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Limits of spatial attention in three-dimensional space and dual-task driving performance

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ABSTRACT

The present study examined the limits of spatial attention while performing two driving relevant tasks that varied in depth. The first task was to maintain a fixed headway distance behind a lead vehicle that varied speed. The second task was to detect a light-change target in an array of lights located above the roadway. In Experiment 1 the light detection task required drivers to encode color and location. The results indicated that reaction time to detect a light-change target increased and accuracy decreased as a function of the horizontal location of the light-change target and as a function of the distance from the driver. In a second experiment the light change task was changed to a singleton search (detect the onset of a yellow light) and the workload of the car following task was systematically varied. The results of Experiment 2 indicated that RT increased as a function of task workload, the 2D position of the light-change target and the distance of the light-change target. A multiple regression analysis indicated that the effect of distance on light detection performance was not due to changes in the projected size of the light target. In Experiment 3 we found that the distance effect in detecting a light change could not be explained by the location of eye fixations. The results demonstrate that when drivers attend to a roadway scene attention is limited in three-dimensional space. These results have important implications for developing tests for assessing crash risk among drivers as well as the design of in vehicle technologies such as head-up displays.

Driving is a task that is highly dependent on vision (Hills, 1980; Evans, 2004). In order to avoid crashes and safely navigate drivers must perform a wide range of visual tasks including steering control (Wallis et al., 2007; Hildreth et al., 2000), collision detection (Andersen and Kim, 2001; Andersen et al., 1999; Ni and Andersen, 2008), braking (Rock et al., 2006; Fajen, 2005), and car following (Andersen and Sauer, 2007). Often drivers must perform several tasks within short time intervals (e.g., maintain a safe headway distance from a lead vehicle while montoring traffic signals). Previous research has shown that human observers have a limited ability to attend and process all information present within a visual scene. These studies have included research on visual search (Wolfe, 1994), spatial attention (Eriksen and Eriksen, 1974; LaBerge, 1983), and change blindness (Simons and Levin, 1997; Rensink, 2002). For most driving situations this limitation will not be problematic for safe driving. However when workload is high or when drivers are performing mulitple tasks this limitation may reduce driving safety. For example, a driver while attending to traffic might fail to see a pedestrian walk into the roadway.

Previous research on visual attention have used different methodologies to determine the spatial limits of attention. In the context of driving this limitation has been examined by measuring the spatial extent of attention while performing two tasks. This spatial extent, which has been referred to as the useful field of view or UFOV (Sekuler and Ball, 1986; Scialfa et al., 1987), has been measured when observers perform two tasks—identifying a centrally presented target (car or truck) and determining the location of a peripherally presented target. Performance on the UFOV has been shown to be a good predictor of accident risk among older drivers (Simms et al., 2000; Owsley et al., 1991; Owsley et al., 1998; see also Hoffman et al., 2005).

The concept of the UFOV is consistent with an extensive body of research demonstrating limitations in the 2D spatial extent of visual attention. For example, to assess the 2D spatial limits of attention studies have used a response compatiability paradigm in which subjects were presented with a central target and adjaent features or flankers. The subjects task was to respond to the central target. In the study by Eriksen and Eriksen (1974) the items were either characters composed of line segments (H and K) or characters composed of curved segments (S and C). If the center target was an H or K then the subjects responded with a button press by one hand whereas if the feature was an S or C then subjects responded with a button press by the other hand. The adjacent features, or flankers, could

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either be consistent with the response of the central feature (e.g., a central "S" with adjacent "C" characters) or inconsistent with the response of the central feature (e.g., a central "S" with adjacent "H" characters). Using this task previous research (Eriksen and Eriksen, 1974) manipulated the separation of the flankers and the central target to measure the 2D spatial extent of attention. The results indicated that flankers located outside a 1° region did not result in interference, suggesting that the 2D spatial extent of attention was approximately 1°. More recent research has shown that the spatial extent of attention is much larger than the 1° limit (LaBerge, 1983; LaBerge and Brown, 1989; Eriksen and St James, 1986). For example, LaBerge and Brown (1989) presented subjects with a precue that varied in size prior to the presentation of the target and flankers. The results indicated that when subjects attended the precue the spatial extent of attention could be as large as 8° visual angle. They concluded that the spatial extent of attention was not a fixed size but could vary depending on the task.

It is important to note that the UFOV is measured by requiring subjects to make responses to a 2D configuration of information on a computer screen. Thus, the size of the UFOV is defined in terms of visual angle. Any information that falls within the UFOV is processed whereas any information that falls outside of this region is not processed. Visual angle is a measure of 2D spatial extent and is not dependent on distance. For example, two objects can subtend the same visual angle but can be located at different distances. This suggests that for real world conditions that involve distance, such as driving, any information in the UFOV, regardless of distance, will be processed whereas any visual information that falls outside the 2D spatial extent of the UFOV will not be processed.

Previous research has also demonstrated that we have a limited ability to attend to information at greater distances (Andersen, 1990; Andersen and Kramer, 1993; Atchley and Kramer, 2001). In the original study by Andersen (1990) a response compatibility paradigm was used to measure the spatial extent of attention in 3D. Subjects were presented with horizontal and vertical bars presented in depth using binocular disparity. The depth separation between the flankers and the central target was varied. In Andersen and Kramer (1993) the 2D spatial separation in the horizontal and vertical directions were also varied. The results indicated that the interference of inconsistent flankers decreased as a function of the 2D spatial separation (a replication of Eriksen and Eriksen, 1974) as well as decreased as a function of the depth separation between the flankers and the target. Other studies using binocular disparity displays have found similar limits in 3D spatial attention (Andersen and Kramer, 1993; Atchley and Kramer, 2001). These results indicate that the spatial extent of attention is limited horizontally, vertically, and in depth.

The construct of the UFOV and laboaratory experiments on the 3D spatial extent of attention suggest different limitations on attention during driving. According to the description of the UFOV, spatial attention is not limited along the depth axis. However, research on 3D attention suggests that the spatial extent of attention along the depth axis is limited. Research relating UFOV and driving have shown that UFOV performance is predictive of crash risk among older drivers—suggesting that limits in the 2D spatial extent of attention are predictive of crash risk. Research on 3D spatial attention has not examined performance limitations during driving. In addition, all 3D spatial attention studies have used binocular information to present depth. This represents a problem in relating these limits to driving because binocular disparity is effective up to distances of approximately 10 m (Cutting and Vishton, 1995) and driving often involves responding to information at distances much greater than 10 m (e.g., reading roadway signs or identifying an upcoming freeway exit). This suggests that driving is likely to be dependent on other sources of depth information such as motion and pictorial cues (texture, shading, relative size, etc.) which are effective at distances well beyond 10 m (for a detailed comparison of the effectiveness of different depth cues as a function of distance see Cutting and Vishton, 1995).

