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The effects of age and workload on 3D spatial attention in dual-task driving

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Abstract

In the present study we assessed whether the limits in visual-spatial attention associated with aging affect the spatial extent of attention in depth during driving performance. Drivers in the present study performed a car-following and light-detection task. To assess the extent of visual-spatial attention, we compared reaction times and accuracy to light change targets that varied in horizontal position and depth location. In addition, because workload has been identified as a factor that can change the horizontal and vertical extent of attention, we tested whether variability of the lead car speed influenced the extent of spatial attention for younger or older drivers. For younger drivers, reaction time (RT) to light-change targets varied as a function of distance and horizontal position. For older drivers RT varied only as a function of distance. There was a distance by horizontal position interaction for younger drivers but not for older drivers. Specifically, there was no effect of horizontal position at any given level of depth for older drivers. However, for younger drivers there was an effect of horizontal position for targets further in depth but not for targets nearer in depth. With regards to workload, we found no statistically reliable evidence that variability of the lead car speed had an effect on the spatial extent of attention for younger or older drivers. In a control experiment, we examined the effects of depth on light detection when the projected size and position of the targets was constant. Consistent with our previous results, we found that drivers' reaction time to light-change targets varied as a function of distance even when 2D position and size were controlled. Given that depth is an important dimension in driving performance, an important issue for assessing driving safety is to consider the limits of attention in the depth dimension. Therefore, we suggest that future research should consider the importance of depth as a dimension of spatial attention in relation to the assessment of driving performance.

Keywords

Attention; Visual Attention; 3D Attention; UFOV; Aging; Ageing; Workload; Perceptual narrowing; Dual-task

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1. Introduction

Per mile driven, older drivers have a greater than average crash risk (Tefft, 2008). The relationship between this increase in crash risk and the vision and attention of older drivers has been an area of increasing interest because the average age of drivers is anticipated to increase at an unprecedented rate (Kinsell & He, 2009; e.g. Borowsky, Shinar, & Oran-Giland, 2010; Adrian, Postal, Moessinger, Rascle, & Charles, 2011; Anstey, Horswill, Wood, & Hatherly, 2012; Marhsall, *et al.*, 2013). Researchers have claimed that this is partially due to reductions in the useful field of view (UFOV), i.e. spatial extent of attention (Hoffman, Mcdowd, Atchley, & Dubinsky, 2005; Owsley *et al.*, 1998; Owsley, Ball, Sloane, Roenker, & Bruni, 1991; Williams, 1988). The UFOV is said to be an attentional window from “which useful information can be acquired without eye and head movements” (Ball *et al.*, 1988; also see Sanders, 1970) and has been found to be predictive of crash risk among older drivers (Sims, McGwin Jr, Allman, Ball, & Owsley, 2000). The UFOV involves the presentation of targets on a computer screen that vary in spatial location on the screen. As a result, the spatial extent of attention as measured by UFOV is two-dimensional, extending in the horizontal and vertical dimensions (Edwards *et al.*, 2005; Sekuler & Ball, 1986; Visual Awareness Research Group Inc., 2004). The measurement of attention with a UFOV test is consistent with theories of visual-spatial attention that were developed using stimuli presented on two-dimensional (2D) displays (B. A. Eriksen & Eriksen, 1974; C. W. Eriksen & St. James, 1986; LaBerge & Brown, 1989). However, previous research has shown that attention can be allocated along the depth dimension (independent of the horizontal and vertical dimensions) and, similar to 2D attention (Ball *et al.*, 1988; B. A. Eriksen & Eriksen, 1974), has a limited spatial extent (Andersen & Kramer, 1993; Andersen, Ni, Bian, & Kang, 2011; Andersen, 1990). If 3D attention changes with age in a similar manner as has been found for 2D spatial attention (as assessed by the UFOV), then it is possible that older individuals would have a decreased ability to attend to targets that vary in depth for tasks that are dependent on depth and distance, such as driving. The primary purpose of the current study was to evaluate whether limits in visual-spatial attention associated with aging occur in the depth dimension during the performance of a driving task.

Previous experiments have not identified any reliable age-related differences in 3D visual-spatial attention (Atchley & Kramer, 1998, 2000). However, these studies used a limited range of depth with distances that are considerably reduced relative to distances used in driving. In addition, the depth values of targets were at two levels, and did not include a ground surface. It is possible that the effects of depth on attention vary with age when additional levels of depth are examined or when the range of depth is increased. Previous research has shown that a ground surface is of critical importance for the perceptual organization of 3D scenes and the layout of the visual world (Bian & Andersen, 2010; Gibson, 1950). It is also possible that intact spatial layout may be required to identify age-related differences in 3D attention especially for tasks that involve spatial layout such as driving. In addition, depth in previous research on attention and aging was specified by binocular disparity. However, disparity information is unlikely to be useful for many driving tasks because the distance is greater than the range of sensitivity for disparity (Cutting & Vishton, 1995). Previous research on 3D spatial attention only examined single task

performance. Other research, however, has shown that age-related differences in 2D visual-spatial attention are more pronounced for dual-task conditions (Ball et al., 1988). For these reasons a driving scenario, with a visually complex scene containing a ground surface with continuous layout, multiple depth values, and a task environment with multiple task demands, such as what is present during driving, may be particularly well suited for detecting and examining age-related differences in the limits of 3D visual-spatial attention.

