

The effects of age and cognitive load on peripheral-detection performance

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Age-related declines in both peripheral vision and cognitive resources could contribute to the increased crash risk of older drivers. However, it is unclear whether increases in age and cognitive load result in equal detriments to detection rates across all peripheral target eccentricities (general interference effect) or whether these detriments become greater with increasing eccentricity (tunnel effect). In the current study we investigated the effects of age and cognitive load on the detection of peripheral motorcycle targets (at 5°–30° eccentricity) in static images of intersections. We used a dual-task paradigm in which cognitive load was manipulated without changing the complexity of the central (foveal) visual stimulus. Each image was displayed briefly (250 ms) to prevent eye movements. When no cognitive load was present, age resulted in a tunnel effect; however, when cognitive load was high, age resulted in a general interference effect. These findings suggest that tunnel and general interference effects can co-occur and that the predominant effect varies with the level of demand placed on participants' resources. High cognitive load had a general interference effect in both age groups, but the effect attenuated at large target eccentricities (opposite of a tunnel effect). Low cognitive load had a general interference effect in the older but not the younger group, impairing detection of motorcycle targets even at 5° eccentricity, which could present an imminent collision risk in real driving.

directly in front of us to monitor its speed and distance relative to our own vehicle while remaining vigilant to hazards such as motorcycles or pedestrians approaching our lane from the periphery. If the driver is distracted by a cognitive task, such as trying to remember route directions or listening to navigation instructions, the ability to detect hazards using peripheral vision may be impaired, especially in older age (Horrey & Wickens, 2006).

Older drivers are overrepresented in collisions at intersections (Caird & Hancock, 2002; Mayhew, Simpson, & Ferguson, 2006; McGwin & Brown, 1999; Preusser, Williams, Ferguson, Ulmer, & Weinstein, 1998). Many reasons have been put forward to account for this (for a review, see Janke, 1994), including age-related declines in both peripheral vision (Ball, Beard, Roenker, Miller, & Griggs, 1988; Ball, & Owsley, 1993) and cognitive resources (Ball & Owsley, 1991; Mathias & Lucas, 2009). Although many studies have investigated the effects of aging on peripheral detection (e.g., Ball et al., 1988; Ball & Owsley, 1993; Rogé et al., 2004; Rogé, Otmani, Pebayle, & Muzet, 2008; Seiple, Szlyk, Yang, & Holopigian, 1996; A. Sekuler, Bennett, & Mamelak, 2000), only a few have directly examined the combined roles of both age and cognitive load (Ball et al., 1988; Holmes, Cohen, Haith, & Morrison, 1977). Therefore, the current study was designed to investigate the effects of both age and cognitive load on peripheral detection in a task relevant to detection of hazards at intersections.

As summarized later, there is a lack of consensus as to whether increasing age and increasing cognitive load result in a general decline in detection performance across the whole visual field or in a decline that is greater at more peripheral locations (i.e., *general*

Introduction

Many real-world situations require the concurrent use of both central and peripheral vision. When driving, for instance, we often need to look at a car

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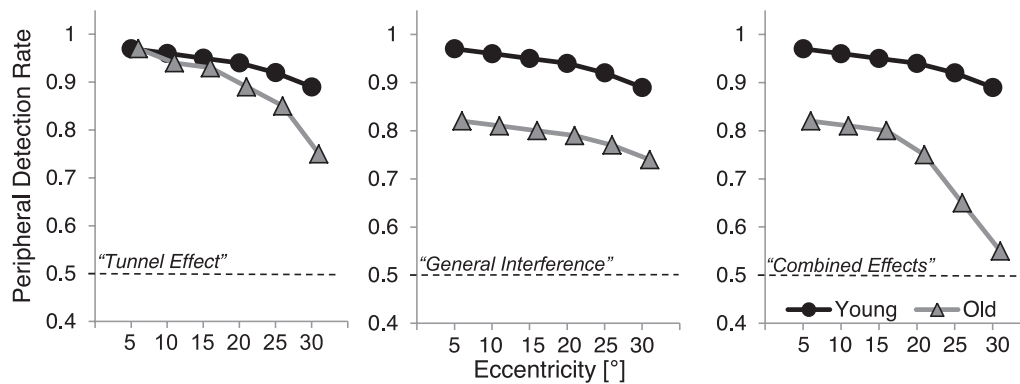


Figure 1. Example plots demonstrating three possible outcomes for the effects of age on peripheral-detection rates for our motorcycle-detection task. Left: tunnel effect; middle: general interference effect; right: combined tunnel and general interference effects. Dashed horizontal line indicates level of chance (50% correct). Connecting lines between markers have been added to more clearly demonstrate the expected pattern of the data.

interference effects vs. tunnel effects). A general interference effect (Figure 1, middle) is indexed by a reduction in peripheral-detection rates which is the same across all levels of retinal eccentricity (Holmes et al., 1977). Conversely, a tunnel effect (Figure 1, left) is characterized by a cost to peripheral-detection rates which is greater at larger than smaller retinal eccentricities (Ikeda & Takeuchi, 1975; Webster & Haslerud, 1964).

The effects of age on peripheral-detection rates

Older adults have frequently been found to perform less well than younger adults on peripheral-detection tasks requiring localization (Ball et al., 1988; A. Sekuler et al., 2000; R. Sekuler & Ball, 1986) or identification (Scialfa, Kline, & Lyman, 1987) of targets at different retinal eccentricities. A majority of studies have found that detection rates declined more strongly in the periphery for older than younger participants, consistent with a tunnel effect (Ball et al., 1988; Cerella, 1985; Rogé et al., 2004; Rogé, Pébayle, El Hannachi, & Muzet, 2003; Scialfa et al., 1987; Scialfa, Thomas, & Joffe, 1994). However, in some cases the tunnel effect was weak, barely reaching significance (Rogé et al., 2004). On the other hand, neither Seiple et al. (1996) nor A. Sekuler et al. (2000) found a tunnel effect of age. In those studies, both older and younger participants experienced an eccentricity-related decline in detection rates, with older participants experiencing a greater decline than younger participants, but there was no interaction between age and eccentricity. These findings support a general-interference account of age on peripheral-detection rates and stand in contrast to tunnel-effect accounts.

The effect of cognitive-task demand on peripheral-detection rates

Prior studies have increased cognitive load in a variety of ways. For instance, cognitive load can be manipulated by increasing the difficulty of a visual task at a central fixation location (foveal load; e.g., L. J. Williams, 1988) or in the auditory domain by increasing the difficulty of an auditory-working-memory task (Pomplun, Reingold, & Shen, 2001; Reimer, Mehler, Wang, & Coughlin, 2012). When foveal load is increased, results typically suggest a tunnel effect, with detection rates for targets further in the periphery decreasing to a greater extent than for targets closer to fixation (Ball et al., 1988; Chan & Courtney, 1993; Ikeda & Takeuchi, 1975; L. J. Williams, 1985). However, some researchers have pointed out that this tunneling may be due to both the increased complexity of the foveal visual stimulus and the increased cognitive demand of the task (Ringer, Throneburg, Johnson, Kramer, & Loschky, 2016; L. J. Williams, 1988). This confound may be avoided by using an auditory-working-memory task. However, some studies using such a task have reported tunnel effects (Atchley & Dressel, 2004; Pomplun et al., 2001), while others have reported general interference effects (Gaspar et al., 2016; Ringer et al., 2016; Strayer, Drews, & Johnston, 2003).

Another approach is to manipulate cognitive load within the visual domain without significantly altering the amount of sensory information received by the participant. For example, L. J. Williams (1985) manipulated foveal cognitive load by asking participants to call out single letters at the fixation location while simultaneously performing a peripheral-detection task. In the low-load condition there were only two possible letters that could be presented, while in the high-load condition there were six possible letters.

