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Nonuniform changes in the distribution of visual attention from visual complexity and action: A driving simulation study

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Abstract. Researchers acknowledge the interplay between action and attention, but typically consider action as a response to successful attentional selection or the correlation of performance on separate action and attention tasks. We investigated how concurrent action with spatial monitoring affects the distribution of attention across the visual field. We embedded a functional field of view (FFOV) paradigm with concurrent central object recognition and peripheral target localization tasks in a simulated driving environment. Peripheral targets varied across 20–60 deg eccentricity at 11 radial spokes. Three conditions assessed the effects of visual complexity and concurrent action on the size and shape of the FFOV: (1) with no background, (2) with driving background, and (3) with driving background and vehicle steering. The addition of visual complexity slowed task performance and reduced the FFOV size but did not change the baseline shape. In contrast, the addition of steering produced not only shrinkage of the FFOV, but also changes in the FFOV shape. Nonuniform performance decrements occurred in proximal regions used for the central task and for steering, independent of interference from context elements. Multifocal attention models should consider the role of action and account for nonhomogeneities in the distribution of attention.

Keywords: visual attention, peripheral vision, attentional narrowing, driver steering, driving simulation, multifocal attention, action

1 Introduction

Attention helps us to keep track of information in a dynamic visual environment (Alvarez, 2014). However, in our everyday lives we have to effectively process visual information while we perform concurrent actions to meet our goals. For example, we walk through our neighborhoods while using our smart phones, and we drive and keep the car on the road while avoiding pedestrians and dogs. There is a constant interaction between visuospatial attention and action in which we control the course and direction of our movements while monitoring for events occurring in the visual field.

To allocate attention across the visual environment, our visual systems tune our attention toward salient and task-relevant information in the visual field. These mechanisms of attentional control are typically divided into stimulus-driven and goal-driven mechanisms (Yantis, 1998). Stimulus-driven attentional shifts occur with abrupt changes in the environment (eg the appearance of a new object, Yantis & Jonides, 1990) or the onset of an event in the environment (Franconeri, Hollingworth, & Simons, 2005). Our attention is also guided toward salient portions of the visual field, such as a location that differs from its surroundings in terms of color or other features (Fecteau & Munoz, 2006; Itti & Koch, 2001). Goal-driven mechanisms enable us to choose which visual information to select so we can control the allocation of attention and direct it towards the most relevant region of the visual field. If the purpose of attention is to facilitate action, visual attention should select the most relevant visual information for action and suppress irrelevant visual information (Allport & Meyer, 1993; Land & Hayhoe, 2001; Neumann, 1990).

Despite widespread acknowledgment about the importance of action, most recent advances in the allocation and distribution of visuospatial attention have been made in studies examining multifocal visual attention where action is considered as a response indicating the detection of an item in the visual field rather than an integral part of the process (Alvarez & Cavanagh, 2005; Pylyshyn & Storm, 1988). Less research has investigated how attention and action interact (eg video gaming; Green & Bavelier, 2006). In this study we investigate how the distribution of attention across a wide visual field is affected by the interaction of action. Specifically, we examine whether the size and shape of the attentional visual field may be affected differentially by visual complexity and acting in the visual field during simulated driving.

While driving, an observer cannot pay attention to everything in the visual field simultaneously, and this becomes more difficult when attention has to be spread and maintained across a large field of view (Pashler, 1998). As a result, the observer has to tune attention to select a subset of the incoming visual information and potential responses depending on the observer's goal. Spot-light (Posner, 1980), zoom-lens (Eriksen & St James, 1986; Eriksen & Yeh, 1985), and gradient theories (LaBerge, 1983; LaBerge & Brown, 1989) of spatial attention describe a capacity limited system in which one or more locations are selected for greater processing, and regions of the visual field further away from these locations receive fewer processing resources. Processing limitations affect the spatial extent of a selected region (Engel, 1971; Eriksen & St James, 1986; Intriligator & Cavanagh, 2001), the two-dimensional and three-dimensional shapes of the selected regions (Downing & Pinker, 1985; LaBerge, 1983; LaBerge & Brown, 1989), how attention can be shifted from one location to another (Remington & Pierce, 1984), whether attention can be split (Awh & Pashler, 2000; McMains & Somers, 2004), and the number of locations that can be selected at once (Franconeri, Alvarez, & Enns, 2007).

Our limited ability to attend to multiple objects or locations simultaneously has been explored using a multiple-object tracking task (Alvarez & Cavanagh, 2005). For example, observers view a set of identical moving objects and are instructed to track a subset that are first highlighted and then changed to be identical with the other moving objects. Because the subset of items cannot be distinguished from the others, observers must continuously attend to the objects in order to track them. Observers can track up to eight objects concurrently, depending on the speed and spacing between the items (Alvarez & Franconeri, 2007). The selection process appears to be multifocal, selecting targets, rather than the space between targets, and does not require target fixation (Intriligator & Cavanagh, 2001; Pylyshyn & Storm, 1988).

Further, limits on one's ability to pay attention to complex visual stimuli with concurrent action can be demonstrated in studies of inattentional blindness (Mack & Rock, 1998; Most, Scholl, Clifford, & Simons, 2005) and change blindness (Simons & Rensink, 2005). For example, when pilots practiced landing an airplane in a flight simulator with a heads-up display that superimposed the cockpit window in the visual field, they did not notice an unexpected vehicle on the runway (Heinze & LuckHaines, 1991). Other studies have cited traffic accident reports in which the drivers reported 'not seeing' obstacles in their visual field that should have been clearly visible (Herslund & Jørgensen, 2003). These types of occurrences are often interpreted as a limited ability to process information outside of a current focus of attention. However, these tasks required actions in an attended visual field, and it is possible that the ongoing action affected the distribution of spatial attention in specific regions, rather than overall reduction in processing resources.

2 Current study

To investigate how concurrent action with spatial monitoring affects the distribution of attention, we studied driving. To be a safe driver, one must be able to perform the central task of navigating the vehicle on the road while distributing visual attention to the surrounding environment. One must attend to objects in the visual periphery, be they potential hazards (eg pedestrians or other vehicles), traffic control devices (eg signs or lane markings), or displays within the vehicle (eg mirrors or dashboard alerts), and guide the vehicle.

In this study we assessed the functional field of view (FFOV) or the attentional visual field in a simulated driving environment. The FFOV is defined as the area from which one can extract visual information in a single, binocular glance without eye or head movements (Sanders, 1970). An index of the total visual field, the FFOV is generally smaller than the total visual field as measured by standard perimetry (Rantanen & Goldberg, 1999; Rogé, Kielbasa, & Muzet, 2002). The size and shape of an individual's FFOV is typically measured using a dual-task paradigm: a central visual task presented concurrently with a single, peripheral target detection task. By presenting a central task that requires focused or foveal attention, overt visual scanning behaviors are reduced during the presentation of the secondary peripheral task. Performance on the peripheral task is then used as an indicator of the extent of an individual's FFOV and the pattern of performance permits an inference about the outer shape of the FFOV. Variations of FFOV tests, such as the well-known useful field of view (UFOV) test developed by Ball and Owsley (1993), have observed correlations between poorer FFOV performance and poorer driving performance (Bolstad, 2001; Wood, 2002) and hazard perception for older drivers (Horswill et al., 2008).