Successful driving involves a variety of separate yet important tasks. These tasks include steering control, car-following, collision detection and avoidance, braking and detection/recognition of traffic relevant targets (traffic signals, signage; Andersen, 2011; Evans, 2004). In addition, successful driving also often involves performing multiple tasks within a short time period (Horberry, Anderson, Regan, Triggs, & Brown, 2006). In the present study, we examined performance of drivers during car-following and recognition of traffic relevant targets under dual task performance conditions in a driving simulator. Driving simulators are considered useful for driving research (Fisher, Rizzon, Caird, & Lee, 2011). Previous research has shown that even low fidelity driving simulators have strong predictive power for the performance of older drivers on the road (cf. Lee, Cameron & Lee, 2003). In the present study we used driving scenes and a simulation environment that exceed suggested guidelines for visual displays in driving simulation research (Andersen, 2011).

We assume that motoric responses will have a constant duration for each subject. Therefore, we can use reaction times (RTs) as an indicator of the extent that attention is allocated in a particular spatial region (e.g., Posner, Snyder, & Davidson, 1980). A previous study using a similar methodology found that younger drivers' RTs increased as a function of depth, i.e. attention is limited along the depth axis (Andersen et al., 2011). We predict older drivers' attention will also be limited along the depth axis. In addition, based on the results of studies examining aging and 2D attention we expect that the extent of 3D attention for older drivers would be smaller than the extent of 3D attention for younger drivers.

Workload has been identified as a factor that can change the UFOV (Atchley & Dressel, 2004; Rantanen & Goldberg, 1999). Previous research has identified two factors that affect performance in the UFOV, general interference and changes in spatial extent (Williams, 1988). Reaction times (RTs) for all targets in the UFOV increase independent of location when general interference occurs. If changes in the spatial extent of attention occur, then RTs for targets should change in a spatially dependent manner. For example, if RTs for targets with greater spatial separation from the focus of attention increase as compared to targets with less spatial separation from the focus of attention, then it may suggest that there is a reduction in the spatial extent of attention. Previous research has identified three key factors that can result in a reduction in the spatial extent of the UFOV. These factors include high foveal cognitive load, a focused attention strategy, and speed stress (Williams, 1988).

Previous research has examined the effects of workload on the limits of 3D visual-spatial attention in a driving scene (Andersen et al., 2011; Experiment 2). In that experiment, younger drivers were engaged in a simulated car-following task and detected light changes above the roadway at varying horizontal and depth positions. Workload was manipulated by adjusting the variability of lead car speed. Although light changes that occurred closer in

simulated depth had a greater separation in 2D spatial extent relative to the central task (because of perspective geometry; see Figure 1 for an example scene and note that the 2D distance between lights is larger for lights nearer in depth than for lights further in depth), drivers responded more quickly to light changes that were closer in simulated depth than to light changes that were farther away in simulated depth. In addition, the 3D horizontal position of targets affected the RT of participants more when targets were far than when they were near. This was true even though the 2D spatial separation (as measured in visual angle) between targets was greater at near distances in depth than far distances in depth. With regards to workload, drivers demonstrated greater error in maintaining the target-following distance in the high workload as compared to the low workload condition. Drivers in the high workload condition, as compared to a low workload condition, responded more slowly to light change targets. However, there was no additional slowing due to the combination of higher workload and greater 3D simulated horizontal or depth position. It is possible that distant lights in that experiment were perceived to be less driving critical than lights that were nearer. However, in order to assess the driving critical nature of the light the driver must first process the distance of the target, suggesting that distance has an important role in driving performance and attention to critical events in the driving scene.

Drivers in the present experiments performed a car-following and light-detection task. We compared RTs and accuracy to light change targets that varied in horizontal position and depth location. If there are age-related reductions in the spatial extent of 3D attention, then these reductions should be apparent in the pattern of RTs and/or accuracy in response to the light change targets. Specifically, the RTs of older drivers to light change targets should increase more rapidly as a function of distance than that of younger drivers.

2. Experiment 1

In Experiment 1, we examined 3D spatial attention by requiring drivers to detect a light change that varied in horizontal location and varied along the depth axis. Drivers also performed a car-following task in which we manipulated the variability of lead vehicle speed to examine the effects of workload on age-related differences in 3D spatial attention. This manipulation might increase the degree to which participant drivers would use a focused attention strategy and their speed stress, and thereby decrease the spatial extent of drivers' attention. That is, drivers' reaction times to lights near the focus of attention under high workload should be the same as when drivers are under low workload, but drivers' reaction times to targets further away from the focus of attention should be slower under high workload than under low workload. If increased workload results in a more narrow focus of attention, then there may be a decrease in performance for target presented more peripherally in the horizontal dimension and targets positioned greater in depth with higher workload. In addition, if the extent of attention is different for older and younger drivers then the impact of increased workload may result in age-related differences in RT under increased workload conditions.