Thus, it was possible to increase cognitive load (the number of possible letters) without altering the amount of visual information on the screen (only one letter was ever presented at a time). This study demonstrated moderate tunnel effects on peripheral-detection rates. Chan and Courtney (1993) used three levels of foveal cognitive load without changing the complexity of the visual stimulus, which was a two-digit number presented at the fixation location. Participants were asked to either passively look at the number (lowest load), identify the number (middle load), or mentally sum the two digits (highest load) while detecting peripheral targets. A significant interaction between cognitive load and eccentricity was reported, suggesting mild evidence of a tunnel effect on peripheral-detection rates. Although these early studies provided some evidence of a tunnel effect, the participants were all young undergraduate students. Furthermore, only a limited range of peripheral eccentricities was tested (3° to 9° by Williams, 2° to 12° by Chan & Courtney).

The current study

The aim of the current study was to determine the effects of increasing cognitive load on peripheral-detection rates in younger and older participants over a range of eccentricities (5° to 30°) likely to be encountered at an intersection and without confounding effects of changes in the visual complexity of the cognitive-task stimulus. The goal was to evaluate the effects of cognitive load as it might be encountered when distracted by trying to remember route instructions or items on a grocery list while driving. Many studies have investigated the effects of aging and foveal load on peripheral detection (e.g., Ball et al., 1988; Ball & Owsley, 1993; Rogé et al., 2004; Rogé et al., 2008; Seiple et al., 1996; A. Sekuler et al., 2000). However, to our knowledge, none have examined how age and cognitive load—as separate from foveal visual-stimulus complexity (foveal load)—might affect peripheral detection. To this effect, we presented either a fixation cross or a letter at a central fixation location while older and younger participants performed a peripheral-detection task. In the no-load condition, participants maintained fixation on the cross; in the low-load condition, they read out loud the letter presented on each trial; and in the high-load condition they stated out loud the letter presented on the previous trial (modified *n*-back-1 task). Therefore, we were able to alter cognitive load while keeping constant the visual complexity of the cognitive task. The only difference between the high- and low-load conditions was the task instructions. Thus, we argue that any differences in peripheral-detection performance between the letter

and *n*-back-1 tasks would be caused by the increase in cognitive load alone.

We were primarily interested in determining whether our two factors (age and cognitive load) resulted in a tunnel effect, a general interference effect, or even a combination of both tunnel and general interference effects. As discussed already, age and cognitive load have each been shown to result in either tunnel or general interference effects. We therefore posited that it might be possible for a tunnel effect and a general interference effect to occur at the same time. If our independent variables (IVs) resulted in a general interference effect, we predicted that we would see main effects of eccentricity and our IV but no interaction between the two (Figure 1, middle). A tunnel effect would be evident if we saw no main effect of our IV but a significant main effect of eccentricity and a significant interaction between the two (provided the effect of the IV became larger with increasing target eccentricity; Figure 1, left). Finally, for a combined tunnel and general interference effect we predicted significant main effects of eccentricity, our IV, and the interaction between the two (if the effect of our IV became larger with increasing retinal eccentricity of the target; Figure 1, right).

Prior studies examining the effects of cognitive load on peripheral detection have used abstract stimuli that were not a natural part of a traffic scene—for example, a cartoon of a human face among distracters that were outlines of boxes presented against a plain background (Ball et al., 1988) or Gabor patches that were size-scaled to be equally discriminable at all peripheral eccentricities (Ringer et al., 2016). While these approaches enable strict control of stimulus parameters, ecological validity may be limited. We therefore used stimuli in which the detection target (a motorcycle) was part of a traffic scene and was always the correct size relative to the scene (i.e., was not size-scaled). Failure to detect motorcycles at intersections is an issue which has been recognized for a long time (e.g., Robertson, McLean, & Ryan, 1966; M. J. Williams & Hoffmann, 1979); however, the reasons for these detection failures remain unclear. Of relevance to the goals of this study, older drivers are more likely than younger drivers to fail to detect motorcycles at intersections (Clarke, Ward, Bartle, & Truman, 2010), with the most common type of collision occurring when a vehicle violates the motorcyclist's right of way by pulling out in front of them (Clabaux et al., 2012; Clarke et al., 2010; Hurt, Ouellet, & Thorn, 1981; Pai, 2011; Pai, Hwang, & Saleh, 2009). For these reasons, we modeled our peripheral task on the detection of motorcycles in images of intersections created in our driving simulator.

Methods

Participants

We recruited 51 participants (24 women, 27 men) in two groups: 24 younger (20–40 years; mean = 25.4) and 27 older (60+ years; mean = 68.7) from a database of participants who had participated in prior studies at Schepens Eye Research Institute. The main inclusion criteria were vision that met the visual requirements for driving in Massachusetts (20/40 visual acuity) and no history of ocular disease that might impair visual acuity or cause visual-field deficits. Median visual acuity was 20/15 (range = 20/15 to 20/30) in the younger group and 20/25 (range = 20/15 to 20/40) in the older group (TestChartPro2000, Thomson Software Solutions, Herts, UK). Three participants from the older group were excluded due to poor performance on the high-cognitive-load task (<50% correct). Thus, data from 24 younger and 24 older participants were included in analyses. All participants provided informed consent in accordance with institutional review board approval at Schepens Eye Research Institute. The study was conducted in accordance with the tenets of the Declaration of Helsinki.

Materials

The stimuli for the peripheral-detection test were static images of intersections created within our driving simulator (FAAC, Inc., Ann Arbor, MI). The traffic scenes depicted the point of view of a driver approaching a T-shaped intersection with a motorcycle target appearing on either the left or right side of the perpendicular crossroad (Figure 2).

In each intersection, the motorcycle could appear at one of six different eccentricities (5°, 10°, 15°, 20°, 25°, 30°). Motorcycle eccentricity was defined with respect to the participant's straight-ahead gaze position, which was held by the central task at the horizontal center of the image, coincident with the horizontal center of their travel lane (Figure 2). For the central task, either a black cross or a random letter selected from a corpus of 22 uppercase letters (height 1.5°) was presented on a white square background outlined in red.

We conducted a pilot experiment (see Appendix 1) in which we tested three different target sizes (subtending 1.3°, 2.1°, and 3.4° vertically) to determine a size of motorcycle that would give a measurable range of peripheral-detection rates for both older and younger participants across the six eccentricities. Participants in the pilot experiment were different from those who participated in the main experiment. We found that the 3.4° target was too large, such that