By embedding a dual-task FFOV paradigm into a driving simulation environment with demanding central task and steering requirements and a visual field with 60 deg of visual angle, we can provide insight into whether concurrent action within a wide visual field has different effects on the size and shape of the FFOV than added visual complexity. To do so, we compared the size and shape of the FFOV in three different conditions: (1) the basic FFOV task with no background; (2) the FFOV task with a moving, driving background context; and (3) the FFOV task with the same driving background but with the additional action requirement of steering to keep the car on the road.

Our baseline condition was the basic FFOV task. Typically, FFOV tests are conducted using a uniform, blank background that is absent of context, let alone steering. The peripheral target detection task by itself produces high localization accuracy for targets at relatively high eccentricities and short display durations. When a concurrent central task is added, localization accuracy decreases for peripheral targets positioned farther away from the central task (Ball, Beard, Roenker, Miller, & Griggs, 1988; Scalf et al., 2007). As more attention resources are required for the central task with increasing central task prioritization, increasing central task complexity, and decreasing visual salience of the peripheral targets, secondary peripheral target detection performance tends to deteriorate at the most eccentric peripheral target locations—that is, the FFOV shrinks (Rogé et al., 2002). This shrinking FFOV is also known as tunnel vision, cognitive tunneling, or attentional narrowing. It is consistent with spotlight or zoom-lens limited resource models (Eriksen & St James, 1986; Posner, 1980) in which the focus of attention receives the greatest proportion of processing resources that decrease systematically for positions further away from the focus. Compared with the other conditions, the basic no-background FFOV task should produce the broadest FFOV and best peripheral performance.

Our second condition adds a background driving context and a moving road (no steering) to the basic FFOV task to assess the influence of additional visual complexity on the FFOV. If the context acts as a visual distractor or creates additional regions of visual salience that interfere with the processing of nearby visual targets, then additional errors may be found for peripheral targets that appear near visual context elements (Alvarez & Cavanagh, 2005; Carlson, Alvarez, & Cavanagh, 2007). Distractors in the visual field may deform the FFOV in a nonuniform manner. In a study by Wood et al. (2006) participants made more peripheral target errors in the *lower* region of the assessed FFOV when visual distractors were provided alongside the peripheral targets. Thus, the specific context could affect the distribution of visual attention in that the distribution of peripheral target errors may be clustered in locations near driving context elements. Alternatively, the added context may act to generally increase the processing load. Compared with the no-context baseline condition, we would then expect additional symmetric shrinking of the FFOV size while maintaining the shape of the FFOV. This pattern of performance would be consistent with limited resource theories such as the zoom-lens model.

Our third condition adds the action of vehicle steering (ie lane position maintenance) to the driving context in the FFOV task. Steering requires directing peripheral visual attention to locations in the lower visual that are also relevant to the performance of the dual FFOV task. For most drivers, steering a vehicle on the road is a highly automaticized action developed through years of driving exposure (Trick & Enns, 2009). Despite a seemingly low attentional workload, a complex interplay of central and peripheral visual attention resources occurs during pursuit tracking tasks such as vehicle steering. If the addition of steering has an additive effect on overall visual attention resources, then we should observe an additional shrinkage of the FFOV across radial positions. However, the attentional sharing of common spatial locations for FFOV task and steering task performance may differentially affect the size and shape of the FFOV in a nonuniform manner.

Vehicle steering requires primarily peripheral vision resources directed toward the near road and its defined boundaries at the bottom of half of the screen. Steering requires a greater reliance on peripheral vision over central vision for adequate steering performance. The central vision of the 'far' road allows the driver to recognize, anticipate, and prepare for changes in the path ahead, while the peripheral vision of the 'near' road allows the driver to track and null instantaneous errors with the steering wheel in order to stabilize the vehicle's lane position (Schieber, Schlorholtz, & McCall, 2008). If a driver's FFOV is sensitive to this integration of attentional requirements, we would expect the FFOV to be differentially distributed (or impaired) in the lower visual fields as it competes with other tasks demanding peripheral attention resources. In other words, the ongoing processing of two regions of the visual field—the central portion for the central task and the portions of the visual field relevant for steering—may result in a specific collapsing of FFOV peripheral regions that require additional processing resources. This finding would require a revised model of visuospatial attention in which resources for peripheral attention are considered as well as those for focal attention.

3 Methods

3.1 *Participants*

Thirty healthy subjects (fifteen males, $M_{\text{age}} = 20.2$ years, age range = 18–25 years) from the Claremont McKenna subject pool participated for course credit in undergraduate psychology courses. Participants reported having at least corrected 20/20 vision. This experiment was carried out in accordance with the relevant institutional and national regulations and legislation and with the World Medical Association Helsinki Declaration as revised in October 2008 (http://www.wma.net/en/30publications/10policies/b3/index.html).

3.2 *Stimuli and apparatus*

All FFOV task stimuli and simulation graphics were processed using STISIM Drive (v2.08) on a PC desktop (2.0 GHz, 1 GB of RAM, 60 Hz frame rate) and displayed onto a white screen area of 170 × 109 cm (67 × 43 inch) using a single LCD projector (Infocus LP2590;

1024 × 768 resolution). The Microsoft Sidewinder Force Feedback Wheel was used for driver steering control. Brake and accelerator pedals were not used for this study. Steering wheel torque force was held at the factory default constant rate. Steering wheel buttons were programmed for the recording of button responses for the central object recognition task. Driver viewing distance to screen center was set at 70 cm (27.6 inch) using a chin-rest positioned above the steering wheel.

A grayscale, low-fidelity driving environment was designed to isolate the driving task and control peripheral target presentations (figure 1). A vehicle hood provided participant drivers a reference for vehicle lane position during steering conditions. Numbered labels were located around the periphery of the display monitor, similar to a clock face, to aid in the radial localization task of peripheral targets.

For conditions with a driving background, the roadway design had a total track length of 4.9 miles (7.9 km) at a set vehicle speed of 30 mph (44 ft s^{-1}, 13.4 m s^{-1}). Road width was set at 12 ft (3.7 m) using black-colored lane boundaries. A series of alternating left/right curves (28 total) was presented with curvature lengths varying from either 300 or 500 ft (91 or 152 m) with a constant curvature of 0.003 (1⁄radius of curvature). Entry and exit spiral lengths to the curve varied from 100 to 400 ft (30 to 122 m). A total drive time of approximately 10 min was required for each condition.

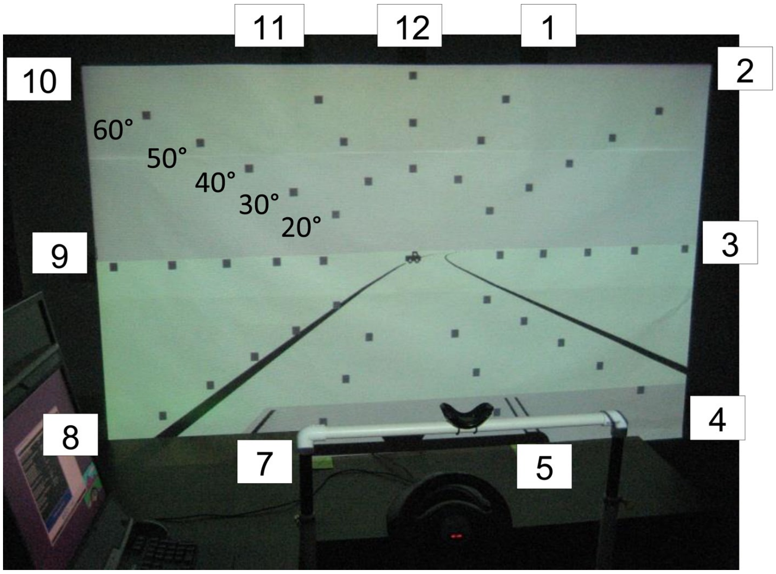

Figure 1. [In color online, see http://dx.doi.org/10.1068/p7737] Driving simulator configuration with projected roadway scene. An example functional field of view task is displayed with a truck symbol for the central task and all potential peripheral field target locations. Radial spoke numbers were labelled for participant reference. Targets could appear from 20 deg to 60 deg eccentricity; labels on the figure indicate visual angle and were not visible to participants. No targets were presented at radial spoke 6 because the participant's head cast a projector shadow at this point. Roadway lines moved depending on roadway curvature and driver steering ability; they typically did not overlap targets.

