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Useful field of view in simulated driving: Reaction times and eye movements of drivers

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Abstract. To examine the spatial distribution of a useful field of view (UFOV) in driving, reaction times (RTs) and eye movements were measured in simulated driving. In the experiment, a normal or mirror-reversed letter "E" was presented on driving images with different eccentricities and directions from the current gaze position. The results showed significantly slower RTs in the upper and upper left directions than in the other directions. The RTs were significantly slower in the left directions than in the right directions. These results suggest that the UFOV in driving may be asymmetrical among the meridians in the visual field.

Keywords: useful field of view, reaction time, driving simulator, eye tracking.

1 Introduction

To drive a car safely, drivers must perceive relevant objects (e.g., traffic signs, pedestrians, and cars) quickly and accurately in a dynamically changing environment. Since foveal (central) vision, perceived through the area of the retina with the best resolution, is very narrow (e.g., Millodot, 1965), drivers need to acquire relevant information with not only central vision but also peripheral vision (e.g., Miura, 1992). The spatial range in which an observer can perform cognitive tasks (e.g., detection, identification, or discrimination) by using both central and peripheral vision is called the useful field of view (UFOV; e.g., Ball, Wadley, & Edwards, 2002; Miura, 1992; Sanders, 1970; see also Engel, 1975). Since research has shown that the risk of accidents correlates with the size of the UFOV and the number of accidents increases as the size of the UFOV decreases (Owsley et al., 1998; Owsley, Ball, Sloane, Roenker, & Bruni, 1991; Rogé, Pébayle, Campagne, & Muzet, 2005), it is widely accepted that the UFOV plays an important role in perceiving relevant objects while driving (e.g., Hills, 1980).

Many psychophysical studies have measured the UFOV by using simplistic stimuli and examined the effects of various factors affecting the UFOV, such as foveal load (Bartz, 1976; Ikeda & Takeuchi, 1975; Leibowitz & Appelle, 1969), age (Ball, Beard, Roenker, Miller, & Griggs, 1988; Richards, Bennett, & Sekuler, 2006; Sekuler & Ball, 1986; Sekuler, Bennett, & Mamelak, 2000), and practice (Ball et al., 1988; Richards et al., 2006; Sekuler & Ball, 1986). In a standard task used in those studies, participants were required to perform an identification task presented in the central part of the visual field while detecting or localizing a target presented in the peripheral area of the visual field. For example, Ikeda and Takeuchi (1975) examined the UFOV with different foveal task loads. In their experiment, participants were asked to detect a peripheral target (a star) presented within distracters (distorted triangles) while performing a central task (e.g., identification of letters, numbers, or traffic signs). The results showed that the UFOV became narrower with increasing foveal load. Furthermore, the size of the UFOV widened more in the horizontal directions than in the vertical directions.

However, there are several difficulties in relating the findings of these previous studies to UFOV in an actual driving situation. First, the studies examined the UFOV without driving images or tasks (e.g., turning right or left or changing lanes). In actual driving, drivers are required to detect and/or identify relevant information located in very complicated images while performing various driving tasks. Research has demonstrated that the size of UFOV decreases with increasing complexity of visual scenes (Leibowitz & Appelle, 1969; Miura, 1992; Sanders, 1970) and driving tasks (Miura, 1992). Second, participants in the previous studies kept their fixation on the central position on the display. Research has shown that various eye movements, such as saccades, are used to perceive relevant information in driving (e.g., Miura, 1992; Mourant & Rockwell, 1972; Seya, Nakayasu, & Patterson, 2008). Since research has demonstrated that visual sensitivity decreases during saccades (Matin, Clymer, & Matin, 1972; Volkman, 1962), it is possible that the UFOV is affected by saccades in actual driving.