An important difference between the UFOV research and the research on 3D spatial attention concerns the tasks examined. The UFOV is measured by requiring subjects to perform an object identification of a centrally located target while indicating the location of a peripherally presented target. Thus subjects are performing two tasks. Studies examining 3D spatial attention have used a single task in which spatial attention is measured using interference produced by differences in response compatability. In an attempt to match the dual task requirements of the UFOV assessment we required subjects to perform two driving relevant tasks. The first task was a car following task in which subjects were required to vary speed in a simulator to maintain a fixed driving distance behind a lead vehicle (Andersen and Sauer, 2007). The lead vehicle was always located in the center of the display (see Fig. 1).

While performing the car following task the driver's vehicle would pass under a series of light arrays located above the roadway and at equal intervals along the roadway. The second task was to detect a color change in a light located on the light array (see Fig. 1). In the first experiment a single light changed from red to green or from green to red. This is a particularly demanding task as it requires the driver to encode both location and color information. We systematically varied the distance of the light-change target to measure the effects of distance on spatial attention. In addition, we systematically varied the horizontal position of the light-change target to measure the 2D spatial extent of attention.

This driving scenario allows us to test different predictions regarding the spatial extent of attention. If the spatial extent of attention is only limited in two dimensions, as assumed with the UFOV test, then an increase in the distance of the lights should result in no change in performance. However, if the spatial extent of attention varies in three dimensions then we should see a decrease in performance in the light change task as a function of distance. In addition, Andersen (1990) proposed that the extent of 3D spatial attention was shaped like an asymmetric ellipsoidal region with the allocation of processing resources decreasing, in all three dimensions, from a centrally attended point in space. According to this theory the allocation of processing resources decrease as a function of distance and the horizontal and vertical extent of attention also decrease as a function of distance from the attended point. Now consider the primary (car following) and secondary (light change) tasks in the present study. The secondary task was designed in the

Fig. 1. Single frame of the driving simulation scene. Drivers were required to maintain a fixed distance from a lead vehicle (in the center of the display) and detect a light change in the array of lights located above the roadway.

simulation to always be located at a greater distance than the primary task. Assume that all targets that a driver can process will fall within the ellipsoidal region of 3D spatial attention. If the theory of 3D attention proposed by Andersen (1990) is correct then the processing resources in the horizontal and vertical dimension will decrease with an increase in distance from the primary task. As a result this theory predicts that the effects of the projected horizontal position of light-change targets will increase as a function of distance.

In summary, the purpose of the present study was three-fold. First, to determine whether spatial attention is limited along the depth axis while performing driving relevant tasks. Second, to determine whether the spatial extent of attention varies as a function of distance when depth information is specified by motion and pictoral cues. Previous research has shown that an increase in workload of a central task can result in decreased performance of a second task (Williams, 1982, 1989). Thus, a third purpose was to determine whether variations in the workload results in differential changes in the spatial extent of 2D and 3D attention.

An important factor that may affect light detection performance is that changes in distance result in changes in the projected size of the light. Thus, any performance differences due to distance might be the result of differences in the projected size of the light. To address this issue we used a multiple regression analysis to assess the independent contribution of projected size and simulated distance on driver performance in the light detection task.

1. Experiment 1

1.1. Methods

1.1.1. Drivers

The drivers were 6 college age students (3 women and 3 men; mean age of 20.2; standard deviation (SD) of 1.77) at the University of California, Riverside who were paid for their participation. All drivers had a minimum of 2 years of driving experience, had normal or corrected to normal vision, were prescreened for color blindness, and were naïve with regard to the purpose of the experiment.

1.1.2. Design

The independent variables were the simulated distance of the light when a change occurred (24, 36, 48, and 60 m), the horizontal position of the light when a change occurred (3, 6 or 9 position), and the side of the light-change target (left or right). All variables were run as within-subject variables.

1.1.3. Apparatus

The displays were presented on a Dell PC computer system. The visual angle of the displays was 42.7° (horizontal dimension) by 24.5° (vertical dimension), with the refresh rate of 60 Hz and the resolution of 1280 × 1024. A Thrustmaster Formula T2 control system, including acceleration and brake pedals, was used for closed loop control of the simulator. The foot pedal and a BG systems serial box were used to produce closed loop control that was updated at 60 Hz. Drivers viewed the displays binocularly through a large glass plano-convex collimation lens (to reduce the effects of accommodation) at a distance of approximately 60 cm from the screen.

1.1.4. Stimuli

The displays depicted a roadway scene of city blocks (see Fig. 1). The roadway consisted of a black and white gravel texture pattern to simulate asphalt. Dashed white lines were presented on the roadway to indicate the traffic lanes. The city buildings were produced by digitally photographing real buildings and using the digital images as texture maps for the roadway scenes. The driving scene also contained four vehicles located in adjacent lanes. The speed of the adjacent vehicles matched the average speed of the LV but varied according to a sum-of-sine wave function. This resulted in a simulation in which the adjacent vehicles appeared to be driving at a speed similar to the lead vehicle but which appeared to be independent. Lane width was 3.8 m.

At the beginning of each trial (for a 5 s period) the LV (lead vehicle located in front of the driver) speed was constant with a fixed headway of 18 m. Drivers were presented the constant speed and distance to establish a perception of the desired headway to be maintained. After 5 s the LV varied its speed according to a complex sine wave. The complex waveform was the sum of 3 equal-energy sinusoids (i.e. the peak accelerations and decelerations of each sine wave in the signal were equivalent). The three frequencies used were .033, .083, and .117 Hz. The corresponding amplitudes for these sinusoids were: 9.722, 3.889, and 2.778 kph. The three sinusoids were out of phase with one another. The initial phases of the high and middle frequency sinusoids were randomly determined with the phase value of the low frequency sinusoid selected to produce a sum on the first frame of zero. This ensured that the beginning of the speed variation of the lead vehicle (following the 5 s of constant speed) would always be 40 kph, yet the velocity profile of the lead car would vary from trial to trial.