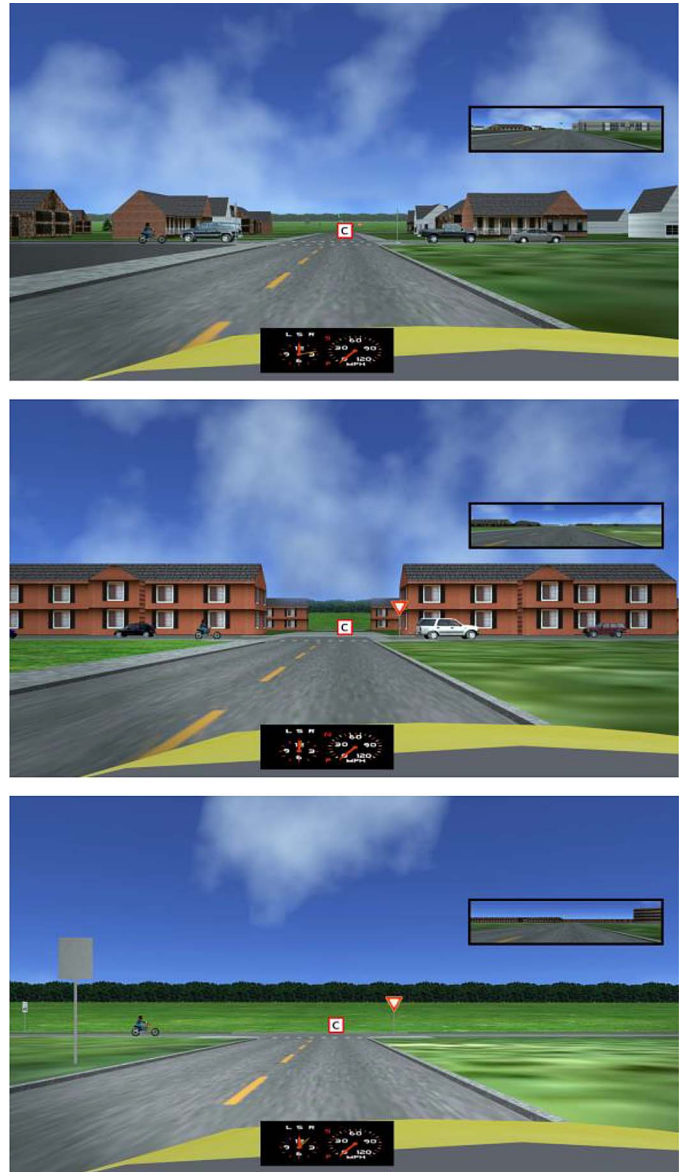


Figure 2. Example stimuli for each of the three intersections. Top panel: suburban intersection (Suburban 1) with background clutter and other traffic (subsequently excluded from analyses). Middle panel: suburban intersection (Suburban 2) with background clutter and other traffic. Bottom panel: rural intersection (Rural 1) without background clutter and without other traffic. The motorcycle appears at 20° to the left of the intersection in the top and bottom panels and 15° to the left in the middle. The letter stimulus is at the straight-ahead gaze position in all panels. First-person view includes rearview mirror in upper right and car hood and instrument display at bottom.

younger participants were performing at ceiling, while the 1.3° target was too small, with older participants performing at floor level. The 2.1° target resulted in a measurable range of peripheral-detection rates across all eccentricities and was used in the main study (Figure A1.1).

We used three intersections: two suburban intersections (Figure 2, top and middle panels) and one intersection in a rural environment (Figure 2, bottom panel). For the two suburban intersections, the motorcycle appeared against a cluttered background of houses and windows. For the rural intersection, it appeared against a less cluttered, more uniform background of grassy fields. For each intersection, we had 24 motorcycle situations: 6 eccentricities (5° , 10° , 15° , 20° , 25° , 30°) \times 2 traffic densities (with and without other traffic) \times 2 sides of the road (left and right). In the scenes with traffic, we included three to five other cars, which never overlapped with the target motorcycle and were distributed randomly on the left and right of the intersection. The center of the intersection was kept free of other traffic. We created three images for each situation, giving a total of 72 unique images per intersection.

Procedure

The peripheral-detection test was administered in a dark room with the stimuli presented on a large rear-projection screen (120 cm \times 170 cm). Participants were seated 120 cm away from the screen with their head supported by a chin rest and used their habitual spectacle corrections as appropriate for that viewing distance. Intersection images with either a cross or a random letter superimposed at the straight-ahead gaze position were displayed only briefly (250 ms), so as to simulate a single fixation (Rayner, 2009) and to prevent the participant from using eye movements to view the scene. Each presentation was followed by a blank screen with a central fixation cross to help maintain the participant's fixation at the central location while they used a keyboard to indicate the side of the screen on which the motorcycle target had appeared (peripheral-detection task). The next image was displayed 500 ms after the response key was pressed. Participants always used their right hand on a key on the right of the keyboard to indicate that the target had appeared on the right side and their left hand on a key on the left of the keyboard to indicate that the target had appeared on the left side of the screen.

During the peripheral-detection task, cognitive-task load was manipulated by means of a central fixation task with three levels: no load, low load, and high load. In the no-load condition, participants fixated a central cross while performing the peripheral task. In the low-load condition, a random letter was presented at the central fixation location and participants were asked to state out loud the letter presented on the current trial. In the high-load condition, they were instructed to state out loud the letter they had seen on the previous trial (*n*-back-1 task). In the low- and high-load conditions

they were told to call out the letter while pressing the response key to indicate whether the motorcycle was on the left or right. Although participants were given unlimited time to make their responses, they were encouraged to respond as quickly and accurately as possible on both tasks.

Participants completed three blocks of trials (one in each cognitive-load condition) consisting of 216 trials each (i.e., each of the unique images for each of the three intersections, as detailed previously), resulting in a total of 648 trials per participant. The presentation order of each block was counterbalanced by means of a 3×3 Latin-square design. Participants completed a block of 50 trials in each condition prior to the start of testing to familiarize themselves with performing the peripheral-detection task and each of the cognitive tasks. Participants' responses on the letter and *n*-back-1 tasks were recorded by means of a voice recorder. Letter and *n*-back-1 task performance was later transcribed and added to the data set.

Statistical analyses

We first examined peripheral-detection rates at each eccentricity for each of the three intersections in the high-cognitive-load (*n*-back-1 task) condition to determine whether peripheral-detection performance was significantly different from chance. We found that older participants reached floor performance (chance, 50% correct) at 30° target eccentricity for one of the suburban intersections (Suburban 1: Figure 2, top panel). We therefore excluded that intersection from all analyses and report data collapsed over the remaining two intersections (Suburban 2; Figure 2, middle panel; and Rural 1: Figure 2, bottom panel). See Appendix 2 for details.

To determine the effects of cognitive-task load, age, and eccentricity on peripheral-detection rates, data were analyzed by means of generalized linear mixed models (GLMMs) using the lme4 package (Version 1.1-17; Bates, Mächler, Bolker, & Walker, 2015) in the R statistical programming environment (R Core Team, 2018).

In constructing models for the main analyses, age (young or old), cognitive load (none, low, or high) and eccentricity (5° , 10° , 15° , 20° , 25° , or 30°) were entered as fixed factors. Age and cognitive load were entered as categorical variables, whereas eccentricity was entered as an integer variable. Categorical predictors were sum coded, which produces effects for each predictor that are equivalent to main effects in analyses of variance. We explored any significant interactions using follow-up models to test the relevant simple effects within the interaction. We also included stimulus image as a random factor to account for any variability across

items, as well as a random factor for participants to account for any individual differences between our participants. The side of motorcycle appearance was not a significant factor affecting correct response rates and was therefore not included in the models. For the random-effects structure, we attempted to include random slopes and intercepts for the fixed effects of age, cognitive load, and eccentricity, and for their interactions, in order to produce a maximal random-effects structure (Barr, Levy, Scheepers, & Tily, 2013). However, maximal structure models often fail to converge. When these models did not converge, we first removed the computation of correlation parameters within the random-effects structures. If further simplification was required for convergence, we first began by simplifying the stimulus term in the random-effects structure. We removed the age \times eccentricity interaction, and then the cognitive-task load \times eccentricity interaction. Next we removed the random slopes sequentially for eccentricity, then age, then cognitive load. If the model still failed to converge, we replicated this simplification procedure for the participant term in the random-effects structure. In the sections that follow, the results are reported for the most complex random-effects structure for which the models converged. We estimated p values for main effects by means of the `lmerTest` package (Kuznetsova, Brockhoff, & Christensen, 2016).

For any interactions between the three fixed factors, p values were calculated by means of model comparisons. For each interaction, we compared a baseline model (with all interactions between the fixed factors removed) with the same model plus the interaction of interest by means of analyses of variance. The resulting χ^2 values represented the significance of the interaction of interest.

It was possible that there might have been a trade-off between performance on the peripheral-detection task and on the cognitive n -back-1 task. Therefore, before running the main analyses, we examined performance on the cognitive task in the high-load condition. We found no evidence of any trade-off with peripheral-detection rates (see Appendix 3 for details). We therefore analyzed peripheral-detection rates regardless of the accuracy on the central task, and performance on the cognitive n -back-1 task was not included as a covariate.