Modeled after the UFOV test (Ball & Owsley, 1993), the FFOV task was composed of a central, two-choice symbol recognition task requiring a steering wheel button response with a concurrent peripheral target detection task requiring a verbal indication of target location. In the central object recognition task a central fixation cross was replaced by a black car or truck symbol (~4 × 3 deg in size) for a display duration of 160 ms. A single, peripheral target (gray box, ~1 × 1 deg in size) was concurrently displayed in duration with the car/truck symbol.

Peripheral target position varied in eccentricity from the central task from 20, 30, 40, 50, and 60 deg in 11 radial spoke positions. Five radial spokes (labeled 1, 5, 7, 11, and 12) provided 20, 30, and 40 deg, and six radial spokes (labeled 2, 3, 4, 8, 9, and 10) provided additional 50 deg and 60 deg for a total of 45 different target positions to represent the measured visual field (figure 1). No targets were presented at radial spoke 6 so that the participant's head would not interfere with that part at the bottom of the projected display. Participants' head shadows covered only the very bottom of the screen.

Immediately following the presentation of central and peripheral task stimuli, a visual mask appeared for 250 ms. The mask consisted of a central black box and 45 black boxes located at all peripheral target locations. Interstimulus delay was randomized and ranged from 3 to 4 s. Each peripheral target position was randomly presented three times for a total 135 trials per condition. Figure 2 illustrates the sequence of events for a single FFOV task trial.

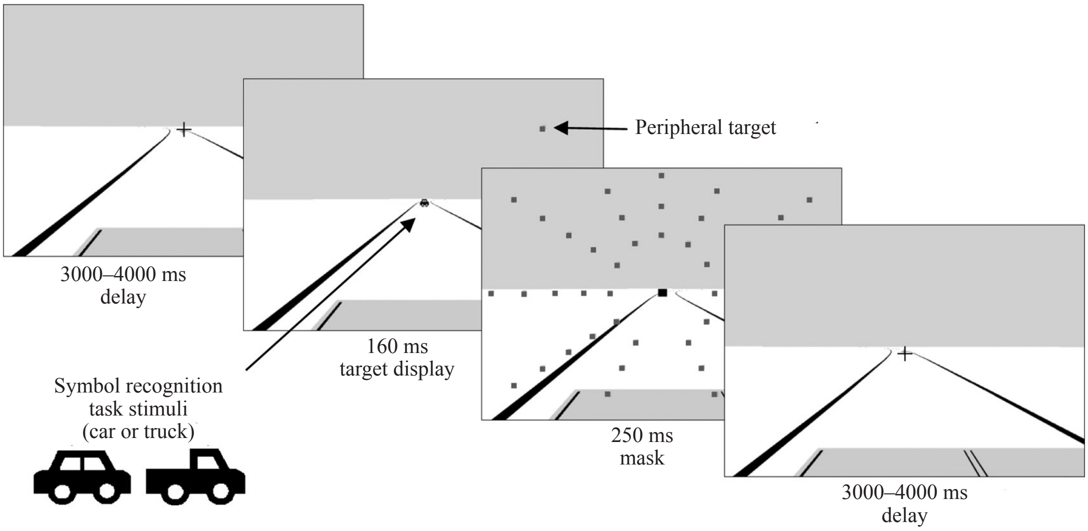

Figure 2. Sequence of events (start: top left) for a single trial in the functional field of view task in the DrB (driving background) and DrS (driving background + steering) conditions. For the NoB (no-background) condition, only the center fixation cross was presented with a white background.

3.3 *Procedure*

Participants were tested individually after providing informed consent. They viewed a slideshow presentation that introduced the tasks and then completed a 10 min practice session that included all test conditions.

To ensure that the peripheral targets fell in the visual periphery, participants were instructed to prioritize and respond first to the central symbol recognition task. When a car/truck symbol appeared, participants used one of their thumbs to respond as quickly and as accurately as possible with the appropriate steering wheel button (top-right button for car; top-left button for truck). For the central task, performance was measured in terms of reaction time (RT, in ms) and accuracy (% correct).

After responding to the central task, participants responded verbally to indicate where the peripheral target appeared on one of the 11 radial spokes using the numbered labels around the display screen as a guide. Participants were told to imagine the numbered positions similar to a clockface to minimize head movements and off-center glances. They were also instructed to guess if unsure of a target's position. Verbal responses for radial positions were manually recorded by the experimenter. Performance on the peripheral target was measured as radial spoke localization accuracy (% correct).

Participants performed all three conditions of the FFOV test: NoB (no background; baseline), DrB (driving background), and DrS (driving background + steering). In all conditions they were instructed to maintain hand position on the steering wheel, maintain fixation on the center cross, and always prioritize the central task over all other tasks. When steering in the DrS condition, the initial vehicle position was centered on the road at the start of a drive and participants' task was to maintain this position for the duration of the drive. Performance was measured as the standard deviation of lateral lane position (SDLP, in feet).

Each condition lasted approximately 10 min. The order of the conditions was counterbalanced across participants. At the completion of the test conditions, participants filled out an exit questionnaire and were debriefed. The entire session was approximately 1 h in duration.

4 Results and discussion

Mean percent accuracy and correct RT data for central and peripheral tasks were calculated for each participant. Nine participants were removed from statistical analysis because errors exceeded 2.5 SDs of the overall mean (central task: $n = 4$; peripheral task: $n = 2$) or a failure to complete the experiment due to persistent afterimage effects of peripheral targets ($n = 3$). Thus, data from twenty-one participants (twelve males, $M_{\text{age}} = 19.9$ years, age range = 18–25 years) were included in subsequent data analyses.

4.1 *Central task performance*

To confirm that participants prioritized the central, symbol detection task relative to the addition of the driving background and steering tasks, a repeated-measures ANOVA for condition (3: NoB, DrB, DrS) was conducted for central task RT and accuracy data. For the central task, RTs did not differ across conditions ($F_{2,40} = 1.54$, $p = 0.226$), suggesting overall compliance to central task prioritization. Mean RTs (SD) for NoB, DrB, and DrS were 901 ms (189 ms), 907 ms (165 ms), and 862 ms (141 ms), respectively. Accuracy did differ across tasks ($F_{1.4,28.8} = 7.45$, $p = 0.005$, $\eta^2_{\text{p}} = 0.271$), Greenhouse–Geisser correction applied. Bonferroni pairwise comparisons showed that participants were less accurate in DrS ($M = 92\%$, SD = 7%) compared with NoB ($M = 95\%$, SD = 4%, $p = 0.018$) and DrB ($M = 95\%$, SD = 3%, $p = 0.039$). While no differences were observed for central task RTs, the addition of a steering task decreased response accuracy.