To our knowledge, few studies have measured the UFOV in realistic settings (e.g., actual driving settings and video clips) with experimental controls. Miura (1992) measured reaction times (RTs) and eye movements to a visual target that appeared peripherally on a windshield with different eccentricities and directions during actual driving on a variety of roads (e.g., high- and low-traffic roadways and expressways). In his experiment, participants were asked to drive safely and respond orally to the onset of the target stimulus. He assumed that, if the UFOV was narrow, then the participants would move their eyes toward the target position before responding to the target stimulus. As a result, response eccentricities (distances between the eye and target positions on the windshield when the participants responded to the target stimulus) would be shorter and corresponding RTs would be slower. He found that the response eccentricities were shorter and the RTs were slower as the complexity of the driving scene increased. He concluded from his results that the UFOV became narrower as the complexity of the driving scenes increased (see also Satoh, 1993). Crundall, Underwood, and Chapman (1999) measured several items (e.g., RTs and hit rates for peripheral targets and eye movements) while participants with different amounts of driving experience watched video clips of driving scenes. They found that the hit rates to a visual target that appeared on the video images decreased when processing demands increased (e.g., when hazards occurred), suggesting that the UFOV in driving became narrower with increasing processing demands. In addition, the hit rates changed with the level of driving experience; they were significantly lower in non-drivers than in experienced drivers, and they were lower, although not significantly, in novice drivers than in experienced drivers. This suggests that UFOV in driving widens with more driving experience. Using a similar method, Crundall, Underwood, and Chapman (2002) examined the effects of driving experience on the time course of potential narrowing of the UFOV with increasing processing demands. They found that although the magnitude of decreases in hit rates by processing demands was larger in experienced drivers than in inexperienced (learner) drivers, the decreases recovered more rapidly in experienced drivers than in inexperienced drivers.

Unfortunately, there are two difficulties in interpreting the findings of studies examining the UFOV during actual driving or viewing video clips of driving scenes. First, the driving task during the measurement of UFOV was not manipulated. In actual driving, it is very difficult experimentally to manipulate visual scenes presented for drivers because the visual scenes change dynamically even when drivers drive on the same road. Since drivers have to perform various driving tasks (e.g., turning right or left or changing lanes) depending on the driving scenes, it is possible that the driving tasks during the measurement of the UFOV differ among the drivers during actual driving. Using video clips, the same visual scenes can be presented to all drivers. However, it is very difficult to synchronize a driver's maneuvering of a car with the visual scenes. Second, the previous studies presented a peripheral stimulus independent of the participant's gaze position. Research has demonstrated that as retinal eccentricity (distance between stimulus and foveal positions) increases, visual sensitivity decreases (Loschky, McConkie, Yang, & Miller, 2005; Rovamo, Franssila, & Näsänen, 1992). Furthermore, many studies suggest that visual sensitivity changes depending on the direction of the visual field; the performance of visual tasks (e.g., discrimination task and visual search) is higher in the horizontal direction than in the vertical direction (Carrasco, Penpeci-Talgar, & Cameron, 2001; Carrasco, Williams, & Yeshurun, 2002; Corbett & Carrasco, 2011; Ikeda & Takeuchi, 1975; Kumada, Kuchinomachi, & Saida, 1995) and in the lower direction than in the upper direction (Carrasco et al., 2001, 2002; Corbett & Carrasco, 2011; Liu, Heeger, & Carrasco, 2006). Although the previous studies analyzed retinal eccentricity of target from a gaze position at target onset and used it as a factor

(Crundall et al., 1999, 2002), few studies have focused on the effects of the direction in the visual field on the UFOV in driving.

To solve these difficulties, we investigated the UFOV by using a driving simulator and an eye-tracking system. The simulator used in this study replicates images from a driver's viewpoint and provides the motion dynamics and sounds of a car, such as acceleration, braking, and steering, so that the participants can experience realistic images and dynamics of driving. With the eye-tracking system, eye movements were measured and analyzed immediately. The location of the peripheral stimulus was determined on the basis of the participant's current gaze position, just as in psychophysical studies examining visual search (e.g., Geisler, Perry, & Najemnik, 2006; see also Geisler & Perry, 1998; Loschky & McConkie, 2002; Shioiri & Ikeda, 1989). Therefore, the eccentricity and direction of the visual target in the visual field were accurately manipulated while the participants moved their eyes freely. Recently, several studies (e.g., Rogé & Gabaude, 2009; Rogé, Pébayle, Hannachi, & Muzet, 2003; Rogé et al., 2004) examined the UFOV in detail by using a driving simulator. However, in those studies, the stimuli were not manipulated according to participant's eye movements.