Results

We report results for the main factors of interest—age, cognitive load (task type), and eccentricity—on detection rates for the peripheral-detection task. Peripheral-detection rates for each intersection are

reported in Appendix 2. Details of performance on the cognitive tasks are reported in Appendix 3. In brief, correct response rates were high on the low-load letter task (overall, 98% for younger and 90% for older) and lower, but still relatively high, on the more demanding n -back-1 task (overall, 83% for younger and 76% for older), and did not vary with peripheral target eccentricity.

Main effects of age, task type, and eccentricity

To begin with we constructed a GLMM with 2 (age: old, young) \times 3 (task type: cross, letter, n -back-1) \times 6 (eccentricity: 5°, 10°, 15°, 20°, 25°, 30°) fixed factors. Main effects of age, task type, and eccentricity can be seen in Figure 3 (left: age and eccentricity; right: task type and eccentricity). As expected, peripheral-detection rates were lower for older than younger participants, $\beta = -0.65$, $SE = 0.15$, $z = -4.45$, $p < 0.001$; decreased the further the target appeared in the periphery, $\beta = -0.33$, $SE = 0.04$, $z = -7.57$, $p < 0.001$; and decreased with increasing cognitive load. Compared to the cross task, peripheral-detection rates were worse in both the letter task, $\beta = -0.67$, $SE = 0.2$, $z = -3.46$, $p < 0.001$, and the n -back-1 task, $\beta = -2.37$, $SE = 0.17$, $z = -13.73$, $p < 0.001$.

Age \times task type \times eccentricity interaction

In the original GLMM we found a significant three-way age \times task type \times eccentricity interaction, $\chi^2(5, 12) = 91.99$, $p < 0.001$. We therefore simplified the analysis by investigating each of the two-way interactions separately: age \times eccentricity, age \times task type, and task type \times eccentricity.

Age \times eccentricity interaction

In order to determine whether age had a general interference effect, a tunnel effect, or a combination of these two (Figure 1) on peripheral-detection rates, we split the data by the type of cognitive task (cross, letter, and n -back-1) and ran three 2 (age: old, young) \times 6 (eccentricity: 5°, 10°, 15°, 20°, 25°, 30°) GLMMs. For these models we were primarily interested in the age \times eccentricity interaction, as well as the main effect of age.

For the cross task we found no main effect of age, $\beta = -0.002$, $SE = 0.26$, $z = -0.007$, $p = 0.99$, but we did find a significant age \times eccentricity interaction, $\chi^2(1, 16) = 3.92$, $p = 0.048$. As can be seen in Figure 4 (left panel), the effect of age becomes larger as the target

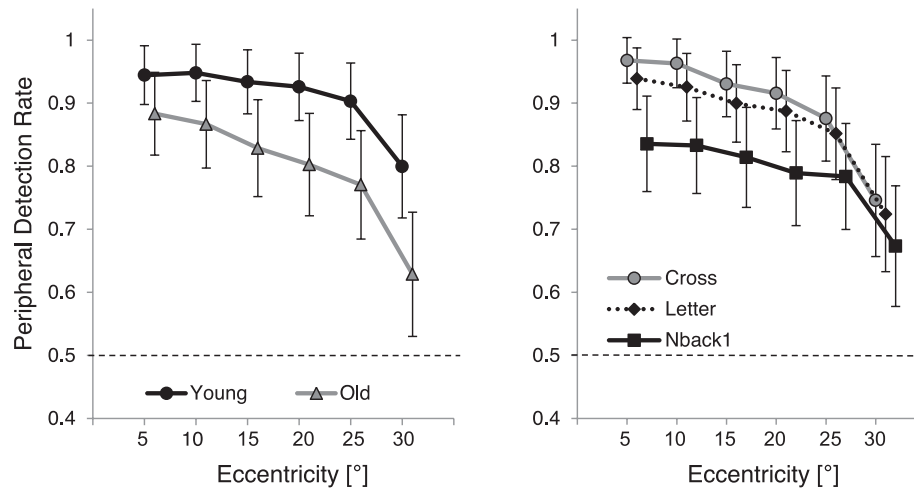


Figure 3. Mean peripheral-detection rates at each target eccentricity, split by age (left) and cognitive-task type (right). Horizontal dashed lines represent chance level (50% correct). Error bars represent the standard error of the mean. Lines connecting data points have been added to assist with visualizing the patterns in the data.

eccentricity increases, indicating a tunnel effect but no general interference effect of age.

For the letter task, we found a significant main effect of age on peripheral-detection rates, $\beta = -0.51$, $SE = 0.21$, $z = -2.45$, $p = 0.014$, suggesting a general interference effect (Figure 4, middle panel). The age \times eccentricity interaction approached but failed to reach significance, $\chi^2(1, 16) = 3.36$, $p = 0.067$; however, the trend in the data was for the effect of age to become greater with increasing peripheral target eccentricity, suggestive of a tunnel effect.

Finally, for the n -back-1 task (Figure 4, right), there was a clear main effect of age in that older participants performed consistently worse than younger participants at all eccentricities, $\beta = -0.49$, $SE = 0.18$, $z = -2.62$, $p = 0.009$. However, we did not find a significant age \times eccentricity interaction, $\chi^2(1, 16) = 0.23$, $p = 0.63$. Thus in the condition of highest cognitive load, there was only a general interference effect of age on

peripheral-detection rates. To determine whether floor effects were affecting our analyses of the age \times eccentricity interaction, we compared peripheral-detection rates at 30° eccentricity to chance performance (0.5, or 50% correct) using one-sample t tests.

Detection rates of both older, $t(23) = 3.68$, $p = 0.001$, and younger participants, $t(23) = 17.53$, $p < 0.001$, were significantly different from chance, indicating that floor effects were not affecting our analyses.

Age \times task type interaction

In order to determine whether the level of cognitive-task load had a different effect on the overall detection rates of older and younger participants, we collapsed the data over all eccentricities and constructed a 3 (task type: cross, letter, n -back-1) \times 2 (age group: young, old) GLMM. Specifically, we were interested in determining

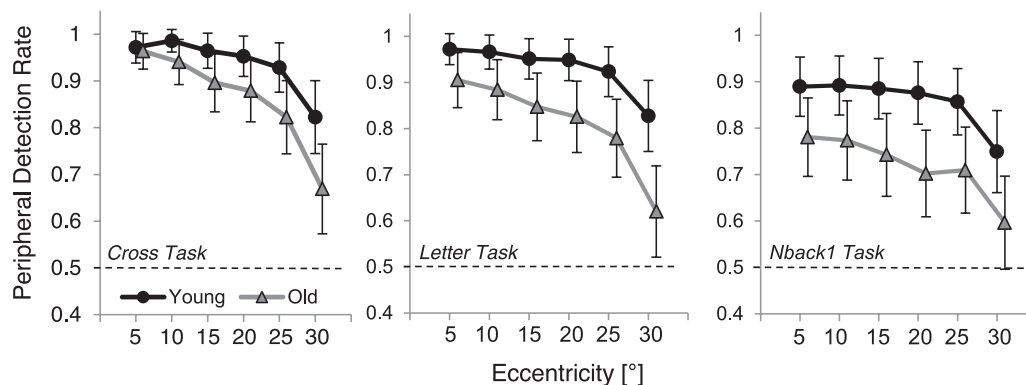


Figure 4. Mean peripheral-detection rates for each cognitive-task type (left: cross; middle: letter; right: n -back-1), with separate lines for older and younger participants. The dashed horizontal line indicates level of chance (50% correct). Error bars represent the standard error of the mean. Lines connecting data points have been added to assist with visualizing the patterns in the data.