4.2 *Steering task performance*

To confirm adequate performance of the steering task in DrS, we measured the mean SDLP. Previous work has indicated that participants can readily prioritize steering when instructed to do so over a secondary FFOV task (Park & Reed, 2010). Participants produced an overall mean SDLP of 0.27 m (SD = 0.11 m). Results suggest that participants steered within the range of normal operating levels (SDLP of 0.2–0.3 m) reported in previous driving studies (Green, Cullinane, Zylstra, & Smith, 2003; Kircher, Uddman, & Sandin, 2002).

4.3 *Peripheral task performance: target eccentricity*

To confirm that our FFOV paradigm produced similar results to prior FFOV studies and that the addition of visual complexity and steering affected the overall size of the FFOV, we assessed whether peripheral target localization accuracy decreased as target eccentricity increased. We conducted a condition (3: NoB, DrB, DrS) × target eccentricity (5: 20, 30, 40, 50, 60 deg) repeated-measures ANOVA for peripheral target localization accuracy (% of correct radial spoke responses). The main effects of condition ($F_{2,40} = 33.31$, $p < 0.001$, $\eta^2_{\text{p}} = 0.625$) and target eccentricity ($F_{4,80} = 46.25$, $p < 0.001$, $\eta^2_{\text{p}} = 0.698$) were mediated by the condition × target eccentricity interaction ($F_{4.3,86.0} = 5.26$, $p = 0.001$, $\eta^2_{\text{p}} = 0.208$), using the Greenhouse–Geisser correction. The interaction indicated that peripheral target accuracy decreased with increasing eccentricity, but more for DrS than NoB and DrB (figure 3).

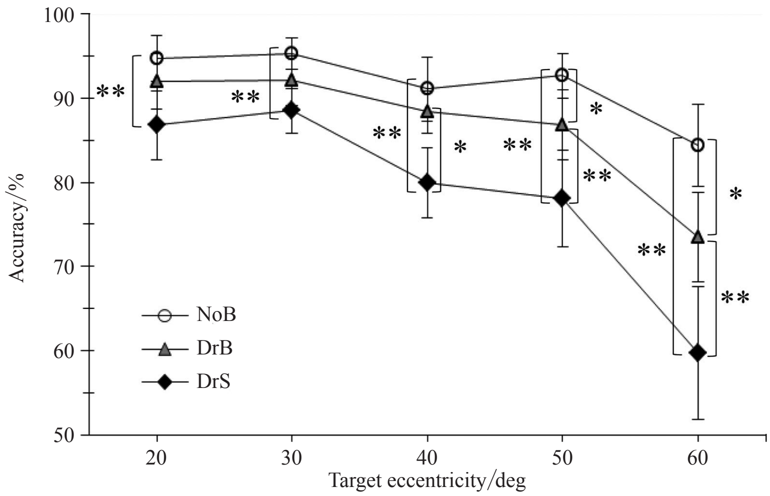

Figure 3. Peripheral target localization mean accuracy (% correct) with 95% confidence intervals across target eccentricity and test condition. Left-side brackets indicate Bonferroni pairwise comparison *p*-values (* <0.05, ** <0.01) between NoB–DrS conditions. Right-side brackets indicate *p*-values between NoB–DrB and DrB–DrS conditions. Note: NoB = no-background condition; DrB = driving background condition; DrS = driving background + steering condition.

Simple main effects followed by Bonferroni pairwise comparisons performed at each eccentricity confirmed condition differences: 20 deg eccentricity ($F_{2,40} = 11.46$, $p < 0.001$, $\eta_p^2 = 0.364$; NoB vs DrS, $p < 0.001$), 30 deg eccentricity ($F_{2,40} = 10.40$, $p < 0.001$, $\eta_p^2 = 0.342$; NoB vs DrS, $p = 0.001$), 40 deg eccentricity ($F_{2,40} = 10.64$, $p < 0.001$, $\eta_p^2 = 0.347$; NoB vs DrS, $p = 0.001$, and DrB vs DrS, $p = 0.017$), 50 deg eccentricity ($F_{2,40} = 18.02$, $p < 0.001$, $\eta_p^2 = 0.474$; NoB vs DrS, $p < 0.001$, NoB vs DrB, $p = 0.041$, and DrB vs DrS, $p = 0.002$), and 60 deg eccentricity ($F_{2,40} = 19.60$, $p < 0.001$, $\eta_p^2 = 0.495$; NoB vs DrS, $p < 0.001$, NoB vs DrB, $p = 0.010$, and DrB vs DrS, $p = 0.009$).

Thus, as shown in figure 3, peripheral target accuracy decreased with increasing target eccentricity and changes in the display background and steering demands. Task performance during NoB appeared relatively stable until 60 deg eccentricity. NoB and DrB did not differ significantly until eccentricity reached 50 deg and 60 deg. Performance for DrS was consistently worse at all eccentricities in comparison with NoB, but differed from DrB only at eccentricity 40 deg and higher. In sum, the size of the FFOV decreased with the addition of the driving background and steering as indicated by decreasing accuracy at greater eccentricities. Further, the addition of steering decreases performance to a greater extent at lesser eccentricities than just the driving background.

4.4 *Peripheral task performance: target radials at each eccentricity*

To examine changes in the FFOV shape, we tested radial position differences at each target eccentricity. For 20, 30, and 40 deg eccentricities we conducted a condition (3: NoB, DrB, DrS) × radial position (11: radials 12, 1, 2, 3, 4, 5, 7, 8, 9, 10, 11) repeated-measures ANOVA for peripheral target localization accuracy. Given the different number of radial positions for 50 deg and 60 deg, we conducted separate condition (3: NoB, DrB, DrS) × radial position (6: radials 2, 3, 4, 8, 9, 10) repeated-measures ANOVAs. Because condition differences at each target eccentricity were already assessed in the above analyses, only main effects for radial position were followed with repeated contrasts (radial vs adjacent radial). The *p*-values for repeated contrasts were adjusted using the Holm–Bonferroni sequential correction (Holm, 1979), and Greenhouse–Geisser corrections for sphericity violations were used when necessary. Figures 4 and 5 illustrate condition differences across radial positions at each target eccentricity in radar and line graphs. A condition × radial position interaction is found only at 40 deg. Note that the proximity to and potential overlap of driving background elements with peripheral target locations occurs at radial position 8 for 20, 30, and 40 deg eccentricities. However, DrS is significantly different from DrB only at 40 deg because that is the portion of the visual field that is used for steering.

4.4.1 *Eccentricity 20 deg.* Despite no interaction ($F_{20,400} = 1.23$, $p = 0.227$), main effects were found for condition ($F_{2,40} = 11.46$, $p < 0.001$, $\eta_{\mathrm{p}}^2 = 0.364$) and radial position ($F_{3.4,68.3} = 6.13$, $p = 0.001$, $\eta_{\mathrm{p}}^2 = 0.235$). Repeated contrasts for radial positions showed significant differences between radials 2 and 3 ($p = 0.024$), 7 and 8 ($p = 0.001$), 8 and 9 ($p = 0.003$), and 9 and 10 ($p = 0.049$). Performance declined at the diagonal radials (2, 4, 8, and 10) when conditions were assessed together (figure 4a). Condition effects occurred at radial 4 ($F_{2,40} = 4.04$, $p = 0.025$, $\eta_{\mathrm{p}}^2 = 0.168$), radial 8 ($F_{2,40} = 3.33$, $p = 0.046$, $\eta_{\mathrm{p}}^2 = 0.143$), and radial 10 ($F_{2,40} = 6.03$,