Located above the roadway was a series of horizontal arrays. Each array consisting of 21 red and green lights (a light located directly above the driver and positioned in the horizontal midpoint in the display with 10 lights located to the left and 10 lights located to the right of the central position). The light arrays were positioned at 110 m intervals along the roadway. As the driver approached the lights a single light would change color (either red to green or green to red). The light-change target occurred at the 3, 6 or 9th position from the center of the array on either the left or right side. The visual angles of the location of the light-change target, relative to the center of the array, varied as a function of distance. For the 24 m distance condition the location of the light-change target (relative to the horizontal center of the display) was ±4.3°, 8.5°, or 12.7° visual angle from the center. For the 36 m distance condition the location of the light-change target was ±2.86°, 5.7°, or 8.5° visual angle from the center. For the 48 m distance condition the location of the light-change target was ±2.1°, 4.3°, or 6.4° visual angle from the center. For the 60 m distance condition the location of the light-change target was ±1.7°, 3.4°, or 5.1° visual angle from the center. Thus light-change targets on arrays located at greater distances were positioned closer to the position of the lead vehicle and thus closer to the center of the display. When the light change occurred at the four different distances the light array was always the closest array relative to the driver (i.e., although several light arrays were visible to the driver there were no other light arrays between the driver and the array that contained a light change).

One potential problem is that drivers might ignore the car following task and primarily focus on the light detection task. To avoid this problem a horn was sounded (two short beeps) if the headway distance increased greater than 27 m. The horn was used to ensure that drivers maintained attention on the car following task and to simulate an impatient driver behind the driver in the study.

1.1.5. Procedure

Drivers were seated in the simulator and told to perform two tasks: maintain their initial separation from the lead vehicle by accelerating or decelerating in response to changes in lead vehicle speed and to detect, as soon as possible, whether a light-change target occurred on the left or right side. When a driver noticed the light-change target they responded by pressing a button on the right side of the steering wheel (to indicate the change was on the right side) or by pressing a button on the left side of the steering wheel (to indicate the change was on the left side). At the beginning of each trial run, participants were given 5 s of driving at a constant speed 18 m behind the constant speed lead vehicle to establish a perception of the desired headway distance to be maintained followed by 60 s of variations in lead vehicle speed according to the sum of sines function. Light-change events occurred on average every 10 ± 2 s to prevent drivers from anticipating the light-change target. Six light-change events occurred on every trial. 20 blocks of four trials were run over 2 days. Each block consisted of each combination of side of light change, position of light change, and distance of light change. Order of presentation of the light change target was randomized across blocks. Drivers were given a brief break after each block.

At the beginning of each session subjects were given 5 min of practice driving to familiarize themselves with the control characteristics of the accelerator and brake. Drivers were then presented with 2 trials in which forward motion was perturbed by a single sine wave (0.033 Hz with amplitude of 9.722 kph) to illustrate the displays. Once the drivers understood the task they were given two 60 s practice trials in which they responded to a single sine wave forcing function to familiarize the driver with the task.

2. Results

The mean reaction time (RT) and accuracy for the light change detection task is shown in Fig. 2. No significant differences were found ($p > .05$) for the left/right location of the light-change target for either accuracy or RT measures. As a result, all remaining analyses were collapsed across this variable. The mean accuracy and RT for each driver in each condition was calculated and analyzed in a 3 (horizontal position) by 4 (distance location) analysis of variance (ANOVA). With regard to accuracy, the main effect of light position was significant ($F(2,10) = 11.9$, MSE = 1.6, $\omega^2 = 0.11$, $p < .05$). Mean percent correct for the 3, 6 and 9 position conditions were 92.5% (SD = 4.5%), 91.4% (SD = 4.1%), and 84.5% (SD = 6.9%), respectively. Post hoc comparisons (Tukey HSD test) indicated significant differences ($p < .05$) between the 3 position and 9 position, and between the 6 position and the 9 position. These results indicate that accuracy decreased with more peripherally located targets. The main effect of array distance was also significant ($F(3,15) = 5.7$, MSE = 2.3, $\omega^2 = 0.18$, $p < .05$). Mean percent correct for the 24, 36, 48, and 60 m distance conditions were 91.5% (SD = 4.1%), 95.0% (SD = 3.1%), 89.5% (SD = 5.0%), and 81.9% (SD = 6.0%), respectively. Post hoc comparisons (Tukey HSD test) indicated significant differences ($p < .05$) between the 24 m and 60 m conditions and between the 36 m and 60 m conditions. These results indicate that accuracy decreased with an increase in distance. The two way interaction of position and distance was not significant ($F(6,30) < 1$, $p > .05$).

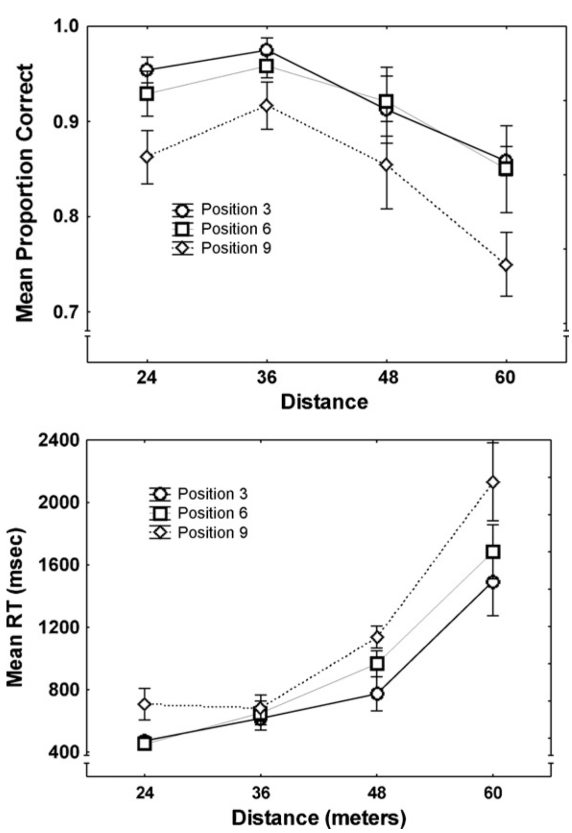

Fig. 2. Reaction time (top graph) and accuracy (bottom graph) as a function of light-change target position and distance. Error bars are ± 1 standard error. The results are from Experiment 1.