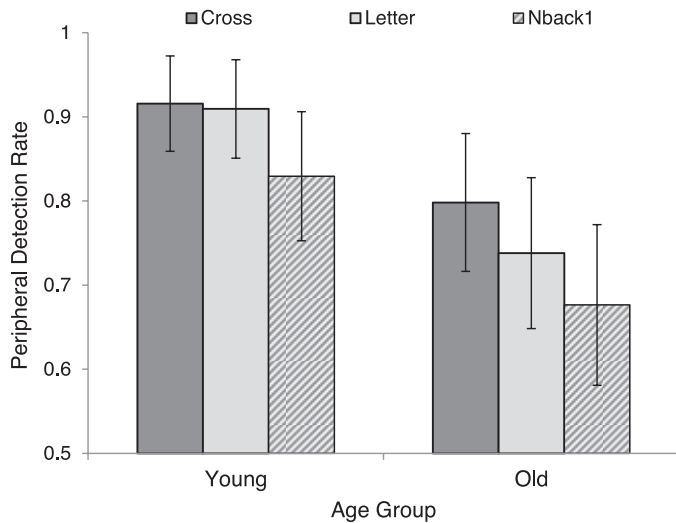


Figure 5. Mean peripheral-detection rates, collapsed across all eccentricities for each cognitive-task type, separately for younger and older subjects. Error bars represent the standard error of the mean.

whether we would see an age \times task type interaction. Results indicated a significant age \times task type interaction, $\chi^2(2, 8) = 6.87, p = 0.032$ (Figure 5). In order to determine the source of this interaction we split the data by age and ran two GLMMs with overall peripheral-detection rates as the outcome variable and cognitive-task type as the fixed factor. As compared to the cross task, older participants' peripheral-detection rates were worse in the letter task, $\beta = -0.49, SE = 0.08, z = -6.19, p < 0.001$, and the *n*-back-1 task, $\beta = -1.33, SE = 0.07, z = -17.7, p < 0.001$. For younger participants, however, simultaneously performing the letter task did not affect peripheral-detection rates, $\beta = -0.13, SE = 0.11, z = -1.76, p = 0.24$, but performing

the *n*-back-1 task did significantly decrease peripheral-detection rates, $\beta = -1.18, SE = 0.09, z = -11.82, p < 0.001$.

Task type \times eccentricity interaction

In order to assess whether cognitive load had a general interference effect, a tunnel effect, or a combination of the two (see Figure 1) on peripheral-detection rates of older and younger participants, we constructed two 2 (task type: cross, *n*-back-1) \times 6 (eccentricity) GLMMs. Given that younger participants did not show a significant difference in detection rates between the cross and letter tasks, whereas older participants did, the letter task was excluded from the analysis. This enabled us to better understand the effects and interactions of high cognitive load and eccentricity as compared to the no-cognitive-load condition (cross task).

For young participants we found a significant main effect of task type, indicating that they had lower detection rates when also performing the *n*-back-1 as compared to the cross task, $\beta = -2.27, SE = 0.22, z = -10.27, p < 0.001$. We also found a significant task type \times eccentricity interaction, $\chi^2(1, 5) = 20.92, p < 0.001$ (Figure 6, left panel). Similarly, for older participants we found a significant main effect of task on peripheral-detection rates, $\beta = -2.53, SE = 0.21, z = -12.03, p < 0.001$, as well as a significant task type \times eccentricity interaction, $\chi^2(1, 5) = 44.46, p < 0.001$ (Figure 6, right panel). Taken together, these results indicate a combination of both a general interference effect and a task type (cognitive load) \times eccentricity interaction for younger and older participants. As can be seen in Figure 6, the difference in peripheral-detection rates between the cross and *n*-back-1 tasks actually became

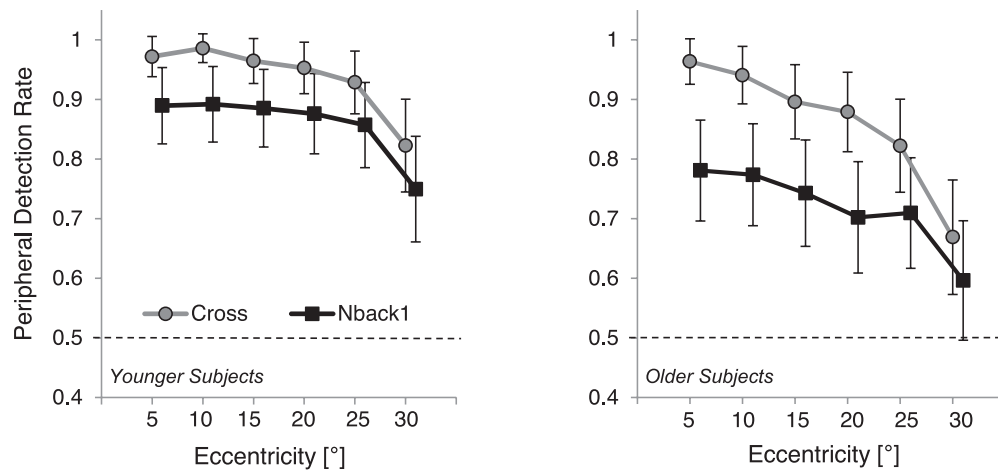


Figure 6. Mean peripheral-detection rates for younger (left) and older (right) participants, with separate lines for each concurrent cognitive-load task. The dashed horizontal line represents chance level (50% correct). Error bars represent the standard error of the mean. Lines connecting data points have been added to assist with visualizing the patterns in the data.

smaller with increasing target eccentricity for both older and younger participants, which is the opposite of a true tunnel effect (Figure 1, left panel). We refer to this interaction as an attenuation effect rather than a tunnel effect.

Discussion

The current study was aimed at assessing the effects of age and cognitive load on peripheral-detection rates while keeping the foveal visual complexity of the cognitive task constant. We were particularly interested in determining whether age and cognitive load resulted in a tunnel effect, general interference, or a combination of both effects.

Overall main effects

As expected, peripheral-detection rates were lower in older participants, decreased with increasing eccentricity of the target, and were lower when cognitive load was high. Overall these results are consistent with the previous literature (Ball et al., 1988; Chan & Courtney, 1998; Ringer et al., 2016; A. Sekuler et al., 2000). We found evidence indicating that even small increases in cognitive load had a significant detrimental effect on older, but not younger participants', detection performance. This was indexed by a significant decrease in older participants' peripheral-detection rates when simultaneously performing the letter task as compared to the cross task. The fact that older participants showed this performance decrement in the letter task but younger participants did not is most likely due to older participants having a reduced cognitive resource pool (Mathias & Lucas, 2009) to allocate between the cognitive and peripheral-detection tasks.

Age \times eccentricity interaction

To better understand the effects of age on peripheral-detection rates under different cognitive-load conditions, we split the data by each level of cognitive load. We were especially interested in determining whether age had a significant main effect on peripheral-detection rates and whether age and eccentricity interacted significantly. We found that as the demands of the cognitive central task increased, the pattern of age effects on peripheral-detection rates changed.

In the no-cognitive-load condition, when participants simply fixated upon a centrally located fixation cross (cross task), we found that age did not have a significant effect on peripheral-detection rates. How-

ever, we did find a significant age \times eccentricity interaction. As can be seen in the left panel of Figure 4, the effect of age on peripheral-detection rates became greater as target eccentricity increased. This pattern of results is consistent with tunneling accounts of the effects of age on peripheral detection (Ball et al., 1988; Chan & Courtney, 1993; Ikeda & Takeuchi, 1975; L. J. Williams, 1988).

In the low-cognitive-load condition, when participants simultaneously performed the letter task, we found that age had a significant main effect on peripheral-detection rates but the age \times eccentricity interaction only approached significance. This pattern of results suggests that age had a general interference effect with the addition of a trend toward a tunnel effect superimposed on the general interference. This finding is of particular interest, as it demonstrates that even small increases in cognitive load (i.e., the difference between looking at a cross and simply calling out a letter presented at a central fixation location) changed the pattern of the effects of age on peripheral-detection rates.