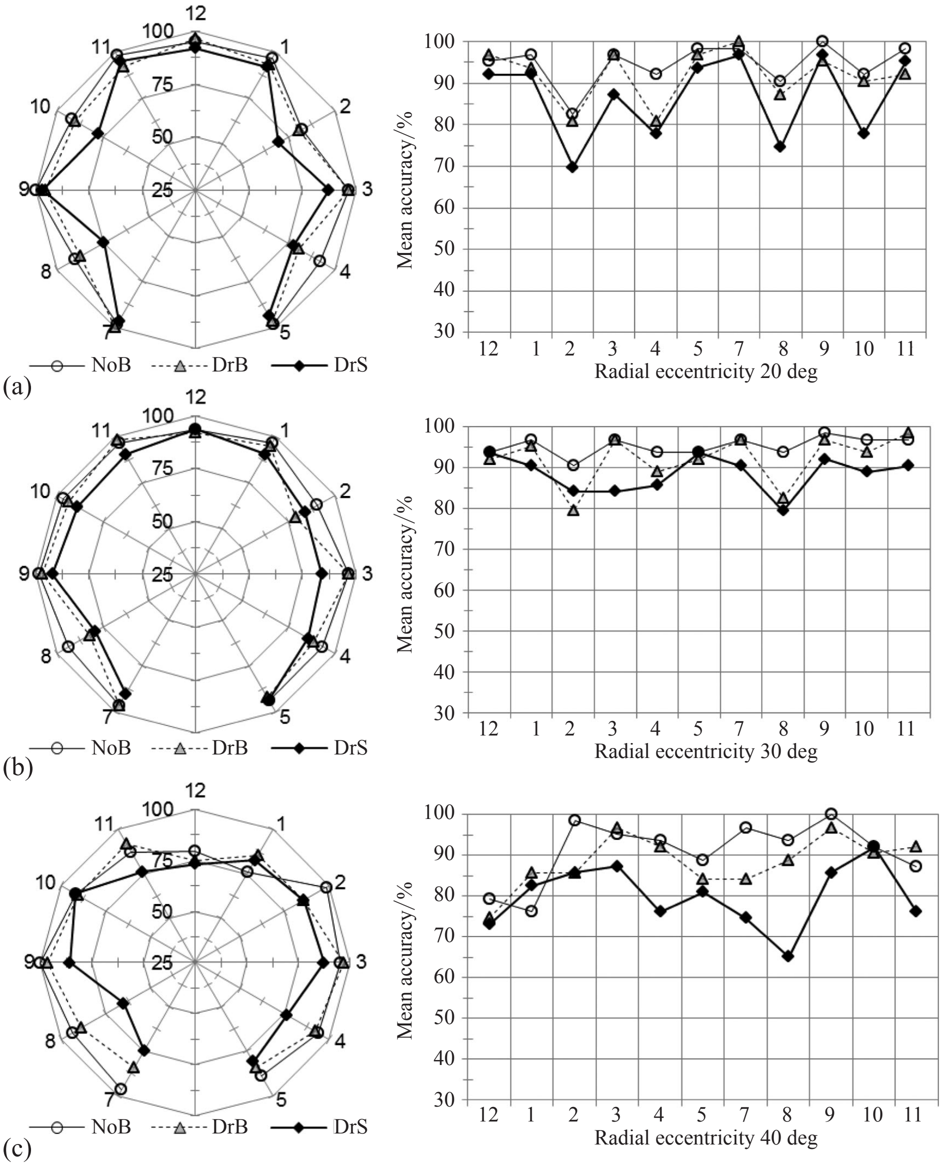

Figure 4. Radar and line graphs of mean accuracy for peripheral target localization across radial positions at eccentricity (a) 20 deg, (b) 30 deg, and (c) 40 deg. Note: NoB = no-background condition; DrB = driving background condition; DrS = driving background + steering condition.

$p = 0.005$, $\eta_p^2 = 0.232$). However, a significant DrB–DrS difference was only found only at radial 10 ($p = 0.034$). At 20 deg performance decrements were observed at the diagonals even for NoB and DrB, where there was no reason to shift focal attention away from the central task. This pattern suggests that the location of focal attention affects attention in regions around it.

4.4.2 *Eccentricity 30 deg.* Despite no interaction ($F < 1.0$, $p = 0.709$), main effects of condition ($F_{2,40} = 10.40, p < 0.001$, $\eta_p^2 = 0.342$) and radial position ($F_{4.4,87.0} = 2.50, p = 0.044$, $\eta_p^2 = 0.111$) were found. Repeated contrasts showed significant differences between radials 7 and 8 ($p = 0.045$) and radials 8 and 9 ($p = 0.008$). At radial 8, where there is potential target and background overlap, no significant difference was found between conditions ($F_{2,40} = 2.01, p = 0.148$) or at any other radial position. As shown in figure 4b, target accuracy at eccentricity 30 deg was relatively high compared with 20 deg and did not differentiate across radial positions.

4.4.3 *Eccentricity 40 deg.* Unlike the other eccentricities, main effects of condition ($F_{2,40} = 10.63$, $p < 0.001$, $\eta_p^2 = 0.347$) and radial position ($F_{10,200} = 4.08, p < 0.001$, $\eta_p^2 = 0.169$) were mediated by a condition × radial position interaction ($F_{8.7,174.4} = 2.20$, $p = 0.026$, $\eta_p^2 = 0.099$), indicating that condition affected accuracy differently across radial positions. Significant differences were found for condition at specific radial positions: radial 2 ($F_{2,40} = 5.57$, $p = 0.007$, $\eta_p^2 = 0.218$; NoB vs DrB, $p = 0.016$); radial 4 ($F_{2,40} = 5.36$, $p = 0.009$, $\eta_p^2 = 0.211$); radial 7 ($F_{1.3,27.3} = 8.32$, $p = 0.004$, $\eta_p^2 = 0.294$; NoB vs DrB, $p = 0.004$); radial 8 ($F_{2,40} = 10.75$, $p < 0.001$, $\eta_p^2 = 0.350$; DrB vs DrS, $p = 0.008$); radial 9 ($F_{1.2,24.1} = 5.40, p = 0.024$, $\eta_p^2 = 0.213$); and radial 11 ($F_{2,40} = 3.38$, $p = 0.044$, $\eta_p^2 = 0.145$; DrB vs DrS, $p = 0.042$). As shown in figure 4c, all conditions showed decreased accuracy at the upper visual field radials 11, 12, and 1, suggesting a vertical flattening of the FFOV. Accuracy remained high at the across radial positions for NoB, but it declined during DrB at radials 2 and 7. Further performance decrements were found for DrS at the lower radial 8, and at the higher diagonal radial 11.

4.4.4 *Eccentricity 50 deg.* Despite no interaction ($F_{10,200} = 1.39, p = 0.186$), main effects were found for condition ($F_{2,40} = 18.02$, $p < 0.001$, $\eta_p^2 = 0.474$) and radial position ($F_{5,100} = 4.83$, $p = 0.001$, $\eta_p^2 = 0.184$). A significant difference was found between radials 2 and 3 ($p = 0.028$), radials 4 and 8 ($p = 0.028$), and radials 8 and 9 ($p = 0.025$). Condition differences were found at specific radial positions: radial 2 ($F_{2,40} = 6.79$, $p = 0.003$, $\eta_p^2 = 0.254$; DrB vs DrS, $p < 0.001$); radial 3 ($F_{2,40} = 5.39$, $p = 0.008$, $\eta_p^2 = 0.212$; NoB vs DrB, $p = 0.042$); radial 8 ($F_{2,40} = 4.12$, $p = 0.024$, $\eta_p^2 = 0.171$); and radial 9 ($F_{2,40} = 5.40$, $p = 0.008$, $\eta_p^2 = 0.213$). As shown in figure 5a, accuracy dropped at the diagonals relative to the horizontal axis (radials 9 and 3). For DrS, a large decline in accuracy was observed at radial 2, but for both DrB and DrS reduced accuracy was observed at radial 8.