Research examining performance of older drivers has demonstrated that older drivers have reductions in the spatial extent of 2D attention in response to workload and multiple-task demands (Ball et al., 1988; Daigneault, Joly, & Frigon, 2002; Hakamies-Blomqvist,

Mynttinen, Backman, & Mikkonen, 1999). In addition, secondary task performance is said to degrade more for older adults than younger adults in high workload conditions (Baldwin & Schieber, 1995). Therefore, a failure to find a spatially dependent effect of workload for older drivers, would provide further evidence that variability of lead car speed might only produce generalized interference.

2.1 Materials and methods

2.1.1 Drivers—The drivers were 20 college students, 3 male and 17 female, ($M = 23.74$ years; $SD = 2.64$ years; range 22 - 34 years) and 22 older adults, 10 male and 12 female ($M = 75.36$ years; $SD = 6.04$ years; range 68 - 88 years) who were paid for their participation. All drivers had normal or corrected-to-normal vision and were naïve to the purpose of the study and at least 1.5 years of driving experience.

2.1.2 Driving Simulator—The simulator consisted of a Dell XPS (Gen 2) desktop computer, an ECCI Trackstar 6000 wheel unit and pedal unit, simulation code written in C++ with OpenGL Performer libraries, and 23.1" diagonal LCD monitor with a driver resolution of 1024×768 and a visual angle of $28.77^\circ \times 21.78^\circ$ when viewed from 91.5cm. The ECCI pedal unit provided closed loop control of the simulator. The controls and the rest of the simulation software updated at 30Hz. The simulation code was modified from a version previously reported by Andersen et al. (2011) to account for updates and modifications to the experimental equipment and procedures.

The computer generated 3D scene was of a 12.68m wide three-lane one-way road situated with two-story office buildings on both sides to a distance of 407 meters from the drivers' vehicle. Scene textures were derived from digital photographs of a real vehicle and real buildings, but were digitally altered and rescaled to realistically fit the simulation environment. Asphalt was simulated using a black and white gravel texture pattern. The average luminance of the driving scene was 24.70 cd/m^2 . The only vehicle visible in the scene was the lead vehicle, a white sedan initially displayed at a headway distance, i.e. the distance between the drivers' vehicle and the lead vehicle, of 20.50 m. The driver and the lead vehicle were located in the center lane. Above the roadway centered at a height of 2.35 m, there were arrays of 21 evenly spaced 41.50 cm diameter red and green lights. Each array had a different random order of red and green lights, extended 12.68 m horizontally and 0.60 m vertically, and was separated from the next array by a distance of 72 m (see Figure 1 for an example). Only four arrays were displayed at any given time.

In all simulations the lead vehicle's average speed was 60 kph (37.28 mph). During simulator sessions, the lead vehicle's speed varied according to the sum of three sine waves with equal peak accelerations and decelerations. Specifically, the frequencies of the sine waves were .033, .083, and .117 Hz. The phases of the sine waves were restricted such that the speed of the lead vehicle started no more than ± 1 kph from 60 kph. The amplitude of the sine waves depended on the workload condition. Lead vehicle speed in the low workload condition was calculated using sine waves with amplitudes of 9.722, 3.889, and 2.778 kph respectively. This resulted in an average range of speed of ± 14.30 kph (8.89 mph) about the mean speed. In the high workload condition, the sine wave amplitudes were 220% the size

of the sine waves in the low workload condition. For an example of the low-workload speed profile, see Figure 2.

2.1.3 Procedure—The experiment took place in a darkened room. The drivers were seated in front of the display with their hands on the steering wheel and feet on the pedals as if they were operating a vehicle. When the drivers were ready to start the simulator session, they pulled a paddle behind the steering wheel attached to the steering column. Participants completed five training sessions followed by four experimental sessions. Each session began with the lead vehicle and the drivers' vehicle moving at a constant speed of 60 kph with a constant separation of 20.5m. Control input (acceleration/deceleration) was not allowed and drivers were instructed to remember this distance as the desired headway distance for the rest of the trial. After 5 seconds, drivers heard a tone that indicated the start of the experimental task, the lead vehicle began varying its speed according to the experimental design, and the driving controls became active.

The first training session familiarized participants with the light detection task. Prior to the session, participants were told that they would not need to use the gas or brake. They were told that their task in this session was to notice when one of the lights in the array turned yellow, determine whether it was on the left half of the array or on the right half of the array, and then to pull a response paddle on the corresponding side of the steering wheel. Lights turned yellow when the drivers' vehicle was 24m, 36m, 48m, or 60m away from the light array at the 3rd (1.21m), the 6th (3.02m), or 9th (4.83m) light position from the center. Feedback on the light detection task was given by activating a high-tone sound (indicating a correct response); no feedback was given for incorrect responses. If the drivers failed to make a response before passing the light array, then a neutral sound was activated as a reminder. The first training session ended after one minute of task performance. In all sessions with the light detection task, if participants failed to respond, or gave the incorrect response, to four lights, then they repeated the session.