The purpose of this study was to investigate the anisotropy of the UFOV in driving under a simulated situation without any constraints of eye movements. RTs and eye movements to a visual target that appeared at various eccentricities and directions of the visual field from a current gaze position were measured. In this study, the effects of saccades on UFOV, not usually examined in studies of UFOV in driving, were also investigated.

In the experiment, before the target stimulus presentation, a gaze marker was presented at the location where participants were currently looking, and the marker moved in synchrony with participants' eye movements. We decided to do this for two reasons. First, we wanted to minimize potential noise that could affect RTs in order to examine the basic features of the UFOV in driving. Drivers have to perform many tasks in order to control a car, such as steering and pedaling. Hence, RTs to a target stimulus might change depending on the degree to which drivers allocate their attentional resources for a current driving task. In addition, the RTs could also be affected by accidental oversights (e.g., when drivers look in the rear or side mirrors). The presentation of the gaze marker could encourage participants to sufficiently allocate their attentional resources to the RT task and discourage them from shifting their eyes to the periphery (e.g., mirrors or speedometer) in the simulator before the target presentation (Posner, 1980; Yantis & Jonides, 1984, 1990). However, it is also conceivable that the use of the gaze marker causes another noise, because it is intended to bring participants' resources to the marker's position (i.e., current gaze position) and would thereby reduce resources for target detection. However, in the present study, the direction of the target presentation in the visual field was randomized across trials and participants were unable to change their resources in accordance with the target direction. Therefore, this effect should not differ across the target directions. Second, we wanted to check the accuracy of eye tracking during the task in order to accurately manipulate the eccentricity and direction of the visual target in the visual field.

2 Method

2.1 Apparatus and stimuli

Figure 1 shows the experimental set-up and a schematic view of the apparatus. A driving simulator with a 6-axis motion base system (Honda Motor DS-DA1102) was used to simulate driving a car with an automatic transmission. The simulator was controlled by five networked computers which also generated scene images from the driver's point of view, those in the side-view and rear-view mirrors, car dynamics (such as steering and braking motions), sounds, and traffic scenarios. The scene images and car dynamics were generated in real time according to the participant's maneuvering in the simulator. The dashboard instrumentation, steering wheel, gearshift, side brake, accelerator, and brake pedal were positioned similarly to those in an actual car.

The driving scenes were presented on a high-resolution color monitor (Princeton PTFBHF-19W) located 57 cm in front of the participants and three 6.5-inch monitors located in the positions of the right and left side-view mirrors and rear-view mirror, respectively. Note that, in this study, we did not use the frontal screen (138 × 27 deg in width and height) in the simulator because the screen was too large to record the participant's gaze positions on the screen (see Figure 1). The area of the front monitor was 41 × 25.6 cm in width and height. The driving scenes were presented at a sampling rate of 60 Hz and a resolution of 1280 × 800 pixels in width and height. In this study, an expressway