4.4.5 *Eccentricity 60 deg.* Despite no interaction ($F_{10,200} = 1.51, p = 0.186$) or radial position effect ($F < 1.0$, $p = 0.455$), a main effect for condition was found ($F_{2,40} = 19.60$, $p < 0.001$, $\eta_p^2 = 0.495$). At particular radial positions, test condition differences were observed at: radial 3 ($F_{2,40} = 6.88, p = 0.003$, $\eta_p^2 = 0.256$; NoB vs DrB, $p = 0.024$); radial 4 ($F_{2,40} = 12.58$, $p < 0.001$, $\eta_p^2 = 0.386$; NoB vs DrB, $p = 0.024$ and DrB vs DrS, $p = 0.029$); and radial 8 ($F_{2,40} = 14.70$, $p < 0.001$, $\eta_p^2 = 0.424$; DrB vs DrS, $p < 0.001$). Accuracy at eccentricity 60 deg was the lowest for all conditions (figure 5b). Radials 2, 3, and 4 provided strong separation between conditions with comparable performance for NoB and DrB at radials 8, 9, and 10. The one exception was at radial 8 for DrS, which provided the lowest accuracy performance score of all peripheral targets.

In summary, an examination of performance at different eccentricities across radial positions indicated a nonuniform distribution of attention across the visual field. Regions near

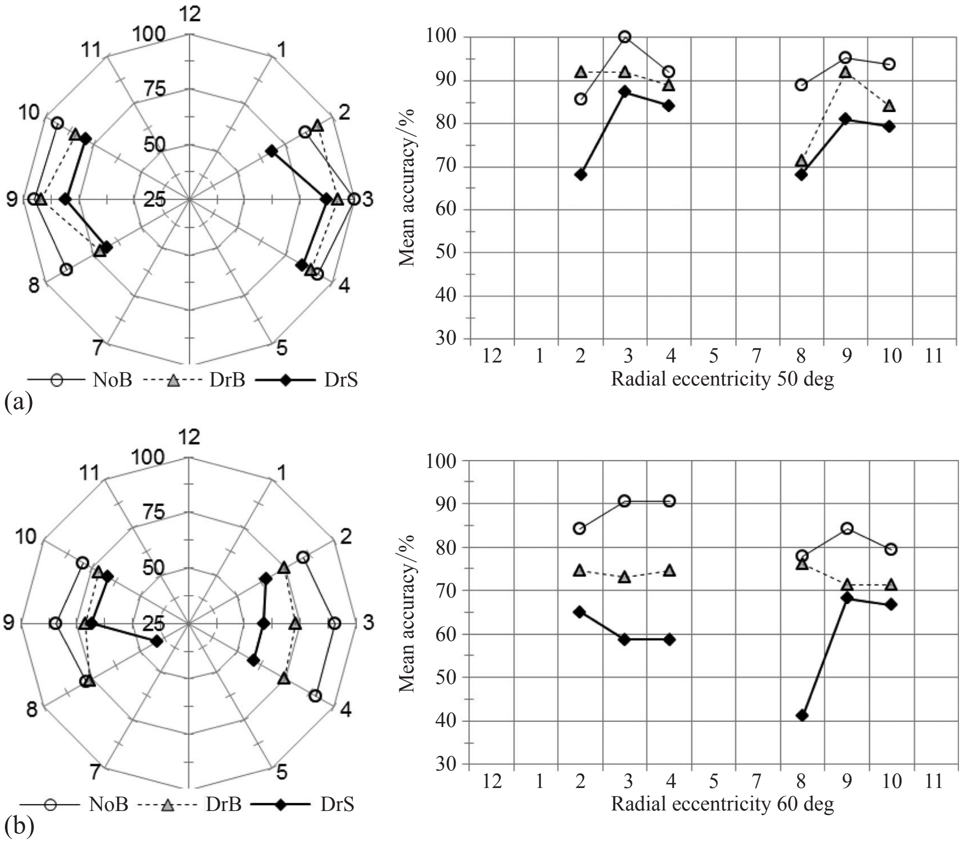

Figure 5. Radar and line graphs of mean accuracy for peripheral target localization across radial positions at eccentricity: (a) 50 deg and (b) 60 deg. Note: NoB = no-background condition; DrB = driving background condition; DrS = driving background + steering condition.

the focal location for the central task and in regions near locations required for the steering task showed specific performance decrements. Despite an overall shrinkage in the FFOV with additional task requirements (eg NoB vs DrB vs DrS) as observed at 50 deg and 60 deg eccentricity, decrements in performance were not equally distributed across the radial positions at all eccentricities. Across conditions at 20 deg eccentricity, a collapse in performance was observed particularly at diagonal positions but not at the farther 30 deg eccentricity. Further, performance decrements were observed for DrS for radial position 8 at 40 deg eccentricity, a region likely used to maintain car position while steering. This collapse could not be attributed to overlapping background elements with peripheral targets because a corresponding performance deficit was not observed for DrB.

5 General discussion

Researchers acknowledge the interplay between action and attention, but typically they consider action as a response to successful attentional selection or the correlation of performance on separate action and attention tasks. We investigated how concurrent action with spatial monitoring affects the distribution of attention across a wide visual field. We embedded a demanding FFOV paradigm with concurrent central object recognition and peripheral target localization tasks in a simulated driving environment. Peripheral targets varied across 20 deg to 60 deg eccentricity at 11 radial spokes. We designed three conditions to assess the differential effects of visual complexity and concurrent action on the size and shape of the FFOV: (1) with no background, (2) with driving background, and (3) with driving background and vehicle steering.

When drivers performed a driving task representative of relatively realistic driving conditions with quick moving visual stimuli, an expanded visual field with 60 deg eccentricity, and a changing road that required steering, we observed significant changes in the distribution of attention in the periphery. After confirming high levels of performance in the central task across conditions, we observed an expected decrease in peripheral task performance as targets were displayed at increasing eccentricities, especially over 50 deg eccentricities, indicating a decrease in the size of the FFOV. The baseline, no-background condition replicated other studies with peripheral targets positioned in relatively low target eccentricities (eg less than 30 deg) and few radial spoke positions and showed little differential allocation of peripheral attention ability across the visual field (Ball et al., 1988; Ball, Owsley, Sloane, Roenker, & Bruni, 1993; Scalf et al., 2007). The FFOV task with a driving background showed additional performance decrements only at 50 deg and 60 deg, eccentricity consistent with added processing load from visual complexity. However, action—or vehicle steering—appears to affect the size of the FFOV more than just added visual complexity. Unlike the driving background condition, performance decrements with steering occurred at all eccentricities compared with the no-background condition. Relative to the driving background, steering caused deficits to also occur at a nearer eccentricity (40 deg) and became increasingly larger with greater eccentricity.