An ANOVA of RT performance indicated a similar pattern of results. The main effect of light position was significant, $F(2,10) = 13.7$, MSE = 96,966, $\omega^2 = 0.04$, $p < .05$, with greater RTs occurring for more peripheral light positions. Mean RT was 839 (SD = 393), 938 (SD = 475), and 1160 ms (SD = 393) for the 3, 6 and 9 light positions, respectively. Post hoc comparisons indicated significant differences ($p < .05$) between the 3 position and 9 position, and between the 6 position and the 9 position. The main effect of distance was significant, $F(3,15) = 33.6$, MSE = 329,747, $\omega^2 = 0.58$, $p < .05$. Mean RT was 543 (SD = 165), 649 (SD = 41), 959 (SD = 151), and 1770 ms (SD = 284) for the 24, 36, 48, and 60 m conditions. Post hoc comparisons indicated significant differences ($p < .05$) between the 24 m and 48 m conditions, the 24 m and 60 m conditions, the 36 m and 60 m conditions, and between the 48 m and 60 m conditions. These results indicate that RT increased as a function of distance. The two way interaction of position and distance was significant, $F(6,30) = 6.9$, MSE = 28,870, $\omega^2 = 0.02$, $p < .05$. According to this result (see Fig. 2), RT increased with more peripheral light locations, but the difference in RT between central and peripheral light locations was greater at far distances as compared to near distances.

Of course, one factor that might account for these results is the projected size of the target. As distance increased the projected size of the light decreased. Thus, the greater RT and lower accuracy, obtained with increased distance, may be due to the target light subtending a smaller visual angle. To determine the relative effects of target distance and target size we conducted a multiple regression analysis in which we used distance and projected size (based on the horizontal extent of the target) as predictors of mean RT and mean accuracy. A multiple regresion analysis allows us to examined the combined effects of both variables as well as the separate effects of each variable while controlling for the variance due to the other variable. Thus, we can examine the effects of projected size independent of distance and the effect of distance independent of projected size. With regard to the accuracy analysis, the multiple regression was significant $F(2,21) = 12.2$, $p < .01$, with an adjusted r^2 of 0.49. The effect of projected size was not significant, $t(21) = -1.90$, $p > .05$. The effect of distance was significant, $t(21) = -3.85$, $p < .01$. With regard to the RT analysis, the multiple regresssion was also signficant, $F(2,21) = 62.2$, with an adjusted r^2 of 0.84. The effect of projected size was not significant, $t(21) = 1.87$, $p > .05$. The effect of distance was signficant, $t(21) = 6.48$, $p < .01$. These results indicate that variations in RT and accuracy performance were based on the simulated distance and not the projected size of the target light.

3. Experiment 2

In the first experiment we found that the ability of drivers to detect a light-change target decreased as a function of distance in the roadway scene. The light detection task required drivers to detect a change in a red light to a green light or a green light to a red light in a field of red and green lights and thus required drivers to encode both color and location. This is a particularly difficult task as it requires subjects to encode the color at each location in the array in order to detect a change. In the second experiment we examined the spatial extent of attention when the task required drivers to detect the onset of a color. Drivers were presented with the same driving scenario examined in Experiment 1. However, for the light detection task drivers were required to detect the onset of a yellow light (i.e., a light in the array changed from red to yellow or from green to yellow). This is an easier light detection as the detection event is identified by a single source of information (the presence of a yellow light), does not require the driver to encode location information to detect a change (drivers only need to detect the onset of a yellow light and do not need to encode each color at each location in the array), and is a task that can occur in real world driving conditions.

In addition to the change in the light detection task we also examined the effects of workload on the primary task. As noted earlier, previous research has shown that an increase in workload of a central task can result in decreased performance of a second task (Williams, 1982, 1989). With regard to the UFOV, this finding suggests that as the difficulty of the primary central task is increased the UFOV will decrease in spatial extent resulting in poorer performance in responding to more peripherially located targets. The results of the first experiment indicated a decrease in performance in the light detection task as a function of distance and horizontal position. In the second experiment we examined whether an increase in workload of the central task (car following) would result in a decrease in the spatial extent of attention in the depth and horizontal dimensions. The car following task required drivers to maintain a following distance behind a lead vehicle when the velocity of the lead vehicle varied according a the sum of three sinusoids. To increase workload we increased the amplitude of the sinusoids by 50%. Of particular interest was whether an increase in workload would result in differential changes in the spatial extent of attention along the depth and horizontal dimension.

3.1. Methods

3.1.1. Drivers

The drivers were 20 college age students (9 women and 11 men; mean age of 20.8; SD = 1.63) at the University of California, Riverside who were paid for their participation.[1] All drivers had a minimum of 2 years of driving experience, had normal or corrected to normal vision, were prescreened for color blindness, and were naïve with regard to the purpose of the experiment. None of the drivers had participated in Experiment 1.

3.1.2. Design

The independent variables were the distance of the light when a change occurred (24, 36, 48, and 60 m), the horizontal position of the light when a change occurred (3, 6 or 9 position), the side of the light-change target (left or right), and the amplitudes of the sine waves in the forcing function (for the low workload condition the amplitudes for the three sine waves were 9.722, 3.889, and 2.778 kph; for the high workload condition the amplitudes were 14.583, 5.8335, and 4.167 kph). All variables were run as within-subject variables.

3.1.3. Apparatus

The apparatus was the same as that used in Experiment 1.

[1] We increased the sample size in Experiment 2 because of the addition of the workload variable in Experiment 3.

3.1.4. Stimuli

The stimuli were the same as that used in Experiment 1 with the following exceptions. The amplitudes for the three sine waves were 9.722, 3.889, and 2.778 kph for the low workload condition (the same task difficulty in Experiment 1) and 14.583, 5.8335, and 4.167 kph for the high workload condition. The desired headway distance was increased from 18 m (the headway distance in Experiment 1) to 20.5 m. This increase was necessary because the increased difficulty of the car following task under the high workload condition might increase the likelihood of a crash. At the beginning of each trial run, participants were given 5 s of driving at a constant speed (40 kph) 20.5 m behind the constant speed LV to establish a perception of the desired distance to be maintained. The light-change target that the driver was required to detect was a change from a red light to a yellow light or a green light to a yellow light.

3.1.5. Procedure

Drivers were seated in the simulator and told to perform two tasks: maintain their initial separation from the lead vehicle by accelerating or decelerating in response to changes in lead vehicle speed and to detect, as soon as possible, whether a yellow light appeared on the left or right side of the array. Similar to Experiment 1 drivers pressed a button on the right or left side of the steering wheel to indicate a right or left location response. At the beginning of each trial run, participants were given 5 s of driving at a constant speed 20.5 m behind the constant speed lead vehicle to establish a perception of the desired headway to be maintained followed by 60 s of variations in lead vehicle speed according to the sum of sines function. Light-change targets occurred on average every 10 ± 2 s to prevent drivers from anticipating the target. Six light change targets occurred on every trial. Drivers were given four blocks of 12 trials with six replications of each combination of side of light change, position of light change, distance of light change, and workload conditions presented in a random order.

