, p = .004$. As the number of saccades increased, RTs also increased, supporting the idea that more saccades are necessary to compensate for a smaller attentional window.

For mean fixation duration, repeated-measures ANOVAs conducted separately for each group in full view and scotoma conditions showed similar main effects (Figure 6). For younger adults, we found an effect of scotoma size, $F(2.3, 27.6) = 12.9, p < .001, \eta^2_p = .519$. With Holm-Bonferroni corrected post-hoc t -tests, we found differences between full view and scotoma conditions, but not between different scotoma sizes. Full view condition ($M = 137.3$ ms) was different from 3° scotoma ($M = 183.2$ ms, $t(12) = 3.7, p = .003$), 5° scotoma ($M = 191.3$ ms, $t(12) = 6.4, p < .001$) and 7° scotoma ($M = 192.7$ ms, $t(12) = 5, p < .001$). No other difference was found ($p > 0.017$, Holm-Bonferroni corrected). Similar to what was found in RT analyses, the presence of the scotoma, but not its size, required younger adults to fixate longer.

Figure 6. Mean fixation duration in relation to scotoma size in pop-out search. (A) Younger adults' mean fixation duration in seconds (s) according to scotoma conditions (full-viewing condition, scotomas of 3°, 5° and 7° of visual angle). (B) Older adults' mean fixation duration in seconds (s) according to scotoma conditions (full-viewing condition, scotomas of 3°, 5° and 7° of visual angle).

For older adults, we also found a main effect of scotoma size, $F(1.9, 22.9) = 31.3, p < .001, \eta^2_p = .723$.

Post-hoc Holm-Bonferroni corrected t -tests revealed differences between every condition except one.

As with younger adults, full view condition ($M = 147.2$ ms) was different from 3° ($M = 194.3$ ms, $t(12) = 4.7, p < .001$), 5° ($M = 209.5$ ms, $t(12) = 6.1, p < .001$) and 7° scotomas ($M = 221.9$ ms, $t(12) = 7.3, p < .001$). Additionally, 3° scotoma was different from 5°, $t(12) = 4.2, p = .0017$, and 7° scotomas, $t(12) = 4.2, p = .001$. Only a tendency was found between 5° and 7° scotomas, $t(12) = 1.8, p = .092$.

In sum, contrary to younger adults, older adults fixated longer with bigger scotomas. In contrast to saccade number however, there was no significant correlation between fixation durations and RTs for the younger, $r(12) = .197, p = .518$, or older groups, $r(12) = .156, p = .611$, groups.

Effect of scotoma size on serial search

For serial visual search, we analysed the effect of scotoma size on performance in the same manner outlined in the pop-out task above (Figure 7). We observed a main effect of scotoma size, $F(2, 47) = 6.6, p = .003, \eta^2_p = .216$, and group, $F(1, 24) = 26.4, p < .001, \eta^2_p = .524$. However, there was no significant interaction effect, $F(2, 47) = 0.4, p = .682$. These findings show that while older adults had overall longer RTs than younger adults, the scotoma influenced both groups in the same manner. It is likely that for the serial task, central information is used similarly to undertake the task for both groups.

Figure 7. *Reaction time in relation to scotoma size in serial search.* Reaction times (RT) in seconds (s) according to scotoma conditions (full-viewing condition, scotomas of 3°, 5° and 7° of visual angle). Younger adults' performance is shown in white and older adults' in grey.

Discussion

We investigated central and peripheral visual processing among younger and older adults by comparing their performance on two visual search tasks while occluding their central vision with different sized gaze-contingent artificial scotomas. Our results are consistent with the notion of reduced attentional resources for visual search along with more difficulty in peripheral processing during global scene perception for older adults. More specifically, we showed that 1) deficits found in older adults occurred in conditions in which attention was directed in their peripheral visual field, and that 2) they showed impairments both in eye movements and behavioral performance when bigger parts of their central fields were occluded.

In full viewing conditions, we replicated previous findings of longer RTs for older adults compared to younger adults for both types of search (Madden, 1986; Plude & Doussard-Roosevelt, 1989; Treisman & Gelade, 1980). We also replicated findings related to CPI, showing that older adults were not different from younger adults for pop-out search; the set size slope of both younger and older adults' search was similarly efficient (Hommel et al., 2004; Plude & Doussard-Roosevelt, 1989). Previous studies on the effect of aging have reported increased RTs but no difference in CPI for pop-out searches, while RTs and CPIs were increased in serial search (Greenwood & Parasuraman, 1999; Hommel et al., 2004; Müller-Oehring et al., 2013; Plude & Doussard-Roosevelt, 1989).