In the high-cognitive-load condition, when participants simultaneously performed the cognitively demanding *n*-back-1 task, we found a significant main effect of age but no significant age \times eccentricity interaction. As can be seen in Figure 4 (right panel), the effect of age on peripheral-detection rates remains roughly constant as the eccentricity of the target increases. This particular pattern of results suggests that when cognitive load was high, age produced a general interference effect on peripheral-detection rates.

Task type \times eccentricity interaction

After splitting the data by age group, we found significant main effects of cognitive load for both older and younger participants, suggesting a general interference effect. These findings are consistent with general interference effects reported in recent studies where cognitive load was manipulated by means of an auditory *n*-back task with both younger (Ringer et al., 2016) and older observers (Ward et al., 2018). As expected, we found that the general interference effect was greater for older than younger participants, with a difference in peripheral-detection rates between high and no cognitive load of about 17% compared to 7%, respectively, over the 5°–20° eccentricity range. More interesting, however, is that we also found a significant interaction between cognitive load and target eccentricity and that the direction of this interaction was opposite to our expectations. The effect of the high-cognitive-load task became smaller rather than larger with increasing target eccentricity in both age groups,

suggesting an attenuation effect rather than a tunnel effect (Figure 6).

The detection of peripherally presented targets does not occur automatically but requires cognitive resources. The greater the target's retinal eccentricity, the harder (i.e., requiring more cognitive resources) the target is to localize. As cognitive resources are finite, at some point participants likely arrived at a level where the demands of both the cognitive and peripheral-detection tasks were too much to compute simultaneously. It seems that once the peripheral-detection task becomes so difficult that it occupies the majority of participants' cognitive resources, the cognitive task will not lead to a further reduction in peripheral-detection rates, resulting in an attenuation effect at larger eccentricities.

Our finding of an attenuation effect of cognitive load may appear inconsistent with the results of some earlier studies (Chan & Courtney, 1993; L. J. Williams, 1985) that reported a tunnel effect of cognitive load in experimental paradigms which also increased load without changing the visual complexity of the foveal stimulus. However, it is worth noting that those early studies were unlikely to find an attenuation effect because the maximum eccentricity tested (9° by Williams, 12° by Chan & Courtney) was much lower than the eccentricity range (20° – 30°) at which we started to find an attenuation effect.

Implications for driving in the real world

The motivation for the current study was to further our understanding of how increasing age and cognitive load (distraction) might interact to affect peripheral detection, given that older drivers are overrepresented in collisions at intersections. A key finding was that increasing cognitive load resulted in a general interference effect with decreases in peripheral-detection rates for older participants even for motorcycles at relatively small eccentricities (5° from fixation). In the real world, if a driver fails to notice a motorcycle at this eccentricity, it is likely they would pull out into the intersection and collide with it. Our results suggest that older individuals are more likely to be affected by small changes in cognitive load than younger individuals, which is an important consideration, given the ever-increasing number of distractions from in-vehicle information systems and smartphones (e.g., Edwards, 2001). The fact that a very low level of cognitive load (simply calling out a letter which was presented at a central fixation location) decreased peripheral-detection rates in older adults suggests that even minor cognitive distractions might be contributing to older drivers' failures to detect hazards in their periphery when approaching an intersection.

Older and younger drivers may use different strategies for coping with distractions when driving. For example, younger drivers may be more prone to engaging with their smartphones or in-vehicle information systems, whereas older drivers may simply ignore such distractions. However, during driving in the real world, small changes in cognitive load could be caused by listening to and remembering instructions from a navigation system, which are not easily ignored. Therefore, to simulate the situation where resources had to be allocated to both a distracting task and a driving task, we instructed participants to allocate equal priority to both the cognitive and peripheral-detection tasks. Analyses confirmed that there was no trade-off between the two tasks (Appendix 3), thus a consistent level of cognitive load was maintained on average across all trials. Interestingly, L. J. Williams (1988) also reported that when cognitive load was high (manipulated without changing the visual complexity of the foveal stimulus), instructions to give central and peripheral tasks equal priority resulted in a general interference effect on reaction times to peripheral targets (as found for peripheral-detection rates in this study), but instructions to prioritize a task at the fixation location resulted in a tunnel effect.

Previous work by Pollatsek, Romoser, and Fisher (2012) suggests that older drivers scan less frequently into regions of intersections from which hazards may emerge (see also Bao & Boyle, 2009), which could be one reason why older subjects are overinvolved in right-of-way crashes at intersections (Clarke et al., 2010). Peripheral vision is thought to act as an early-warning system, which can help guide our overt visual attention to salient objects in the environment (Yamamoto & Philbeck, 2013). Therefore, drivers with good peripheral vision are likely to be more efficient in detecting hazards in their periphery and directing their overt visual attention (head and eye movements) toward such potential hazards. Conversely, drivers with reduced or inefficient peripheral visual-processing capacities may only become aware of an approaching hazard much later, at which point an evasive maneuver would no longer be possible. We have demonstrated that simultaneously performing an *n*-back-1 task resulted in a general interference effect for older participants. The difference in peripheral-detection rates between the no- and high-load conditions was on average 17% (over 5° – 20°), which is a substantial reduction given that the measurement range was from only 50% to 100%. Therefore, it seems that older drivers, who have a reduced cognitive resource pool, are at risk of being impaired by relatively small changes in cognitive load. Peripheral stimuli might thus not be processed as efficiently as compared to younger drivers, who have a greater pool of resources. Given that peripheral processing is negatively affected by increases

in cognitive load, older drivers have a reduced pool of cognitive resources, and peripheral vision is vital in guiding overt visual attention, our results suggest that older drivers may be overrepresented in collisions at intersections because their peripheral vision does not alert them soon enough to hazards approaching from the left and right. Therefore, older subjects may make fewer glances into the direction of approaching hazards. This in turn results in fewer detections and therefore an increase in crash risk.

Limitations of the current study

Our goal in the current study was to use a peripheral-detection paradigm relevant to driving. However, while the peripheral-detection task and stimuli were modeled on intersection scenarios, caution needs to be exercised in generalizing the results to real-world driving. In particular, our stimuli lacked motion information, which is a salient cue in peripheral vision. Furthermore, participants were not permitted to use natural eye movements to scan the scenes and did not perform any other concurrent driving tasks, such as controlling vehicle speed or steering. In the real world, top-down factors might influence the likelihood of detecting motorcycles, including individual differences in driving strategies, prior motorcycle experience (Crundall, Crundall, Clarke, & Shahar, 2012), and hazard threat value (Pammer, Sabadas, & Lentern, 2018). In our paradigm we suggest that it is unlikely that such top-down factors played a role, because each scene was presented only briefly, the peripheral-detection task was very specific (participants only had to indicate whether the motorcycle target was on the left or right), and participants were not required to make any driving decisions (such as whether it was safe to make a left turn).

Thus, we acknowledge that the results of the current experiment do not necessarily reflect driving in the real world. In laboratory-based paradigms there is always a trade-off between ecological validity and strict control of the experimental manipulation. When designing such experiments, researchers are forced to make decisions about their experimental paradigms and stimuli (in our case, static images with static motorcycle targets of one fixed size presented for 250 ms) that might not be fully representative of real-world driving. Although the results from the current study may not transfer directly to the real world, we argue that understanding the core components underlying complex behavior is a vital first step in understanding behavior in the real world. The next stage in bridging the gap between lab-based studies using abstract stimuli and real-world driving would be to implement a version of the current paradigm in a driving simulator with

moving motorcycle targets at intersections (Savage et al., 2017).

Conclusions

Findings from the current study have demonstrated that when the demands of the cognitive task were extremely low (looking at a fixation cross), the difference in peripheral-detection rates between older and younger participants was best described by tunneling accounts (Ikeda & Takeuchi, 1975; Webster & Haslerud, 1964). However, as soon as the cognitive demand of the central task was increased even slightly (calling out a letter at fixation), we found a general interference effect of age in older participants. Thus, our results suggest that tunnel and general interference effects are not mutually exclusive but can co-occur, and that the predominant effect depends on how much demand is placed on an individual's resources by both cognitive and peripheral-detection tasks.