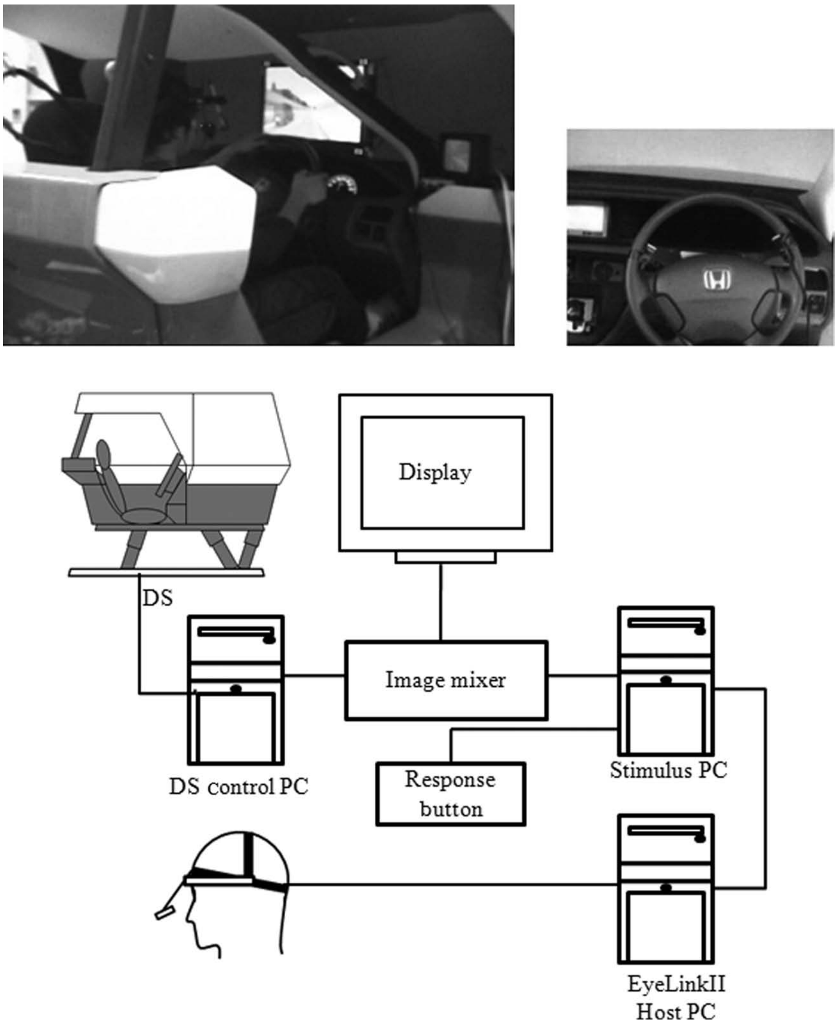

Figure 1. Experimental set-up and schematic view of the apparatus.

course installed in the simulator was used. The course consisted of several road sections, including a straight road and a merging lane, and there were several dangerous places that introduced the possibility of an accident (e.g., a car cutting rapidly into a driver's lane; for details, see Seya et al., 2008). Texture mapping, various buildings, and objects (e.g., other cars) provided the appearance of a realistic expressway.

Eye movements were recorded at 250 Hz with a spatial resolution of 0.022 deg by an eye-tracking system (SR Research EyeLink II) controlled by a personal computer (Dell Dimension 3000), which also generated visual stimuli used in the RT task and controlled the experimental timing and data collection. The delay between eye-movement recordings and stimulus drawing was approximately 17 ms. Head movements were monitored and the system automatically retrieved the data from the eye position. The stimuli used in the RT task were superimposed on the driving scenes through a chroma key image mixer (Hibino MSM-240) and presented on the front monitor. Figure 2 illustrates the stimulus display used in this experiment. In the display, the gaze marker and target stimulus were presented on the driving images. The gaze marker was a white-filled circle (luminance 190.88 cd/m^2) subtending 0.32 deg in diameter. The gaze marker was presented at the current gaze position calculated immediately by the eye-tracking system, and moved along with the eye movements. The target stimulus was either a normal or mirror-reversed letter "E" presented in red (luminance 43.83 cd/m^2). The target stimulus subtended 0.64 × 0.96 deg in width and height and was presented at the center of a gray-filled circle (luminance 129.30 cd/m^2) subtending 1.2 deg in diameter. The target stimulus was presented in one of eight possible directions (horizontal, vertical, and diagonal meridians) from the current eye position and kept stationary at that location. The eccentricity, that is, the distance of the target position from the current eye position on the display, was determined to be 2.5, 5.0, or 7.5 deg.