Drivers were given a break between blocks. At the beginning of each session drivers were given 5 min of practice driving to familiarize themselves with the control characteristics of the accelerator and brake. Drivers were presented with 2 trials in which forward motion was perturbed by single sine waves to illustrate the displays. Once the drivers understood the task they were given two 60 s practice trials in which they responded to the single sine wave forcing function to familiarize the subject with the task and the control dynamics.

4. Results

4.1.1. Car following performance

To determine whether drivers had greater difficulty in car following performance we derived the average RMS error in maintaining headway distance for each driver for the low and high workload conditions and analyzed the performance in a two way ANOVA. The main effect of workload was significant, $F(1,24) = 167.5$, $MSE = 2.20$, $\omega^2 = 0.62$, $p < .05$. According to this result, greater RMS error occurred in the high (mean RMS error of 12.9 m, SD = 2.52) as compared to the low (mean RMS error of 6.8 m, SD = 1.39) workload conditions.

4.1.2. Light detection performance

No significant differences were found ($p > .05$) for the left/right location of the light-change target with accuracy and reaction time measures. As a result, all remaining analyses were collapsed across this variable. The mean accuracy for each subject in each condition was analyzed in a 2 (workload) by 3 (position) by 4 (location)

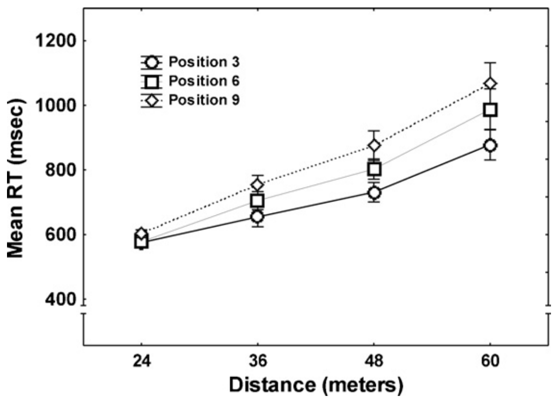

Fig. 3. Reaction time as a function of light-change target position and distance. Error bars are ±1 standard error. The results are from Experiment 2.

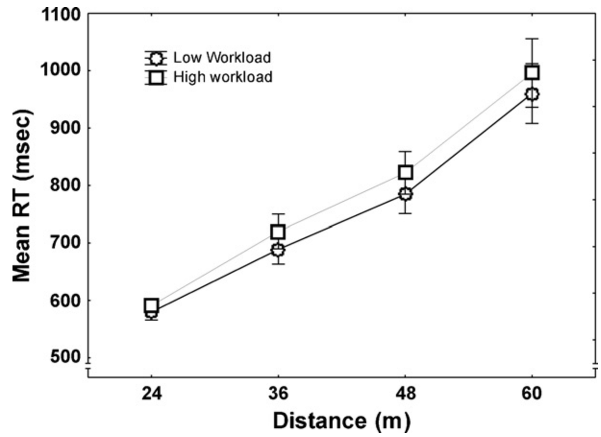

Fig. 5. Reaction time as a function of workload and target position. Error bars are ±1 standard error. The results are from Experiment 2.

ANOVA. There were no significant main effects or interactions, $p > .05$. Overall subjects were quite accurate in performing the light detection task with average accuracy of 98% (SD = 2.3%). For comparison purposes we have included the results for accuracy in Fig. 3.

The mean RT for each subject in each condition was analyzed in a 2 (workload) by 3 (position) by 4 (location) ANOVA. The main effect of workload was significant, $F(1,19) = 11.1$, MSE = 12381, $\omega^2 = 0.006$, $p < .05$. According to this result, greater RT occurred for the high (mean RT of 768 ms, SD = 174) as compared to low (mean RT of 726 ms, SD = 171) workload condition. The main effect of position was significant, $F(2,38) = 35.7$, MSE = 13216, $\omega^2 = 0.04$, $p < .05$. The mean RT for the 3, 6 and 9 position were 699 (SD = 148), 742 (SD = 178), and 799 ms (SD = 185). Post hoc comparisons (Tukey HSD test) indicated significant differences ($p < .05$) between all pairwise comparisons. The effects of position as a function of workload are presented in Fig. 4 for comparison purposes. As is shown in Fig. 4, RT increased as a function of position for both the low and high workload conditions. This result suggests that the increased RT for the high workload condition was similar at each light change position. The main effect of distance was significant, $F(3,57) = 113.0$, MSE = 48527, $\omega^2 = 0.36$, $p < .05$. The mean RT for the 24, 36, 48, and 60 m conditions were 585 (SD = 24), 681 (SD = 53), 778 (SD = 70), and 943 ms (SD = 97). Post hoc comparisons (Tukey HSD test) indicated significant differences ($p < .05$) between all pairwise comparisons. The effect of distance as a function of workload is presented in Fig. 5 for comparison purposes. As is shown in Fig. 5, RT increased as a function of distance for both the low and high workload conditions.

The two way interaction between distance and position was significant, $F(6,114) = 4.02$, MSE = 12291, $\omega^2 = 0.01$, $p < .05$ and is shown in Fig. 6. This result suggests that the increased RT, as a function of position, was greater at far distances than at near distances. There were no other significant interactions, $p > .05$.

To determine the relative effects of target distance and target size we conducted a multiple regression analysis in which we used distance and projected size (based on the horizontal extent of the target) as predictors of mean RT. The multiple regresssion was signficant, $F(2,21) = 65.5$, with an adjusted r^2 of 0.85. The effect of projected size was not significant, $t(21) = 1.08$, $p > .05$. The effect of distance was signficant, $t(21) = 3.99$, $p < .01$. These results indicate that RT was based on distance and not projected size.