When we analyzed the data separately for each age group, we found a general interference effect of high cognitive load for both older and younger participants, which attenuated at large eccentricities (i.e., the opposite of a tunnel effect). By comparison, low cognitive load had a general interference effect only in the older group, reducing detection rates at all target eccentricities, both close to and farther away from fixation. Thus, our findings suggest that even low levels of cognitive distraction may impair the ability of older drivers to detect imminent hazards in peripheral vision.

Keywords: peripheral vision, aging, cognitive load, dual task, general interference, tunnel effect, visual attention

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Appendix 1: Pilot work to determine an appropriate target size

The aim of the pilot study was to find a motorcycle target size which would produce a measurable range of peripheral-detection rates for both older and younger participants without running into either floor or ceiling effects.

Methods

Participants

We recruited 24 participants (eight women, 16 men) in two groups—12 younger (20–40 years; mean = 29.2) and 12 older (60+ years; mean = 69.7)—from a database of individuals who had participated in prior studies at Schepens Eye Research Institute. Inclusion criteria were the same as for the main study. Median visual acuity was 20/15 (range = 20/15 to 20/20) in the younger group and 20/20 (range = 20/15 to 20/40) in the older group.

All participants provided informed consent in accordance with institutional review board approval at

Vertical subtense of motorcycle (°)	Eccentricities at which motorcycle was presented (°)
1.3	5, 10, 15, 20, 25, 30
2.1	5, 10, 15, 20, 25, 30
3.4	10, 20, 30

Table A1.1. Eccentricities at which each motorcycle size was presented.

Schepens Eye Research Institute. The study was conducted in accordance with the tenets of the Declaration of Helsinki.

Materials

Only one intersection was used as the basis for the stimuli in the pilot study (Suburban 2: Figure 1, middle panel). In each image, the motorcycle could subtend one of three different sizes depending on the distance of the driver’s viewpoint from the intersection. The small and medium motorcycle targets (subtending 1.3° and 2.1°, respectively) were presented at six eccentricities (5°, 10°, 15°, 20°, 25°, and 30°), while the large motorcycle target (subtending 3.4°) was presented at only three eccentricities (10°, 20°, and 30°; Table A1.1). Only one of the three central tasks, the low-load letter task (as described for the main study), was used.

We created 36 images for the largest target size (3 eccentricities × 3 traffic densities × 2 sides of the road × 2 versions of each image) and 72 images each for the medium and small targets (6 eccentricities × 3 traffic densities × 2 sides of the road × 2 versions of each image), for a total of 180 images.

Procedure

The procedures for the peripheral-detection test were the same as for our main experiment, with the exception that we made use of only one central task

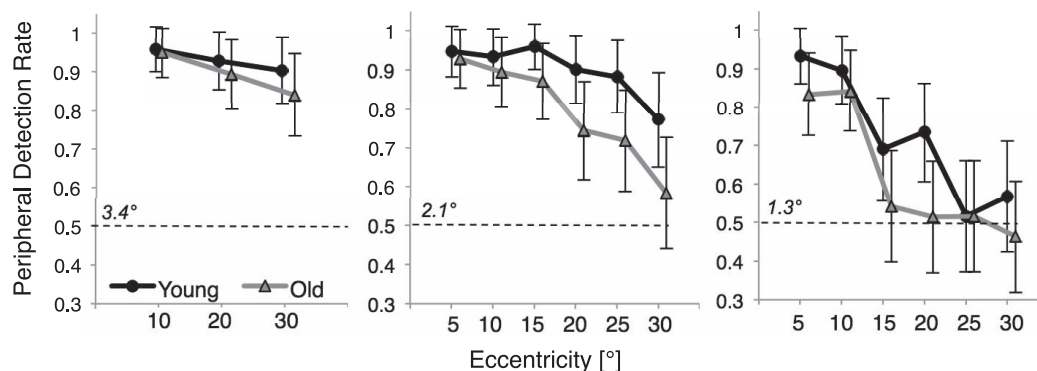


Figure A1.1. Mean peripheral-detection rates at each level of eccentricity for younger and older participants for the 3.4° target (left panel), the 2.1° target (middle panel), and the 1.3° target (right panel). The dashed gray line represents chance performance. Error bars represent the standard error of the mean.

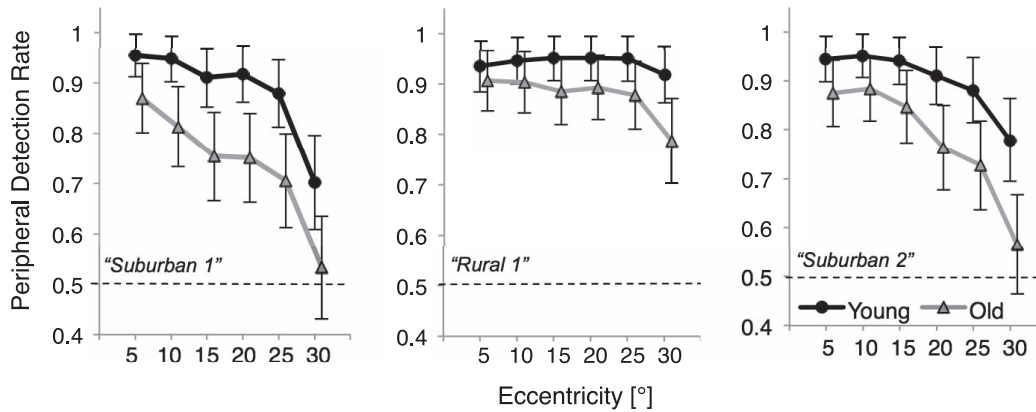


Figure A2.1. Mean peripheral-detection rates for each intersection—left: Suburban 1 (Figure 2, top); middle: Rural 1 (Figure 2, middle); right: Suburban 2 (Figure 2, bottom). The horizontal dashed line represents chance level (50% correct). Error bars represent the standard error of the mean.

(letter task). Before the start of the experimental trials, all participants completed at least 50 practice trials to become familiar with the central and peripheral tasks. The experiment comprised a total of 540 trials divided into three blocks. Each block contained 180 unique images (as described in Materials) in a random order. Thus, each unique image was presented three times, once in each block. A short break was allowed halfway through each block and at the end of each block to help prevent fatigue. Participants were instructed to complete both the peripheral-detection task and the central task as quickly and accurately as possible.

Statistical analyses

The data were analyzed in the same manner as in our main experimental analyses. The primary factors of interest were age (young or old) and target eccentricity.

Results

At the largest target size (3.4°), there were only small decreases in peripheral-detection rates with increasing eccentricity (Figure A1.1, left panel), and there was no significant effect of age, $\beta = -0.48$, $SE = 0.77$, $z = -0.62$, $p = 0.52$. For the 2.1° target size, peripheral-detection rates declined more rapidly with increasing eccentricity (Figure A1.1, middle panel), and older participants had lower detection rates than younger participants, $\beta = -1.32$, $SE = 0.38$, $z = -3.41$, $p < 0.001$. For the smallest target (1.3°), peripheral-detection rates decreased very rapidly with increasing target eccentricity in both age groups (Figure A1.1, right panel), and older participants performed significantly worse than younger ones, $\beta = -0.61$, $SE = 0.13$, $z = -4.56$, $p < 0.001$.