The second training session familiarized participants with the simulated vehicle dynamics and car-following task. Prior to the session, participants were told that they did not need to respond to the lights. Participants were told that their task in this session was to use the acceleration and brake pedals to control their speed with the goal of maintaining the same following distance from the lead car that they saw during the first stage of the simulator session. For the second and third training session, the velocity of the lead vehicle was determined by one sine wave function with a frequency of 0.083 and amplitude of 3.889 kph. If participants' headway distance exceeded 27.3 meters, then a horn sound was activated to simulate an impatient driver behind the drivers' vehicle and to encourage the drivers to attend to the speed variation of the lead vehicle. The second training session ended after one minute of task performance. If participants had a headway distance of 27.3m or greater for 15 seconds or if their headway distance was less than 2.35m, then the participant repeated the session.

The third training session, and all subsequent sessions, required participants to complete the light detection task at the same time as the driving task and terminated after one minute of task performance. In the fourth training session, the lead vehicles' speed was determined

using the low workload sum-of-sines function and terminated after one minute of task performance. In the fifth training session, the lead vehicles' speed was determined using the high workload sum of sines function. Once a participant passed all 24 light arrays, the session was complete.

The remaining four sessions were experimental sessions. In each experimental session, the drivers performed both the car-following task and the light detection task. Participants were instructed to perform both tasks equally well. Participants were allowed a brief break after each session. The variability of the lead vehicle's speed was ABBA counterbalanced between sessions and the identity of A and B were counterbalanced between participants. Each session contained three trials. Each trial consisted of 24 light arrays each, with each unique combination of simulated target depth and horizontal position and side (left/right) presented in random order. Each trial lasted for approximately 65 seconds and the duration of the whole experiment, including breaks, was approximately 60 minutes.

2.1.4 Design—The independent variables in this experiment were: simulated target depth relative to the driver (24m, 36m, 48m, or 60m), simulated target horizontal position relative to the driver (4.83m, 3.02m, or 1.21m), variability of the lead vehicles' speed (range: ± 14.30 or ± 31.50 kph), and participant age group. Participants 65 years and older were assigned to the older driver group. All other participants were assigned to the younger driver group.

2.2 Results

All the analyses presented here used the R statistical program (R Development Core Team, 2011). ANOVAs examining performance differences between conditions were calculated using the ezANOVA function of the ez package (Lawrence, 2011). For ANOVA analyses involving more than two levels of a within subject variable, we reported Greenhouse-Geisser corrected *p* values and the original degrees of freedom. The linear mixed effects regression model was calculated using the lmer function of the lme4 package (Bates, Maechler, & Bolker, 2012). In order to estimate *p*-values from an 10,000 run Markov chain Monte Carlo analysis, significance testing of individual parameters was performed on models without correlated random effects (Baayen, Davidson, & Bates, 2008). All light change RTs and accuracy results are collapsed over the left and right positions.

During the experiment, each participant had the opportunity to respond to 288 light changes. A visual examination of the results showed that if participants responded within 300 milliseconds(ms) of a light change, then their performance was near chance ($N = 103$ responses; M accuracy = 43.69%). Therefore, responses within 300ms of a light change were excluded from analysis. This criterion excluded no more than 5% of trials for any given participant. To eliminate an upward bias in RT as a result of the minimum RT criterion, responses more than 2100ms after a light change were also eliminated from analysis ($N = 112$ responses). This criterion excluded no more than 4% of trials for any given participant. In analyses of RT or accuracy, trials in which participants failed to respond were removed from analysis ($N = 118$). This criterion excluded no more than 5% of trials for any given participant. In analyses of RT, trials in which participants gave the incorrect answer were removed from analysis ($N = 273$). This criterion excluded no more

than 6.5% of trials for any given participant. In combination, these criteria eliminated no more than 5.01% of light change data from any analysis and no more than 10.07% for any given participant. All reported significant results were unaffected by the inclusion or exclusion of any of the aforementioned trials. In order to more accurately reflect RT that is associated with the task (and not a fast guess or a delayed response) we report results in which these outliers in the data have been removed. To confirm that the workload manipulation was successful we examined root mean square error (RMSE) of the participants' velocity relative to velocity of the lead car in an Age x Workload mixed ANOVA. Statistical analyses demonstrated separate main effects of age, $F(1, 39) = 5.58$, $p = .02$, and of workload, $F(1, 39) = 447.48$, $p < .001$. In regards to the effect of age, older drivers had greater error in velocity control ($M = 7.95$; $SD = 2.64$) than did younger drivers ($M = 6.87$; $SD = 2.50$). In regards to the effect of workload, drivers has greater error in velocity control in the high workload condition ($M = 9.18$; $SD = 2.06$) than in the low workload condition ($M = 5.62$; $SD = 1.79$). There was no interaction between these factors, $p = .89$, suggesting that the workload manipulation affected younger and older adults to a similar extent. See Table 1 for mean RMS error in velocity for the car following task by cell of the design.