5. Experiment 3

In the first and second experiment we found that the ability of drivers to detect a peripheral light-change target declined as a function of the distance to the target. This finding was found to be independent of the projected size of the target, suggesting that the result was due to a change in the allocation of attention as a function of distance. One alternative explanation for these results is that the effect observed in Experiments 1 and 2 might be due to where the driver was looking. As depicted in Fig. 1 the array of lights that were at a near distance from the driver were projected to more peripheral regions of the display relative to the lead vehicle. Light arrays that were at greater distances from the driver were projected to more central regions of the display relative to the lead vehicle. If the driver was scanning the upper regions of the driving scene when a light change occurred then the distance effect observed in Experi-

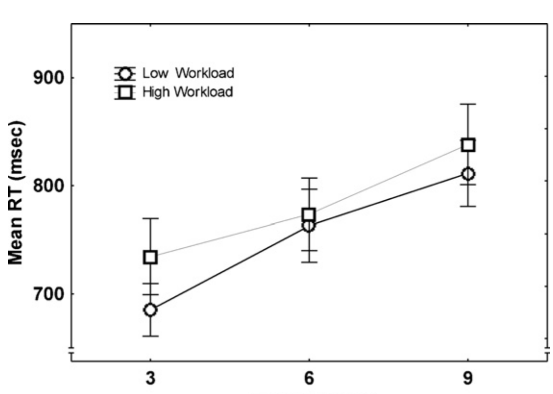

Fig. 4. Reaction time as a function of workload and target position. Error bars are ±1 standard error. The results are from Experiment 2.

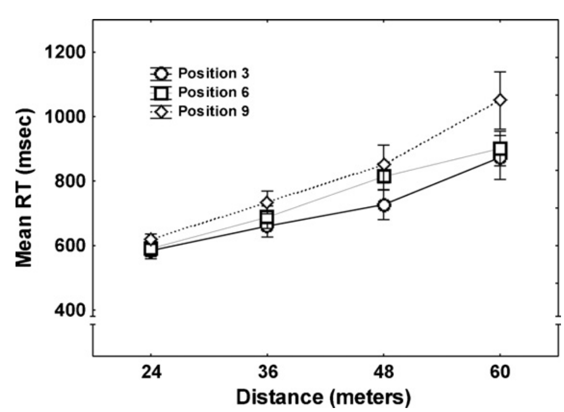

Fig. 6. Reaction time (top graph) and accuracy (bottom graph) as a function of light-change target position and distance. Error bars are ±1 standard error. The results are from Experiment 3.

ments 1 and 2 could be the result of the spatial separation between the eye fixation immediately prior to the light change and the projected location of the light. Specifically, if the light change occurred on a far distance array, near the central region of the display, and drivers were fixating the upper region of the visual field then the drivers eyes would not be fixated near where the light change was about to occur. As a result drivers may have required more time to initiate and complete an eye movement or saccade to the array to determine whether a light change occurred. Thus drivers may have required more time to detect a light change when the change was located at a far as compared to near distance array.

We tested this hypothesis by recording the location of eye fixation immediately before each light change occurred during the experiment. To quantify the data we calculated the standard deviation of eye fixations relative to the center of the lead vehicle. If drivers were fixating the surrounding peripheral regions of the driving scene when a light change occurred then we should find that the standard deviation of fixations should be large across all conditions regardless of the location of the light change. This would result in a benefit in detecting a light change when the change occurred at a near distance (because the light arrays were located in the peripheral regions of the display) and a cost in detecting a light change when the change occurred at a far distance (because the light arrays were located in more central regions of the display).

5.1. Methods

5.1.1. Drivers

The drivers were 10 college age students (5 women and 5 men, mean age of 20.3, SD = 1.9) at the University of California, Riverside who were paid for their participation. All drivers had a minimum of 2 years of driving experience, had normal or corrected to normal vision, were prescreened for color blindness, and were naïve to the purpose of the experiment. None of the drivers had participated in Experiment 1 or 2.

5.1.2. Design

The independent variables were the distance of the light when a change occurred (24, 36, 48, and 60 m), the horizontal position of the light when a change occurred (3, 6 or 9 position), the side of the light-change target (left or right), and the amplitudes of the sine waves in the forcing function (for the low workload condition the amplitudes for the three sine waves were 9.722, 3.889, and 2.778 kph; for the high workload condition the amplitudes were 14.583, 5.8335, and 4.167 kph). All variables were run as within-subject variables.

5.1.3. Apparatus

The apparatus was the same as that used in Experiments 1 and 2 with the following exception. An SR Research Eyelink II head mounted eye tracker was used to monitor eye fixations. Eye fixations were sampled at 500 Hz. The spatial resolution of the eye tracker was 0.2° visual angle.

5.1.4. Stimuli

The stimuli were the same as that used in Experiment 2.

5.1.5. Procedure

The procedure was the same as that used in Experiment 2 with the following exceptions. Drivers had the eye tracker mounted on their head at the beginning of the experiment and before instructions were read. A program was run to calibrate the eye tracker (the program required drivers to fixate targets at extreme and central locations of the display). The calibration was run at the beginning of each block of trials to eliminate any drift of the eye tracker during the experiment. Drivers were given four blocks of 12 trials with six replications of each combination of side of light change, position of light change, distance of light change, and workload conditions presented in a random order.

6. Results

6.1.1. Car following performance

To determine whether drivers had greater difficulty in car following performance we derived the average RMS error in maintaining headway distance for each driver for the low and high workload conditions and analyzed the performance in a two way ANOVA. The main effect of workload was significant, $F(1,9) = 110.6$, MSE = 1.04, $\omega^2 = 0.68$, $p < .05$. According to this result, greater RMS error occurred in the high (mean RMS error of 10.9 m, SD = 2.01) as compared to the low (mean RMS error of 5.4 m, SD = 0.76) workload conditions.[2]

6.1.2. Light detection performance

No significant differences were found ($p > .05$) for the left/right location of the light-change target with accuracy and reaction time measures. As a result, all remaining analyses were collapsed across this variable. The mean accuracy for each subject in each condition was analyzed in a 2 (workload) by 3 (position) by 4 (location) ANOVA. There were no significant main effects or interactions, $p > .05$. Overall subjects were quite accurate in performing the light detection task with average accuracy of 98% (SD = 2.1%).

The mean RT for each subject in each condition was analyzed in a 2 (workload) by 3 (position) by 4 (location) ANOVA. The main effect of workload was significant, $F(1,9) = 9.0$, MSE = 22636, $\omega^2 = 0.02$, $p < .05$. According to this result, greater RT occurred for the high (mean RT of 787 ms, SD = 155) as compared to low (mean RT of 728 ms, SD = 123) workload condition. The main effect of position was significant, $F(2,38) = 20.1$, MSE = 10776, $\omega^2 = 0.04$, $p < .05$. The mean RT for the 3, 6 and 9 positions were 711 (SD = 126), 748 (SD = 155), and 814 ms (SD = 143). Post hoc comparisons (Tukey HSD test) indicated significant differences ($p < .05$) between all pairwise comparisons. The main effect of distance was significant, $F(3,27) = 43.5$, MSE = 29701, $\omega^2 = 0.35$, $p < .05$. The mean RT for the 24, 36, 48, and 60 m conditions were 598 (SD = 26), 694 (SD = 34), 797 (SD = 70), and 941 ms (SD = 103). Post hoc comparisons (Tukey HSD test) indicated significant differences ($p < .05$) between all pairwise comparisons.