As can be seen in Figure A1.1, both older and younger participants performed at or close to ceiling

level across all eccentricities when presented with the 3.4° target, while for the 1.3° target older participants were performing at chance level (floor level) by 15° target eccentricity and younger participants reached chance level at 25° target eccentricity. It was only the 2.1° target that yielded a measurable range of peripheral-detection rates for both older and younger participants across all six levels of target eccentricity. To confirm that participants' detection rates were, on average, above chance at 30° eccentricity for the 2.1° target, we compared their detection rates to 0.5 (chance level, or 50% correct) with one-sample t tests. Both older participants, $t(11) = 2.36$, $p = 0.037$, and younger ones, $t(11) = 5.52$, $p < 0.001$, performed significantly better than chance, indicating that for the 2.1° target we were able to obtain a measurable range of peripheral-detection performance which was not affected by floor effects at the largest eccentricity. Therefore, the 2.1° target was used in our main experiment.

Appendix 2: Analyses of detection rates at 30° eccentricity for each intersection (main study)

In order to test whether performance at 30° eccentricity in the high-cognitive-load (n -back-1 task) condition was significantly different from chance, we compared older and younger participants' peripheral-detection rates at 30° to 0.5 (chance level, or 50% correct) for each intersection separately by means of a one-sample t test. For older participants, peripheral-detection rates at 30° were significantly different from chance for both Rural 1, $t(23) = 9.39$, $p < 0.001$, and Suburban 2, $t(23) = 2.1$, $p = 0.043$, intersections (Figure A2.1, middle and right panels, respectively). However,

we found that older participants' peripheral-detection rates were not significantly different from chance level for Suburban 1, $t(23) = 1.46$, $p = 0.16$ (Figure A2.1, left panel). For younger participants, we found that peripheral-detection rates at 30° were significantly different from chance at all intersections—Rural 1: $t(23) = 27.06$, $p < 0.001$; Suburban 2: $t(23) = 10.04$, $p < 0.001$; and Suburban 1: $t(23) = 6.15$, $p < 0.001$. As older participants were running into floor effects at 30° and their performance was not significantly different from chance for Suburban 1, this intersection was subsequently removed from our main analyses.

Appendix 3: Relationship between peripheral-detection and cognitive-task performances

Correct response rates in the low-load condition (letter task) were high (overall, 98% for younger and 90% for older) and did not vary as a function of the eccentricity of the peripheral-detection target.

To examine whether there was a trade-off between performance on the peripheral-detection task and the n -back-1 task, three models were constructed. The first model was aimed at determining whether n -back-1 performance decreased as the eccentricity of the target increased. The second model was constructed to test whether n -back-1 task performance was lower when peripheral-detection performance was correct. The third and final model was constructed to determine whether performance on the n -back-1 task was predictive of performance on the peripheral-detection task.

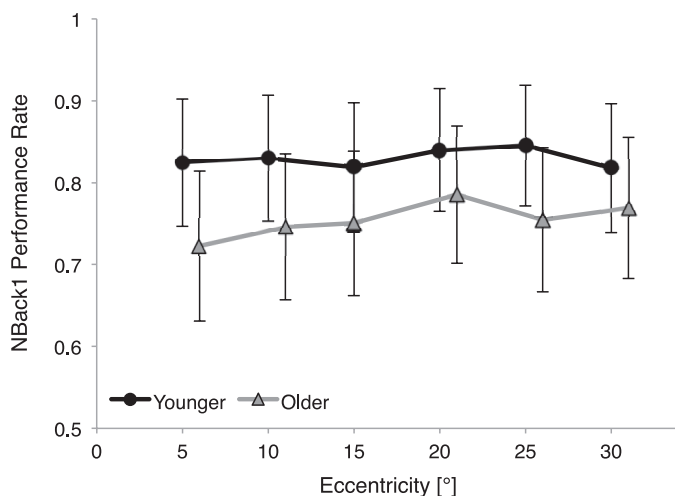


Figure A3.1. High-load (n -back-1) task performance at each level of eccentricity for younger and older participants. Error bars represent the standard error of the mean.

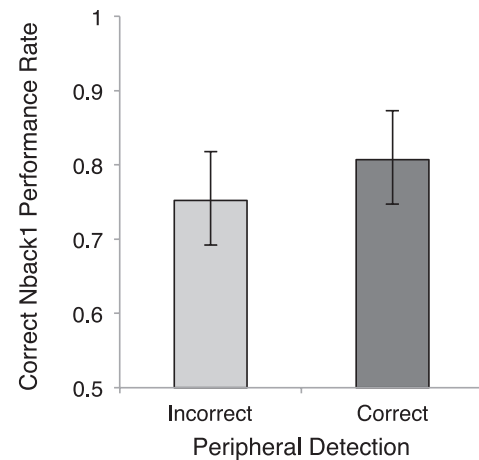


Figure A3.2. High-load (n -back-1) task performance for correct and incorrect peripheral-detection trials. Error bars represent the standard error of the mean.

In constructing the first two models, n -back-1 task performance was entered as the outcome variable, with eccentricity and age group as fixed factors. We also included block number as a fixed factor to account for any presentation-order effects. Finally, we included a random factor for participants to account for the variability contributed by individual differences, and a random factor for stimulus to account for the variability contributed by the individual items. In the third model, we entered peripheral-detection performance as the outcome variable and n -back-1 task performance, age group, and eccentricity as fixed factors. Again, we also included a fixed factor for block number and random-effect structures for participant and stimulus. These analyses were conducted on a subset of the data consisting only of high-load trials.

As expected, in the high-load condition, older participants performed worse than younger partici-

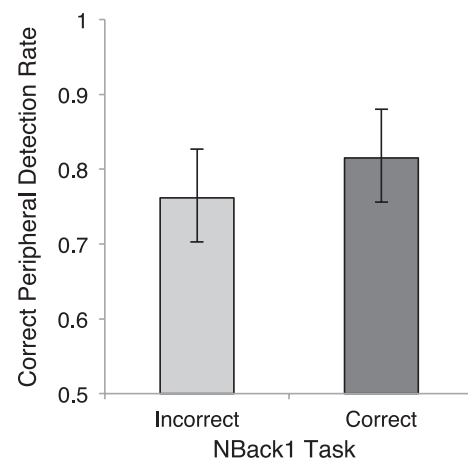


Figure A3.3. Peripheral-detection rates for correct and incorrect n -back-1 trials. Error bars represent the standard error of the mean.

pants (overall, 76% vs. 83%, respectively), $\beta = -0.53$, $SE = 0.22$, $z = -2.45$, $p = 0.015$ (Figure A3.1). However, we found no evidence of a trade-off between performance on the peripheral-detection and n -back-1 tasks, as would have been indicated by a steady decrease in n -back-1 task performance with increasing eccentricity. Compared to trials in which the target appeared at 5° , we found no difference in n -back-1 task performance on trials in which the target appeared at 10° , $\beta = 0.08$, $SE = 0.09$, $z = 0.87$, $p = 0.39$; at 15° , $\beta = 0.05$, $SE = 0.09$, $z = 0.58$, $p = 0.56$; at 25° , $\beta = 0.16$, $SE = 0.09$, $z = 1.8$, $p = 0.07$; and at 30° , $\beta = 0.11$, $SE = 0.09$, $z = 1.19$, $p = 0.23$. However, n -back-1 task performance was slightly higher at 20° as compared to 5° , $\beta = 0.24$, $SE = 0.09$, $z = 2.57$, $p = 0.01$.

In the second model, with peripheral-detection performance (correct or incorrect) as a fixed factor, we

found evidence of n -back-1 task performance being slightly better when participants responded correctly on the detection task, $\beta = 0.16$, $SE = 0.07$, $z = 2.18$, $p = 0.03$ (Figure A3.2). This is the opposite of what we would have expected if there was a trade-off between peripheral and n -back-1 task performance.

Finally, in the third model, with peripheral-detection rate as the outcome variable and n -back-1 task performance as a predictor variable, there was a trend for peripheral-detection performance to be better when participants responded correctly on the n -back-1 task, $\beta = 0.14$, $SE = 0.07$, $z = 1.93$, $p = 0.053$. However, this effect did not reach significance and was, again, in the opposite direction of what we expected from a classic trade-off between peripheral and n -back-1 task performance (Figure A3.3).