When a more precise analysis of peripheral task performance by radial spoke at each target eccentricity was performed, results indicated a more complex distribution of visual attention and FFOV shape due to action. For targets at the closest eccentricity (20 deg), deformations for all conditions appeared at the diagonal radials as opposed to the cardinal axes. During the steering task these radial deformations appeared to be greater in comparison with other conditions in eccentricity 20 deg and in comparison with the steering condition performance in eccentricity 30 deg. At eccentricity 30 deg accuracy levels for all radials except for radial 8 returned to relatively high levels, with no strong effects for the driving background or steering task at any particular radial position. This pattern would have been hidden if we had not analyzed peripheral task performance for each radial position at each target eccentricity.

The results at the nearer eccentricity levels of 20 deg and 30 deg suggest a pattern of FFOV deformations previously unreported by past FFOV driving studies. Instead of deformations increasing by target eccentricity from the central, focal task, deformations were greater for certain radials at an eccentricity closer to the central task. Although this phenomena has been described before as *inverted tunnel vision* (Rogé et al., 2002), the effect has only been briefly reported in past studies (Bartz, 1976). Specifically, the pattern suggests that the attentional requirements for the central task were causing a uniform deformation in the peripheral area surrounding the central task along the diagonal radials. As steering was added to the central task, additional decreases in task accuracy at the same diagonal radials were observed but not necessarily at the other radials. As the driver shifted central focus to anticipate upcoming left/right roadway curves, this may have in turn caused either contralateral FFOV loss or adjacent FFOV loss due to limited attentional resources. Without corresponding eye-tracking data, the specific nature of the near peripheral field loss during steering is unclear.

For peripheral targets presented at eccentricity 40 deg and beyond, we observed several FFOV shape patterns as conditions changed in regards to the background and actions required. The first pattern was a vertical flattening and horizontal maintenance of the FFOV, suggesting an elliptical distribution of attention similar to total visual field. This occurred for all conditions, suggesting a nonuniform reduction in the FFOV, similar to the results found by Rogé et al. (2002), which found differential shrinkage on the vertical and horizontal axes. For the no-background condition this pattern appeared consistent for targets up to 60 deg eccentricity where accuracy at the horizontal meridian remained relatively high.

By examining the driving background condition, we determined how background elements affected the distribution of attention. The background itself appeared to draw peripheral attention resources or provide significant visual distraction to degrade the participant's FFOV in general. Given that peripheral vision is sensitive to low-contrast/low-spatial frequency and particularly sensitive to high temporal variations such as motion or flicker (Merigan & Maunsell, 1993), it is unlikely that changes to peripheral task performance could be attributed to the changes in contrast sensitivity between the peripheral targets and the simulation background (ie horizon and ground). However, it was possible that peripheral targets displayed near the moving road edge lines may have provided a type of visual masking known as metacontrast (or object substitution) masking where the detection of a target signal is impaired by flanking stimuli that is simultaneously presented and prolonged relative to the target signal (Enns & Di Lollo, 2000). Occurring early in the visual system, the mechanisms of metacontrast masking have been shown to be closely related to the same mechanisms involved with the perception of visual motion (Bischof & Dilollo, 1995; Didner & Sperling, 1980). If so, we would have expected decrements in performance on radials 4 and 8 across eccentricities, but this was not what we observed. Instead, the pattern of deficits looked more like the no-background condition than the steering condition.

In the steering condition, which required concurrent action in the attended visual space, additional deformations in the FFOV shape occurred in areas required for steering. Even compared with the driving background condition, the largest performance deficits were found for targets appearing at radial 8 for eccentricities 40 deg and greater. Driving requires peripheral attention and successful steering requires attention to the left road edge line in relation to the left portion of the vehicle hood (as performed in driving on the right side of the road). Thus, attentional resources to this area were limited and likely exacerbated by the background effects. However, deformations in the FFOV were also observed at the upper right diagonal radial 2 and right horizontal radial 3 where no particular simulation background effects were likely and attention was not critical to the steering task. Driving requires peripheral processing resources taxing specific areas required for steering, and we observe a collapse in performance in these regions not found in other conditions.

Overall, these results are consistent with traditional limited-capacity theories of attention (Eriksen & Yeh, 1985) in that prioritizing attention to one part of space has attentional costs to another region. More recent theories allow for more than one focus of attention (LaBerge & Brown, 1989), but do not specify the differential attentional costs to different parts of the visual field. Because we assessed performance at locations distributed across the visual field, we were able to show attentional costs at the diagonals for all conditions related to the central task focus and the additional attentional costs of peripheral attention required by steering. Thus, multifocal theories of attention have to account for not only more than one focus of attention but also how these foci produce subsequent nonuniform costs in the distribution of attention. This is an initial study, but future work could study these nonuniform distributions of attention by calibrating the tasks for each participant for a more precise variation of attentional load.

References

Allport, A., & Meyer, D. (1993). Attention and control: Have we been asking the wrong questions? A critical review of twenty-five years. In D. E. Meyer & S. Kornblum (Eds.), *Attention and performance XIV: Synergies in experimental psychology, artificial intelligence, and cognitive neuroscience* (pp. 183–218). Cambridge, MA: MIT Press.

Alvarez, G. A. (2014). Attention and action. In K. Ochsner & S. M. Kosslyn (Eds.), *The Oxford handbook of cognitive neuroscience: Core topics* (Vol. 1). New York: Oxford University Press.

Alvarez, G. A., & Cavanagh, P. (2005). Independent resources for attentional tracking in the left and right visual hemifields. *Psychological Science*, **16**, 637–643. doi:10.1111/j.1467-9280.2005.01587.x