The two way interaction between distance and position was significant, $F(6,54) = 2.96$, MSE = 9080, $\omega^2 = 0.01$, $p < .05$ and is shown in Fig. 6. This interaction indicates that the increased RT as a function of position was greater at far distances than at near distances. There were no other significant interactions, $p > .05$.

To determine the relative effects of target distance and target size we conducted a multiple regression analysis in which we used distance and projected size (based on the horizontal extent of the target) as predictors of mean RT. The multiple regresssion was signficant, $F(2,21) = 77.5$, with an adjusted r^2 of 0.87. The effect of projected size was not significant, $t(21) = -0.80$, $p > .05$. The effect of distance was signficant, $t(21) = 2.43$, $p < .01$. These results indicate that driver RT was based on distance and not projected size.

[2] We conducted an analysis to compare the RMS error for drivers in Experiments 2 and 3. The results indicated that drivers in Experiment 3 had significantly lower error than drivers in Experiment 2, $F(1,28) = 6.3$, $p < .05$. An analysis comparing performance for RT was also conducted and revealed no statistically reliable difference in light detection performance for drivers in Experiments 2 and 3, $F(1,28) < 1$. In addition this variable did not interact with any other main effect or interaction.

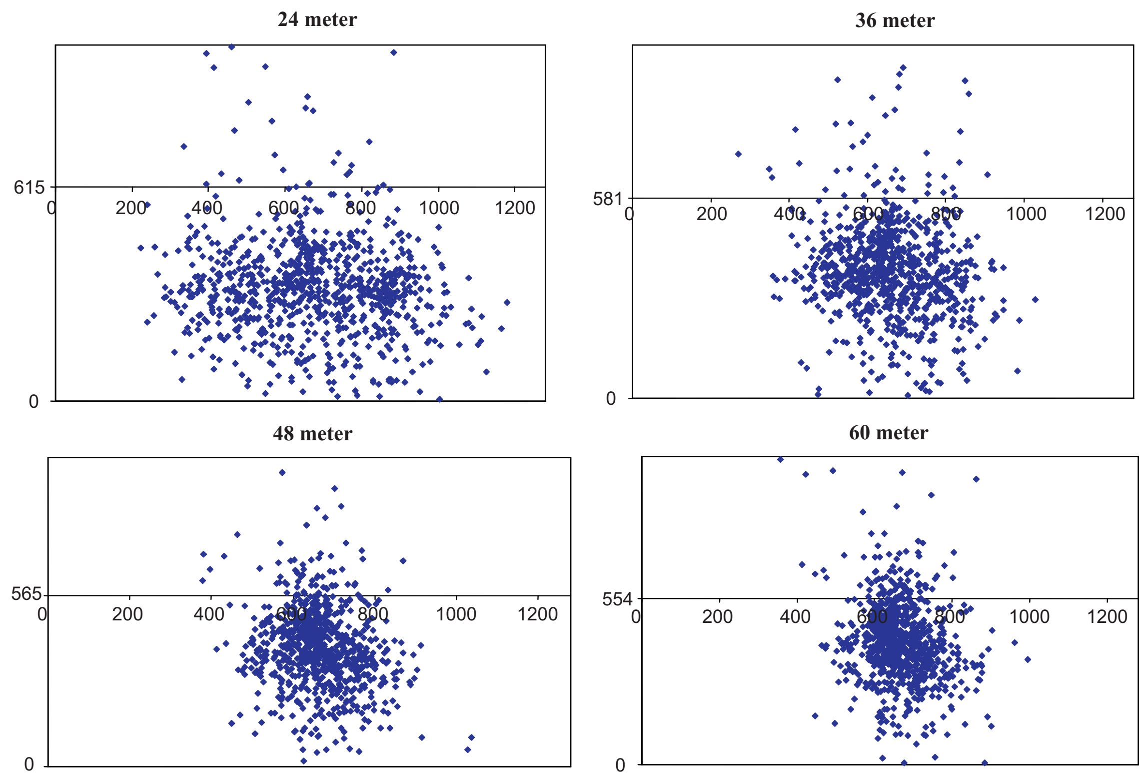

Fig. 7. Location of eye fixations immediately prior to a light change. The fixations are for all subjects for each light change and are presented in screen units (pixel position). Separate graphs are presented for each distance that a light change occurred.

6.1.3. Spatial distribution of eye fixations

The location of eye fixation immediately prior to a light change was recorded for each light change. The overall pattern of eye fixations immediately prior to the light change is presented in Fig. 7 and includes the eye fixations for all subjects. Separate graphs are presented for each distance condition. The spatial separations of the eye fixation from the center of the lead vehicle (in visual angle) were tabulated and used to derive the standard deviation of eye fixations centered on the lead vehicle. These standard deviations were calculated for each subject as a function of amplitude and distance of the light array and analyzed in a 2 (workload) by 4 (location) ANOVA. The results are shown in Fig. 8. The main effect of workload was significant, $F(1,9) = 31.8$, MSE = 0.64, $\omega^2 = 0.06$, $p < .05$. According to this result the spatial distriubtion of eye fixations was lower for the high as compared to low workload conditions. This result indicates that subjects narrowed their pattern of eye fixations when workload increased. The main effect of location was significant, $F(3,27) = 72.4$, MSE = 0.55, $\omega^2 = 0.44$, $p < .05$. As shown in Fig. 7, the spatial distribution of eye fixations decreased as a function of distance, with a more narrow spread of eye fixations for the far as compared to near light change condition. This pattern of results for the spatial distribution of eye fixations indicates that the increase in RT in detecting the light change, as a function of distance, was not due to a wider spatial distribution of eye fixations in the far as compared to near distance condition. To test the effects of location independent of eye fixations we conducated an ANCOVA using the standard deviation of eye fixations as a covariate measure. The main effect of location was significant, $F(3,24) = 12.1$, $p < .01$. This result provides further evidence that the effect of distance was not dependent on spatial distribution of eye fixations. The interaction of workload and location was not significant, $F(3,27) < 1$, $p > .05$.