We conducted an Age x Light Distance x Light Position x Workload mixed ANOVA for reaction time (RT) on the light detection task. There was a non-reliable trend for an interaction between age and workload, $F(1, 40) = 3.82$, $p = .06$. Specifically, a paired samples t-test of older drivers' responses showed slower responses in high ($M = 823.29$, $SD = 294.53$) as compared to low workload condition ($M = 801.86$, $SD = 268.16$), $t(21) = 3.16$, $p = .005$, but there was a reliable difference between high ($M = 757.38$, $SD = 300.28$) and low ($M = 759.51$, $SD = 295.08$) workload for younger adults, $p = .81$. Workload did not interact with any other factors, all $ps > .44$. There was an interaction between age, light distance, and light position on RT, $F(6, 240) = 3.04$, $p = .01$ (see Figure 3 for a graphical depiction of the main effects and interaction). Simple effects analyses split by age revealed that the differences in RT between light positions increased as light distance increased for younger drivers, $F(6, 114) = 8.02$, $p < .001$. However, there was no interaction for these factors among older drivers, $p = .24$. See Table 2 for RT cell means by design conditions.

We also conducted an Age x Light Distance x Light Position x Workload mixed ANOVA for accuracy on the light detection task. There was a main effect of light distance, $F(3, 120) = 30.20$, $p < .001$, no other main effects or interactions reached conventional levels of significance, all $ps > .09$. Bonferroni corrected paired t-tests indicated that accuracy was significantly lower at a distance of 24m ($M = 95.19\%$) compared to 36m ($M = 98.69\%$), 48m ($M = 99.43\%$), and 60m ($M = 99.42\%$), all $ps < .001$; all other comparisons were not significant, $ps > .09$.

Before interpreting these results with regard to 3D spatial attention, one must eliminate two plausible alternative explanations. First, one must eliminate the explanation that drivers' faster responses to targets near the lead vehicle are a consequence of changes in the 2D projected size (i.e., spatial extent) of the target resulting from changes in 3D simulated distance. Second, one must eliminate the explanation that drivers' faster responses to targets near the lead vehicle are a consequence of speed accuracy trade-offs. To test these

alternative explanations, a linear mixed effects regression model was calculated with simulated distance to the light, 2D projected size, and drivers' proportion of correct responses for any given position in depth as predictors of RTs to light change targets. In addition, random effects for subject and subject effects for each within-subjects variable were estimated. Our model structure was as follows:

$$\begin{aligned} \text{Level 1: Response Level} \\ Y_{ij} &= \beta_{0j} + \beta_{1j}(\text{Distance}) + \beta_{2j}(\text{Projected Size}) + \beta_{3j}(\text{Percentage Correct}) \\ \text{Level 2: Participant Level} \\ \text{Random Intercept: } \beta_0 &= \gamma_{00} + u_{0j} \\ \text{Random effect of Distance: } \beta_{1j} &= \beta_{1j} + u_{1j} \\ \text{Random effect of Projected Size: } \beta_{2j} &= \beta_{2j} + u_{2j} \\ \text{Random effect of Percentage Correct: } \beta_{3j} &= \beta_{3j} + u_{3j} \end{aligned}$$

The fixed effect results of this model are available in Table 3 and the random effects of this model are available in Table 4. The effect of simulated distance remained significant, $p = .0001$, after controlling for percentage correct and 2D projected size. Therefore, it is unlikely that the increase in target detection RT associated with simulated distance is due to differences in projected 2D size or speed-accuracy tradeoffs.

3. Experiment 2

Statistical controls for size in Experiment 1 and in Andersen et al. (2011) demonstrate that it is unlikely that drivers' shorter RT to targets close in depth are a consequence of changes in 2D projected size resulting from changes in 3D simulated distance. However, it may be reasonably argued that the statistical controls provided are insufficient because 2D projected size in those analysis are confounded with horizontal position and have limited variability at any given position in depth. Moreover, although a logical argument has been presented as to why 2D position cannot predict faster RTs for targets closer in depth, there has been no statistical or experimental control for the effect of 2D position on performance. In this experiment, we provided a direct control for the effects of projected size and position on light detection RT to eliminate alternative explanations for any 3D attentional effects. If the effects measured in these experiments reflect the effect of a 3D attentional mechanism then the RT to lights simulated as being nearer the driver should be faster than those simulated being further from the driver even if the projected 2D position and size are identical.

The design of Experiment 2 was similar to Experiment 1 with the following exceptions. First, a single level of workload (an intermediate level between the high and low workload conditions of Experiment 1) was examined. Second, we manipulated the simulated 3D size of the light change targets along with their simulated height between blocks. This allowed light change targets to occur at different simulated distances, but at exactly the same 2D position in the scene and with the same projected size. If depth affects the allocation of attention, then responses to light change targets nearer the focus of attention should be faster than those that are further even if they have identical projected 2D positions and sizes.

3.1 Methods

3.1.1 Drivers—Participants 65 years and older were assigned to the older driver group. All other participants were assigned to the younger driver group. The younger drivers were 24 college students, 11 male and 13 female, ($M = 21.75$ years; $SD = 1.03$ years; range 19 - 24 years) and 24 older drivers, 12 male and 12 female ($M = 73.50$ years; $SD = 4.48$ years; range 66 - 83 years) who were paid for their participation. All drivers had normal or corrected-to-normal vision and were naïve to the purpose of the study.