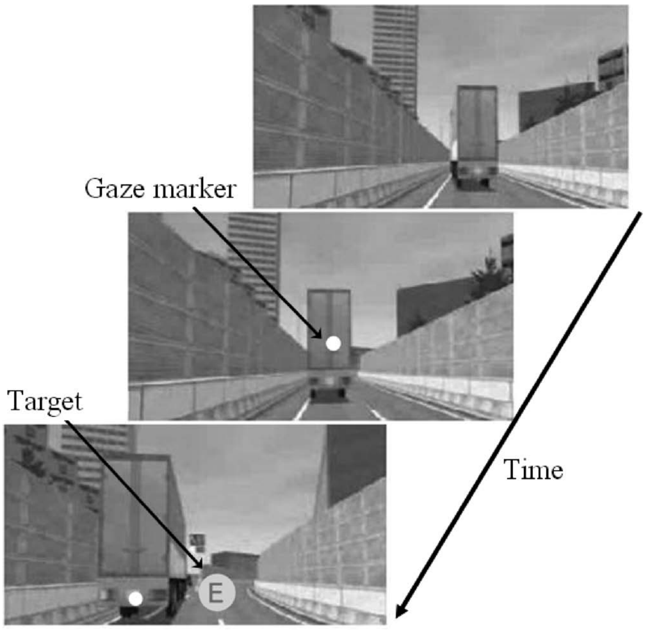

Figure 2. Stimulus display used in this experiment.

2.2 Procedure

The experiment was conducted with the driving simulator under normal room illumination. Participants were seated in the driving simulator. After the participants had practiced driving while performing an RT task on the simulator for one or two runs on the expressway course, an experimental session was conducted. At the beginning of each trial, the gaze marker was presented, followed by the presentation of the target stimulus. The foreperiod from the onset of the gaze marker to the onset of the target stimulus varied randomly in the range of 1–2 s. The participant's task was to drive safely on the driving course at about 100 km/h and to indicate, by using a thumb to press a custom-made response button on the steering wheel (see Figure 1), whether the target stimulus was a normal or mirror-reversed letter. The target and the gaze marker were visible until the participants pressed the response key or 1,000 ms after the onset of the target stimulus. The inter-trial interval was 2,000 ms.

There were five sessions of 64 trials for each eccentricity. Each session was conducted within one run of the driving course (about 6 minutes). The target eccentricity was the same throughout the five successive sessions. The direction of the target location in the visual field was randomized across the trials. The order of the three eccentricity conditions was randomized across the participants. Before each eccentricity condition, participants were given one practice session of 64 trials. All participants completed all the conditions over three days depending on their schedule and availability each day. They were given rest periods of 2 minutes between sessions.

2.3 Design

To examine the effects of target stimulus onsets near saccades on RTs, a two-factor repeated measures design was employed. There were two independent variables: trial type (peri-target onset saccade trial and non-peri target onset saccade trial) and eccentricity (2.5, 5.0, and 7.5 deg). A peri-target onset saccade trial was defined as a trial in which the participants made saccades during the 100-ms intervals just before and after the target stimulus was presented. A non-peri target onset saccade trial was defined as a trial in which no saccades were made during those 100-ms intervals. RT was the dependent variable.

To examine the effects of target stimulus location in the visual field on RTs and eye movements, a two-factor repeated measures design was used. There were two independent variables: visual field (direction of target stimulus presentation: horizontal, vertical, and diagonal meridians) and eccentricity. There were three dependent variables: RTs, number of saccades, and eye movement distance. Eye movement distance was defined as the distance at which participants' eyes approached the target stimulus until the participants pressed the button.

2.4 Eye movement recordings and analyses

In this study, the horizontal and vertical eye movements of the participants were recorded from both eyes. Before the experimental session, the participants were asked to fixate on nine points presented on the front monitor to calibrate the eye-tracking system. All data were stored on the computer. Except for the eye position data used to determine the target position during the RT task, all data were analyzed off-line by computer programs that calculated the number of saccades and eye movement distance.