We also investigated RTs as a function of target eccentricity in full view. In pop-out search, both groups took longer to find eccentric targets compared to those in the para-foveal area. More importantly, we also observed a larger increase in RTs associated with peripheral targets for older adults compared to younger adults. The interaction's effect size was large: knowing participants' age

group and the target's eccentricity category accounted for 65% of the variance in their performances. In serial search, we observed a similar RT increase for both groups associated with target eccentricity.

Then, we occluded participants' central vision with an artificial scotoma of different diameters and compared their performance. In pop-out search, we observed that older adults' search times increased in the presence of a scotoma and with scotoma size in a systematic manner, with a partial eta squared accounting for 58% of their performances' variance. This was not the case for younger adults whose search times were only affected by the presence of the scotoma, but not by its size. We also analysed both groups' eye movements parameters, namely number of saccades and fixation duration, in function of scotoma size. We found that search times patterns were mirrored by eye movement patterns for both groups: older adults generally made more saccades (partial eta squared explaining 45% of the variance) and had longer fixation durations (explaining 72% of the variance) as the scotoma size increased. In contrast, younger adults only fixated longer when the scotoma was present, but not as its size increased, and there was no difference in their saccade number associated with the presence and size of the scotoma.

In serial search, while we did observe overall longer RTs for the older adults, we observed no difference between the two groups in their reaction to scotoma size and eccentricity. Specifically, both groups showed similar increases in RTs for peripheral targets compared to central and both also showed similar increases in RTs as a function of scotoma presence and size.

As described in the introduction, various hypotheses explained differences in performance between younger and older adults, including declines in sensory, motor and cognitive processing. Researchers supporting a sensory decline in aging have associated the decrease in performance in older adults with

lower detectability (Madden et al., 1999). Proponents of the motor hypothesis have focused on changes in motor movement times such as increased saccade latencies, and decreased saccade accuracy and peak velocity (Bono et al., 1996; Irving et al., 2006; Moschner & Baloh, 1994; Paquette & Fung, 2011), as well as on generalized motor slowing in aging (Salthouse, 1996). Finally, those supporting the cognitive hypothesis have suggested that aging impairs top-down attentional control during searches with many distractors resulting in increased response times (Eckstein, 2011; Hommel et al., 2004; Scialfa et al., 1998; Treisman & Gelade, 1980; Treisman & Souther, 1985; Wolfe & Horowitz, 2004; Wolfe et al., 1989). Further, deficits in visuospatial attention, decreased working memory load and decreased central executive resources in normal aging have also been reported (Greenwood & Parasuraman, 1999; Kramer et al., 1999; Van der Linden et al., 1994).

We found that our results, specifically for the pop-out search task, are consistent with declines in cognitive processes, more specifically in attentional resources. While the overall increase in RTs for older adults in the full viewing conditions could be explained by a generalized slowing of sensory or motor processing, this hypothesis cannot account for specific differences between groups that we found only in certain conditions. Indeed, if older adults' deficits were solely sensorimotor in nature, we would expect a homogeneous handicap compared to younger adults across conditions, regardless of target eccentricity and scotoma size. Instead, our results showed specific decreases in older adults' performances in conditions of great eccentricity and scotoma sizes. These results are consistent with the notion of a bias toward central processing at the expense of peripheral processing in older adults for pop-out search, which highlights limitations in visuospatial attention.

Regarding target eccentricity in full viewing pop-out search, our findings that both groups took longer to find eccentric targets is in line with the idea that the search was not executed completely in parallel,

in that not all items were processed at the same time. It also concurs with the notion that we process visual information from the fovea to the periphery consecutively (Larson, Freeman, Ringer, & Loschky, 2014) and that central information is attended to a higher degree compared to peripheral information. Moreover, the proportionally higher cost that we found in older adults suggests that they were more biased than younger adults to process items in their central vision compared to their peripheral vision. Indeed, this difference between the groups is specifically associated with item location with respect to central and peripheral vision, in contrast to the CPI which was similar between younger and older adults. This may reflect a more pronounced bias toward central vision rather than a generalized slowing in processing items as otherwise, there would have been a difference between the groups' CPI as well. In summary, our RT target eccentricity results suggest that for pop-out search, there is a detrimental effect on search for eccentric targets for older adults, supporting the notion of greater reliance on central visual processing for this population, slowing down the spatial shifting of their attention towards more peripheral locations.