3.1.2 Driving Simulator—Except as otherwise noted, the driving simulator used in Experiment 2 was the same as in Experiment 1. We updated the computer being used to a Dell Vostro desktop computer. This allowed the driver resolution to match the LCD native resolution of 1280×1024 pixels, the controls and the rest of the simulation to update at 60 Hz, and for all light arrays within 1km to be displayed in the scene at the same time.

To accommodate variable light sizes and light array heights the layout of the scene was slightly altered. The simulated width of the three-lane one way road was 15.5m and the width of the light array was 13.2m. Each light array had a different random order of 11 red and green lights that had a small, medium, or large diameter (41.25mm, 61.88mm, 82.50mm). The simulated heights of the light array were matched to simulated light diameter to allow for equivalent 2D positions across 3D conditions (2.68m, 3.42m, and 4.16m). The amplitudes of the sine waves generating lead vehicle speed changes were intermediate, specifically, 15.56 kph, 6.22 kph, and 4.44 kph respectively.

Large lights viewed with a horizontal offset of 4.8m at a distance of 60m had the same projected size and position as medium lights viewed with an offset of 3.6m at a distance of 45m and small lights viewed with an offset of 2.4m at a distance of 30m (see Figure 4 for an illustration). In addition, large lights viewed with an offset of 2.4m at a distance of 60m had the same projected size and position as small lights viewed with an offset of 1.2m at a distance of 30m.

3.1.3 Procedure—Except where otherwise noted, the procedure used in Experiment 2 was the same as in Experiment 1. Participants completed only four training sessions, with the fourth training session using the same amplitude sine waves as in the main experiment, and completed two experimental sessions of nine trials each. The size of the lights was ABCCBA counterbalanced between trials and the value of A, B, and C were counterbalanced between participants. Lights turned yellow when the drivers' vehicle was 30m, 45m, or 60m away from the light array at the 1st (1.2m), 2nd (2.4m), 3rd (3.6m), or 4th (4.8m) light position from the center. Simulated light size and matched simulated light height were manipulated across between blocks.

3.2 Results

During the experiment, each driver had the opportunity to respond to 432 light changes, 144 light changes per light size. However, the RTs to light changes analyzed in this experiment only include the 60 lights for each driver that had the same 2D projected sizes and positions as other lights, but were at different simulated depths. A visual examination of

driver accuracy in response to all light changes showed that if participants responded within 300ms of a light change, then their performance was near chance (M accuracy = 51.01%). For this reason, responses that occurred in less than 300ms after a light change were excluded from analysis. This criterion excluded no more than 3.33% of trials for any given participant. To minimize an upward bias in RT as a result of the minimum RT criterion, responses more than 2100ms after a light change were also eliminated from analysis. This criterion excluded no more than 3.33% of trials for any given participant. Trials in which participants failed to respond were removed from analysis. This criterion excluded no more than 3.33% of trials for any given participant. In the remaining trials, the error rate was below 1%, so accuracy analyses were not performed. In analyses of RT, trials in which participants gave the incorrect answer were removed from analysis. This criterion excluded no more than 8.33% of trials for any given participant. In combination, these criteria eliminated no more than 1.91% of light change data from any analysis and no more than 8.33% for any given driver. All reported significant results were unaffected by the inclusion or exclusion of any of the aforementioned trials. Similar to the result of Experiment 1 we report results in which these outliers in the data have been removed.

The RTs to light changes analyzed in this control experiment only included lights that have identical 2D projections and positions, but that are at different simulated depths. This approach yielded two control conditions. The first control condition included large lights viewed with an offset of 4.8 m at a distance of 60 m ($M = 805$ ms; $SD = 281$ ms), medium lights viewed with an offset of 3.6 m at a distance of 45 m ($M = 715$ ms; $SD = 249$ ms), and small lights viewed with an offset of 2.4 m at a distance of 30 m ($M = 640$ ms; $SD = 180$ ms). We employed a mixed ANOVA to compare the RTs of younger and older drivers across these positions. We found that there were differences between RTs as a function of simulated depth, $F(2,92) = 94.03$, $p < .001$, and between younger ($M = 641$ ms; $SD = 207$ ms) and older drivers ($M = 800$ ms; $SD = 264$ ms), $F(1, 46) = 45.04$, $p < .001$, but there was no interaction between these factors, $p = .39$ (see the first panel of Figure 5 for a plot of the relevant cell means).

The second control condition included for small lights viewed with an offset of 1.2 m at a distance of 30 m ($M = 650$ ms; $SD = 175$ ms) and large lights viewed with an offset of 2.4 m at a distance of 60 m ($M = 762$ ms, $SD = 268$ ms). There was no intermediate light position at a distance of 45 meters because this would correspond with a light offset of 1.8 meters at which lights at no other position and depth would provide a perfect correspondence in terms of 2D projection and position. We found that there were differences between RTs as a function of simulated depth, $F(1, 46) = 72.09$, $p < .001$, and between younger ($M = 615$ ms; $SD = 181$ ms) and older drivers ($M = 800$ ms; $SD = 243$ ms), $F(1, 46) = 91.05$, $p < .001$, but there was no interaction between these factors, $p = .22$ (see the second panel of Figure 5 for a plot of the relevant cell means). See Table 5 for a combined summary of these results.