Alvarez, G. A., & Franconeri, S. L. (2007). How many objects can you track? Evidence for a resource-limited attentive tracking mechanism. *Journal of Vision*, **7**(13):14, 1–10. doi:10.1167/7.13.14
Awh, E., & Pashler, H. (2000). Evidence for split attentional foci. *Journal of Experimental Psychology: Human Perception and Performance*, **26**, 834–846.
Ball, K., Beard, B. L., Roenker, D. L., Miller, R. L., & Griggs, D. S. (1988). Age and visual search: Expanding the useful field of view. *Journal of the Optical Society of America A*, **5**, 2210–2219.
Ball, K., & Owsley, C. (1993). The useful field of view test: A new technique for evaluating age-related declines in visual function. *Journal of the American Optometric Association*, **64**, 71–79.
Ball, K., Owsley, C., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1993). Visual attention problems as a predictor of vehicle crashes in older drivers. *Investigative Ophthalmology & Visual Science*, **34**, 3110–3123.
Bartz, A. E. (1976). Peripheral detection and central task complexity. *Human Factors*, **18**, 63–69.
Bischof, W. F., & Dilollo, V. (1995). Motion and metacontrast with simultaneous onset of stimuli. *Journal of the Optical Society of America A: Optics, Image Science, and Vision*, **12**, 1623–1636. doi:10.1364/josaa.12.001623
Bolstad, C. A. (2001). Situation awareness: Does it change with age? *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, **45**, 272–276. doi:10.1177/154193120104500401
Carlson, T. A., Alvarez, G. A., & Cavanagh, P. (2007). Quadrantic deficit reveals anatomical constraints on selection. *Proceedings of the National Academy of Sciences of the USA*, **104**, 13496–13500. doi:10.1073/pnas.0702685104
Didner, R., & Sperling, G. (1980). Perceptual delay: A consequence of metacontrast and apparent motion. *Journal of Experimental Psychology: Human Perception and Performance*, **6**, 235–243. doi:10.1037/0096-1523.6.2.235
Downing, C. J., & Pinker, S. (1985). The spatial structure of visual attention. In M. I. Posner & O. S. M. Marin (Eds.), *Attention & performance XI: Mechanisms of attention* (pp. 171–187). Hillsdale, NJ: Erlbaum.
Engel, F. L. (1971). Visual conspicuity, directed attention and retinal locus. *Vision Research*, **11**, 563–576.
Enns, J. T., & Di Lollo, V. (2000). What's new in visual masking? *Trends in Cognitive Sciences*, **4**, 345–352. doi:10.1016/s1364-6613(00)01520-5
Eriksen, C. W., & St James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics*, **40**, 225–240.
Eriksen, C. W., & Yeh, Y. Y. (1985). Allocation of attention in the visual-field. *Journal of Experimental Psychology: Human Perception and Performance*, **11**, 583–597. doi:10.1037/0096-1523.11.5.583
Fecteau, J. H., & Munoz, D. P. (2006). Salience, relevance, and firing: A priority map for target selection. *Trends in Cognitive Sciences*, **10**, 382–390. doi:10.1016/j.tics.2006.06.011
Franconeri, S. L., Alvarez, G. A., & Enns, J. T. (2007). How many locations can be selected at once? *Journal of Experimental Psychology: Human Perception and Performance*, **33**, 1003–1012. doi:10.1037/0096-1523.33.5.1003
Franconeri, S. L., Hollingworth, A., & Simons, D. J. (2005). Do new objects capture attention? *Psychological Science*, **16**, 275–281. doi:10.1111/j.0956-7976.2005.01528.x
Green, C. S., & Bavelier, D. (2006). Effect of action video games on the spatial distribution of visuospatial attention. *Journal of Experimental Psychology: Human Perception and Performance*, **32**, 1465–1478. doi:10.1037/0096-1523.32.6.1465
Green, P., Cullinane, B., Zylstra, B., & Smith, D. (2003). Typical values for driving performance with emphasis on the standard deviation of lane position: A summary of the literature. Technical Report UMTRI-2003-42, University of Michigan Transportation Research Institute, Ann Arbor, MI.
Heinze, H., & LuckHaines, R. F. (1991). A breakdown in simultaneous information processing. In G. Obrecht & L. W. Stark (Eds.), *Presbyopia research* (pp. 171–175). New York: Plenum Press.
Herslund, M.-B., & Jørgensen, N. O. (2003). Looked-but-failed-to-see-errors in traffic. *Accident Analysis & Prevention*, **35**, 885–891.
Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics*, **6**, 65–70.

Horswill, M. S., Marrington, S. A., McCullough, C. M., Wood, J., Pachana, N. A., McWilliam, J., & Raikos, M. K. (2008). The hazard perception ability of older drivers. *Journal of Gerontology B: Psychological Sciences*, **63**, P212–P218.

Intriligator, J., & Cavanagh, P. (2001). The spatial resolution of visual attention. *Cognitive Psychology*, **43**, 171–216. doi:10.1006/cogp.2001.0755

Itti, L., & Koch, C. (2001). Computational modelling of visual attention. *Nature Reviews Neuroscience*, **2**, 194–203. doi:10.1038/35058500

Kircher, A., Uddman, M., & Sandin, J. (2002). *Vehicle control and drowsiness.* Linköping: Swedish National Road and Transport Research Institute.

LaBerge, D. (1983). Spatial extent of attention to letters and words. *Journal of Experimental Psychology: Human Perception and Performance*, **9**, 371–379.

LaBerge, D., & Brown, V. (1989). Theory of attentional operations in shape identification. *Psychological Review*, **96**, 101–124. doi:10.1037/0033-295x.96.1.101

Land, M. F., & Hayhoe, M. (2001). In what ways do eye movements contribute to everyday activities? *Vision Research*, **41**, 3559–3565.

Mack, A., & Rock, I. (1998). *Inattentional blindness*. Cambridge, MA: MIT Press.

McMains, S. A., & Somers, D. C. (2004). Multiple spotlights of attentional selection in human visual cortex. *Neuron*, **42**, 677–686.

Merigan, W. H., & Maunsell, J. H. R. (1993). How parallel are the primate visual pathways. *Annual Review of Neuroscience*, **16**, 369–402. doi:10.1146/annurev.ne.16.030193.002101

Most, S. B., Scholl, B. J., Clifford, E. R., & Simons, D. J. (2005). What you see is what you set: Sustained inattentional blindness and the capture of awareness. *Psychological Review*, **112**, 217–242. doi:10.1037/0033-295x.112.1.217

Neumann, O. (1990). Visual attention and action. In O. Neumann & W. Prinz (Eds.), *Relationships between perception and action* (pp. 227–267). Berlin: Springer.

Park, G. D., & Reed, C. L. (2010). Distribution of peripheral vision for a driving simulator functional field of view task. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, **54**, 1526–1530. doi:10.1177/154193121005401936

Pashler, H. (1998). *Attention*. Hove, East Sussex: Psychology Press.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, **32**, 3–25. doi:10.1080/00335558008248231

Pylyshyn, Z. W., & Storm, R. W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision*, **3**, 179–197.

Rantanen, E. M., & Goldberg, J. H. (1999). The effect of mental workload on the visual field size and shape. *Ergonomics*, **42**, 816–834. doi:10.1080/001401399185315

Remington, R., & Pierce, L. (1984). Moving attention: Evidence for time-invariant shifts of visual selective attention. *Perception & Psychophysics*, **35**, 393–399.

Rogé, J., Kielbasa, L., & Muzet, A. (2002). Deformation of the useful visual field with state of vigilance, task priority, and central task complexity. *Perceptual & Motor Skills*, **95**, 118–130.

Sanders, A. F. (1970). Some aspects of the selective process in the functional field of view. *Ergonomics*, **13**, 101–117.

Scalf, P. E., Colcombe, S. J., McCarley, J. S., Erickson, K. I., Alvarado, M., Kim, J. S., … Kramer, A. F. (2007). The neural correlates of an expanded functional field of view. *Journal of Gerontology B: Psychological Sciences and Social Sciences*, **62**, 32–44.

Schieber, F., Schlorholtz, B., & McCall, R. (2008). Visual requirements of vehicular guidance. In C. Castro (Ed.), *Human factors of visual and cognitive performance in driving* (pp. 31–50). Boca Raton, FL: CRC Press.

Simons, D. J., & Rensink, R. A. (2005). Change blindness: Past, present, and future. *Trends in Cognitive Sciences*, **9**, 16–20. doi:10.1016/j.tics.2004.11.006

Trick, L. M., & Enns, J. T. (2009). A two-dimensional framework for understanding the role of attentional selection in driving. In C. Castro (Ed.), *Human factors of visual and cognitive performance in friving* (pp. 63–73). Boca Raton, FL: CRC Press.

Wood, J. M. (2002). Age and visual impairment decrease driving performance as measured on a closed-road circuit. *Human Factors*, **44**, 428–494.

Wood, J. M., Chaparro, A., Hickson, L., Thyer, N., Carter, P., Hancock, J., … Ybarzabal, F. (2006). The effect of auditory and visual distracters on the useful field of view: Implications for the driving task. *Investigative Ophthalmology & Visual Science*, **47**, 4646–4650. doi:10.1167/iovs.06-0306
Yantis, S. (1998). Control of visual attention. In H. Pashler (Ed.), *Attention* (pp. 223–256). Hove, East Sussex: Psychology Press.
Yantis, S., & Jonides, J. (1990). Abrupt visual onsets and selective attention: Voluntary versus automatic allocation. *Journal of Experimental Psychology: Human Perception and Performance*, **16**, 121–134.