Concerning scotoma conditions in pop-out search, younger adults' performance was solely impaired by the presence of the scotoma rather than by its size. It is likely that the scotoma itself acted as a distraction for younger adults as they were no less efficient at processing items with a bigger detriment to their central vision compared to a smaller one. In contrast, older adults showed increased search times, more frequent gaze reorienting and slower processing within a single glance in the presence of a scotoma and with scotoma size. These findings show that that central and para-foveal vision play an important role in visual scene processing during pop-out search for older adults, suggesting that they tend to use it more than younger adults when processing scenes. Indeed, a central bias would impair their ability to adapt their saccades to bigger scotomas, since aligning the target to a more peripheral area in their visual field would be more difficult. Focusing their attention further from central vision

would also require more processing time within every glance. These findings, combined with increased search times for eccentric targets in the full viewing condition, imply that older adults rely more on central vision during scene processing. In summary, we propose that these results are consistent with the notion of declines in efficient attentional shifting from the center towards more peripheral locations in aging. They also support the hypothesis that peripheral degradation of natural scenes provokes tunnel vision with a reduced attentional focus that leads to a decreased processing of peripheral stimuli (Mackworth, 1965; Williams, 1988).

Moreover, these pop-out results are consistent with older adults having a reduced attentional window or useful field of view (UFOV) compared to younger adults for pop-out search. The attentional window and the useful field of view (UFOV) are two measures of the visual field in which we can process information efficiently within a fixation point (Ball et al., 1988; Coeckelbergh et al., 2004; Khan et al., 2016). Specifically, the attentional window represents the area in which a target can be detected during a visual search task (Khan et al., 2016) whereas the UFOV measures the divided attention cost when participants simultaneously perform tasks in their central and peripheral visual fields (Sekuler et al., 2000). Previous studies investigating the effect of age on attentional window and UFOV show inconsistent results. Some studies showed reduced UFOV in older adults (Richards, Bennett, & Sekuler, 2006; Scialfa, Thomas, & Joffe, 1994; Sekuler et al., 2000). Other studies observed that this reduction may be plastic and partially regained through training (Ball et al., 1988). In contrast, other authors have not replicated these findings (Hommel et al., 2004; Madden et al., 1999a; Seiple et al., 1996), with some suggesting that deficits were instead associated with more generalized disengaged or diffuse attention (Cosman, Lees, Lee, Rizzo, & Vecera, 2012; Greenwood & Parasuraman, 2004).

Performance deficits that we observed in older adults could be indicative of a smaller attentional window. Indeed, in line with our results, a smaller attentional window would result in longer RTs for older adults as they would take more time to shift their smaller attentional window to find a target located in the periphery. As target location increased in eccentricity, more systematic exploration of the display was needed to locate the target for older adults. In contrast, younger adults with large attentional window sizes required much less exploration to find the target, implying that their attentional window was large enough to match the entire display size (Khan et al., 2016). In addition, difficulties found in older adults in relation to central scotomas (as additional saccades were needed when central vision was occluded) could also be linked to a smaller attentional window: by imposing on its remaining (rather small) spatial range, the central scotoma would hinder older adults' ability to perform the task. For younger adults, who were affected by presence of the scotoma but not by its size, a saccade was therefore only required when the target was located in an occluded area by the scotoma and needed to be uncovered.

In serial search, while we did observe overall longer RTs for the older adults, we observed no difference between the two groups in their reaction to scotoma size and eccentricity. Specifically, both groups showed similar increases in RTs for peripheral targets compared to central and both also showed similar increases in RTs as a function of scotoma presence and size. We surmise that this may be due to the reliance on more central processing required in serial search for both younger and older adults. For example, 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 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). We have shown previously that the size of the attentional window is smaller for

serial search compared to pop-out (Khan et al., 2016), restricting processing to the central and para-foveal visual field. We propose that because the attentional window is small during serial search, items are processed within a smaller window than the search array and thus the eccentricity of the target becomes less relevant, although we are limited in this explanation because we did not measure participants' attentional window directly. If this is the case, a central scotoma would be equally detrimental to younger and older adults as it occludes objects within the restricted attentional window, thus requiring more saccades and more time to find the target for both groups. It is possible that the difficulty of our serial search task was such that the size of the attentional window was similar for both age groups and an easier task would reveal differences like those seen for pop-out search. In any case, since differences in RTs between older and younger adults were the same regardless of conditions, more general impairments could be at play and we can not differentiate without doubt whether older adults' longer search times are due to sensory decreases, motor slowing or attentional impairments in serial search.

Taken together, our findings suggest that there is an attentional impairment in older adults resulting in deficits in pop-out visual search. More specifically, compared to younger adults, older adults had difficulties locating peripheral targets in full viewing conditions and their search was less efficient with bigger scotomas obstructing their central vision. This can be explained by an attentional bias and possible shrinkage which makes them rely more on central vision and less on peripheral vision, especially during global scene processing.

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