4. Discussion

A 2D model of spatial attention would predict two patterns that were not observed in the current results. First, it would predict that RTs to targets near in depth would be the same as targets located further in depth when located at the same 2D position. Second, because

perspective causes targets distant in depth to be projected in 2D with little spatial separation to the center of the display, a 2D model of spatial attention would predict that 3D horizontal light position should have a decreased effect on performance for far targets than for near targets. However, the data from Experiment 1 demonstrated the opposite pattern for younger and older adults. In addition, the results from Experiment 2 used an experimental control to demonstrate that drivers respond faster to nearer light change targets than farther light change targets even when they have identical projected 2D positions and sizes. Therefore, we conclude that for both younger and older drivers spatial attention during a driving task is affected by depth and horizontal position. It is notable that, even though older drivers have more experience than younger drivers do, the effect of distance was virtually the same for both age groups. This suggests that although it is true that older drivers have more experience it does not affect the ability to attend to targets located at different distances during driving.

The extent of 3D attention for older drivers was different than the extent of 3D attention for younger drivers. For younger drivers RT varied as a function of light position and distance whereas for older drivers RT varied only a function of distance. That is, for older drivers, the extent of spatial attention along the 3D horizontal dimension was constant across various depths. Furthermore, the extent of spatial attention along the depth dimension may be somewhat less for older drivers as they responded to targets, at nearly all light positions and distances, more slowly than younger drivers. Specifically, the results from Experiment 1 indicate that the extent of spatial attention for young drivers is broad near the vehicle and reduces in horizontal extent with increased depth (i.e., among younger drivers the extent of attention differs as a function of depth).

Previous experiments that had failed to identify age-related differences in the extent of 3D attention focused on differences only along the depth axis (Atchley & Kramer, 1998, 2000). In the current experiments we also found no statistically reliable age-related differences in the gradient of attention along the depth axis. However, we did find age-related differences in the gradient of attention across the horizontal axis as a function of depth. Thus, our results are consistent with previous research on 3D attention and aging but indicate an age-related effect of horizontal position that varied with distance.

Consistent with previous results (Andersen et al., 2011), the effects of lead car speed variability on drivers' RT did not vary as a function of spatial position. This suggests that variability of lead car speed did not produce a change in the shape of visual spatial attention, and only produced general interference. One possibility, consistent with the 2D theory of attention proposed by LaBerge and Brown (1989) is that the limits of 3D attention are primarily associated with non-spatially specific processing limits of later stages of information processing. If this hypothesis is correct, then workload should only produce general interference for drivers. However, the present research does not definitively show that variability of lead car speed does increase drivers' use of a focused attention strategy and speed stress. Therefore, although we have demonstrated that variability of lead car speed only produces generalized interference, we are unable to determine the specific underlying cause.

Finally, the majority of previous research on 3D visual-spatial attention has employed binocular disparity as primary source of depth information (Andersen, 1990; Andersen & Kramer, 1993; Atchley & Kramer, 2000; Atchley et al., 1997). Like Experiment 1, experiments using other sources of depth information did not experimentally control for 2D factors such as size or position (Andersen et al., 2011; Downing & Pinker, 1985). However, Experiment 2 controlled both the 2D projected size and position of the light change and found that visual-spatial attention is allocated in depth. The results of these studies, considered together, demonstrate that 3D attention is not specific to a particular depth cue (e.g. Cutting & Vishton, 1995) and that 3D attention effects can be obtained from monocular depth information.

The results of the present study suggest that depth is a relevant dimension for visual spatial attention in younger and older drivers. Given that depth is an important dimension in driving performance, then an important issue for assessing driving safety is to consider the limits of attention in the depth dimensions. Notably, we demonstrated an effect of depth in the context of a driving simulator without using binocular disparity as a cue for depth. Therefore, existing driving simulator software and techniques can be used to examine the importance of depth in attentional allocation without additional stereoscopic hardware. Although we did not assess crash risk in these experiments previous research has suggested that visual spatial attention is relevant to crash risk. However, most existing measures of visual spatial attention do not directly assess the extent of attention in depth. Therefore, 2D measures of attention may not be predictive of the spatial extent of attention in depth. For this reason, we suggest that future researchers should consider the importance of depth as a dimension of spatial attention in relation to the assessment of driving relevant visual spatial attention.

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Highlights

The effects of depth on attention are demonstrated in a simulation with only pictorial sources of information for depth

Depth is a relevant dimension for visual spatial attention in younger and older drivers

The effects of depth on attention are independent of projected size and position

There are age-related differences in the gradient of attention across the horizontal axis as a function of depth

Figure 1.
An example of the driving scene used in the present study.

Figure 2.
Speed profile as a function of trial duration for a single trial.

Figure 3.
Effects of age, light distance, and light position on RT.

Figure 4.

A semi-transparent overlay of two light distance conditions to illustrate the conditions examined in Experiment 2. Specifically a) an array of large green lights at a simulated distance of 60m and simulated height of 4.16m and b) an array of small red lights at a simulated distance of 30m and simulated height of 2.68m. The lights that appear yellow in the online color plate are exactly matched across conditions in terms of projected 2D size and position.