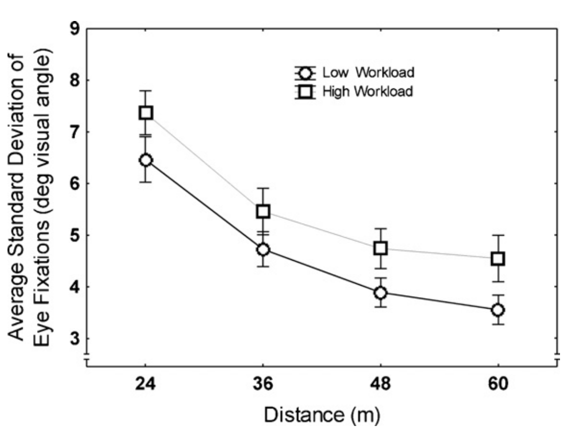

Fig. 8. Mean standard deviation of eye fixations (in visual angle) as a function of workload and distance of light change. Error bars are ±1 standard error. The results are from Experiment 3.

7. General discussion

The results of this research provide several important conclusions regarding driving and visual attention. The results of the present experiments indicate that the ability to detect a peripheral light-change target while performing a centrally located driving task declined as a function of horizontal position and distance in the driving scene. The decline in performance as a function of horizontal position is constent with the concept of a 2D spatial limitation of attention as assumed by the UFOV in which the ability to process information declines as a function of location in the visual field. However, the decline in performance as a function of distance is not consistent with the concept of the 2D spatial extent of of attention defined the UFOV. Indeed, more distant targets were located closer in the projection to the centrally located lead vehicle and, if the UFOV was correct, should have been processed more efficiently. These results are consisent with the theory that spatial attention in 3D scenes is optimal at a particular location in the 3D scene and declines with changes in the 3D location relative to the optimal position. In addition, the effect of the horizontal position of the light-change target increased as a function of distance for both experiments (see Figs. 2 and 3). These results, considered together, suggest that spatial attention during driving is an asymmetric 3D region in space (Andersen, 1990).

The results also indicate that the spatial extent of attention changed as a function of workload of a central task. We manipulated workload of the car following task by increasing the speed variation of the lead vehicle. The results indicated an overall increase in RT as a function of workload for the position of the target as well as the depth of the target. Thus, the present study did not find evidence of differential effects of workload on the spatial extent of attention in the horizontal and depth dimensions.

In Experiment 3 we examined whether the effects of distance on RT was due to the spatial distribution of eye fixations while performing the driving tasks. An analysis of eye fixations indicated that the distribution of fixations was much smaller immediately prior to light changes that subsequently occurred at a far distance as compared to a near distance. The light detection performance was similar to that observed in Experiment 2—RT decreased as a function of distance. Thus, the distance effect observed in Experiments 2 and 3 could not be due to the spatial distribution of eye fixations prior to the light change.

Previous research on 3D attention examined spatial attention when display durations were brief (to control for eye movements) and a flanker task was used. The present study found the same pattern of results when eye movements were not controlled and a dual task paradigm was used in which subjects had to continously monitor a centrally located task. Driving an automobile, as well as other closed loop control tasks such as flying an aircraft, requires the operator to constantly monitor a centrally located task as part of closed loop control (e.g., maintaining a constant glide slope while landing, Galanis et al., 1998). We would expect that the 3D spatial limits of attention obtained in the present study, which involved driving, would also occur in other operator control systems that involve monitoring a centrally located task while attending to information in a 3D scene.

The results of this research suggest an important if not unique aspect of visual processing. It has generally been assumed that when a driver is looking at a target information in the immediate vicinity of the target is processed and the driver can respond to the information present. Targets located in more peripheral regions in the retinal projection receive less processing and as a result the driver is less likely to respond or will respond with a delay. The results of the present study suggest that a driver can be looking or fixating a stimulus and an adjacent stimulus, located at a greater distance, may not be processed or may require additional time to process. This finding has important implications for the design of head up displays (HUDs) which are intended to optimize performance by presenting displays in an overlapped region of the visual field with the outside scene (Martin-Emerson and Wickens, 1997; Sojourner and Antin, 1990). Consider a HUD of a speedometer in a vehicle. By using collimation the optical focus of the driver is at an infinite distance allowing the driver to read the speedometer and monitor the roadway without a change in optical focus. This type of design assumes that minimizing eye movements between an indash speedometer and the outside view of the roadway will result in improved driving performance and increased safety.

The results of the present study suggest a potential serious limitation with HUD (head-up display) technology. Although the driving scene and the HUD symbology are in close 2D spatial proximity the driver might have considerable difficulty in processing both information sources if the information in the driving scene and the HUD symbology are preceived as being separated in depth. This might occur despite the use of collimation if there are scratches or dirt on the windscreen. An important issue for future research will be to examine the attentional limitations in the use of HUDs on tasks such as driving or flying an aircraft.

Recently there has been considerable interest in using UFOV tests to screen at risk drivers including screening drivers at department of motor vehicles when drivers renew or apply for a license (Ball et al., 2006). The proposal to use UFOV to screen at risk drivers is based on correlational studies examinining UFOV scores and accident rates for older drivers. On the one hand the results of the present study are consistent with the effects of limited spatial attention in the horizontal and vertical direction—a limitation of attention assessed by the UFOV. On the other hand, the UFOV test does not assess limits in spatial attention in depth. These effects are quite robust as indicated by the considerably greater increase in RT as a function of distance as compared to the 2D spatial extent (see Figs. 2, 3 and 5). An important goal of future research would be to consider the development of a test that assesses the 3D spatial limits of attention and to examine the relationship between limits of 3D spatial attention and crash risk.

The present study examined limits in spatial attention using two driving-relevant tasks (car following and light detection). The results show clear declines in performance for younger drivers when detecting events that occur at greater distances. A consistent finding from epidemiological studies on crash risk clearly indicate an increased risk of crashes among older drivers (Evans, 2004; Langford and Koppel, 2006). Research has also shown that limitations in the 2D spatial extent of attention, as assessed with the UFOV (Owsley et al., 1998), is a good predictor of crash risk among older drivers. The change in the UFOV with increased age is a finding consistent with previous studies that have shown age-related declines in 2D spatial attention (e.g., Greenwood and Parasuraman, 2004; Plude and Hoyer, 1986; see Rogers, 2000 for a detailed review). Previous research has shown that the abilitiy to control attention in 3D remains intact with increased age (Atchley and Kramer, 2000). In addition, research has shown that the ability to shift attention in 3D is intact with increased age but the time required to shift attention was greater for older as compared to younger observers (Atchley and Kramer, 2000). What is not known is whether the spatial extent of attention in depth varies with age. An important issue for future research will be to examine whether the extent of spatial attention along the depth axis declines with age and how such limitations might be related to crash risk.

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