Figure 5.

Effects of simulated distance on RT experimentally controlling for projected 2D size and position.

Table 1

Mean RMS Error for Car-following Velocity (in kph), Standard Deviations in Parentheses

Workload	Age	
	Younger Drivers ($M = 23.74$ years; $N = 20$)	Older Drivers ($M = 75.36$ years; $N = 22$)
Low (Average $SD = 7.62$)	5.11 (1.43)	6.16 (1.97)
High (Average $SD = 16.80$)	8.64 (2.06)	9.74 (1.92)

Table 2
Average and SD RT(in ms) for Trials Included in RT Analyses for Experiment 1

Age Group	Workload	Horizontal Distance	Distance in Depth			
			24m	36m	48m	60m
Younger	Low	1.21m	587.93 (155.63)	650.26 (203.38)	746.11 (269.03)	842.29 (300.82)
Younger	Low	3.02m	591.47 (155.28)	714.66 (253.59)	771.50 (266.66)	909.47 (347.67)
Younger	Low	4.83m	617.31 (163.89)	775.88 (246.96)	908.80 (350.39)	981.01 (365.35)
Younger	High	1.21m	575.69 (150.30)	658.67 (207.27)	773.75 (283.83)	821.32 (293.02)
Younger	High	3.02m	595.29 (184.45)	718.94 (275.00)	766.53 (283.58)	894.43 (353.26)
Younger	High	4.83m	618.14 (175.84)	761.59 (271.55)	887.23 (333.40)	998.20 (362.97)
Older	Low	1.21m	677.92 (164.72)	758.21 (209.78)	827.13 (280.40)	917.28 (297.23)
Older	Low	3.02m	666.46 (177.49)	733.81 (216.53)	849.12 (288.23)	930.88 (295.81)
Older	Low	4.83m	680.29 (178.21)	768.70 (234.63)	841.46 (282.50)	942.58 (309.13)
Older	High	1.21m	716.68 (217.04)	771.31 (231.58)	831.80 (271.02)	943.20 (351.77)
Older	High	3.02m	678.71 (232.62)	770.63 (272.02)	846.13 (292.02)	939.29 (323.69)
Older	High	4.83m	682.67 (179.46)	788.09 (271.06)	882.18 (281.80)	996.02 (342.03)

Note: The table provides the cell means and standard deviations for the younger ($M = 23.74$ years) and older ($M = 75.36$ years) age groups at low (average $SD = 7.62$ kph) and high (average $SD = 16.80$ kph) workload at each horizontal offset and distance. Values in parentheses are standard deviations within that cell of the design. All cells presented in this table represent between subjects means and do not reflect the within subjects analyses performed for hypothesis testing.

Table 3

Fixed effects of the Multilevel Model

	Coefficient	Std. Error	t-value
Intercept	748.70	13.05	57.38
Distance in Depth (m)	7.41	0.82	9.01
Projected Size in degrees	−10.78	79.40	0.14
Proportion Correct	−9.56	86.33	0.11

Note. Condition number = 5.66. All predictor variables were mean centered on the overall mean of the individual data points, Distance ($M = 42.29$), Projected Size in degrees ($M = .148$), and Proportion Correct ($M = .98$).

Table 4

Random Effects Summary of the Multilevel Model

	1	2	3	4
1. Intercept	4425.68	253.33	14637.23	-3322.75
2. Distance in Depth (m)	1.00	14.50	837.85	-190.20
3. Projected Size in degrees	0.83	0.83	70347.27	-17618.03
4. Proportion Correct	-0.52	-0.52	-0.69	9338.44

Note: The variance and correlations for random effects table presented in this table provide variances provided on the diagonal, Tau above the diagonal, and Tau as correlations below the diagonal. σ^2 for this model was 54,310.20 on 8635 observations within 42 sampling units.

Table 5

Average and SD RT (in ms) for control conditions for Experiment 2

Age Group	Control Condition	Distance in Depth		
		30m	45m	60m
Younger	One	570.61 (137.08)	636.14 (195.18)	718.35 (246.34)
Older	One	712.45 (190.04)	794.70 (271.49)	893.88 (286.96)
Younger	Two	566.96 (133.07)	---	662.65 (207.82)
Older	Two	734.90 (171.45)	---	862.73 (283.13)

Note. The table provides the reaction time cell means and standard deviations in milliseconds for the younger ($M = 23.74$ years) and older ($M = 75.36$ years) age groups in the control conditions. Control condition one refers to large lights viewed with an offset of 4.8 m at a distance of 60 m, medium lights viewed with an offset of 3.6 m at a distance of 45 m, and small lights viewed with an offset of 2.4 m at a distance of 30 m. Control condition two refers to small lights viewed with an offset of 1.2 m at a distance of 30 m and large lights viewed with an offset of 2.4 m at a distance of 60 m; there is no corresponding light position matched in terms of 2D projection and position at a distance of 45 m. Values in parentheses are standard deviations within that cell of the design. All cells presented in this table represent between subjects means and do not reflect the within subjects analyses performed for hypothesis testing.