In the analysis, differences in eye positions in successive frames were calculated. From the differences in the eye positions, eye velocity was calculated and filtered by applying a moving average method (e.g., Madelain & Krauzlis, 2003) over 20 ms. To identify a saccade, we used a velocity criterion: a saccade was defined as an eye movement with a velocity greater than 30 deg/s. In the non-peri target onset saccade trial, the number of saccades and eye movement distance were analyzed. In the analysis, the data during the interval between the onset of the target stimulus and the onset of the response were first extracted. The number of saccades was then counted. In the analysis of eye movement distance, the response eccentricity, defined as the distance between the eye and target positions on the display when the participants pressed the button (Miura, 1992), was calculated; the eye movement distance was then calculated by subtracting the response eccentricity from the target eccentricity.

2.5 RT analyses

In the analyses, only RTs for correct responses (more than 95% of the total trials) were used. From the RT data, we removed RTs below 100 ms (less than 1% of the total trials). To examine the effects of target stimulus onset near saccades on RTs, RT data were first classified into two trial types in terms of eye movement analyses: peri-target onset saccade trial and non-peri target onset saccade trial (see Section 2.3). The RT data for each trial type were then averaged across all directions of the target presentation because there were few trials of the peri-target onset saccade (the mean ratio of the peri-target onset saccade trial was less than 10% of the total trial). In the analysis of the effects of the target presentation direction and eccentricity on RTs, only RT data in the non-peri target onset saccade trial were used and averaged for each direction for each eccentricity.

2.6 Participants

Seven males, including the first and third authors (mean age: 22.71; age range: 21–28 years), participated in this experiment. The participants had regular-class automobile licenses in Japan and 2–9 years of driving experience (mean: 4.29 years). All participants received more than 10 hours of training using the driving simulator before the experiment. Before the experiment, informed consent was obtained. All participants had normal or corrected-to-normal vision.

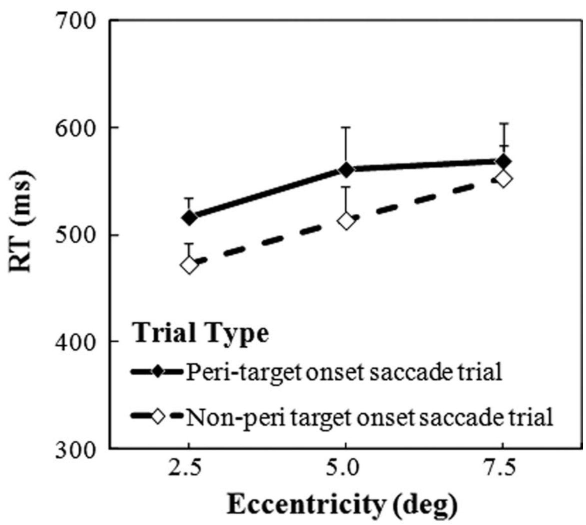

Figure 3. Mean RTs for each eccentricity for each type of trial. Vertical bars indicate standard errors of the mean.

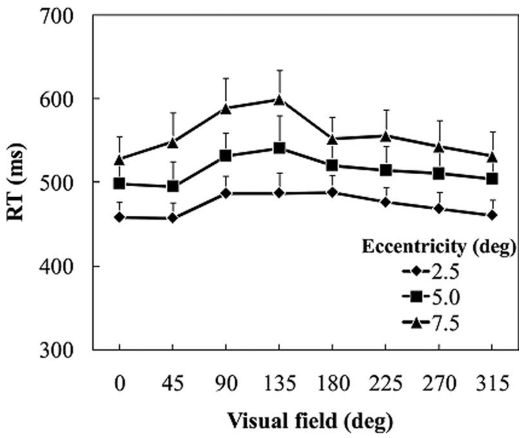

Figure 4. Mean RTs for each visual field for each eccentricity in the non-peri target onset saccade trial. On the horizontal axis, the right direction of the target presentation from the gaze position was defined as 0 deg. Each direction was defined with a 45-deg step from 0 deg in the counterclockwise direction. Vertical bars indicate standard errors of the mean.

3 Results

3.1 RTs

Figure 3 shows the mean RTs for each eccentricity for the two types of trials. As shown in the figure, there were large differences in the RTs between the two types of trials. The RTs increased systematically with increasing retinal eccentricity of target. The RT data were entered into a 2 (Trial type) × 3 (Eccentricity) ANOVA, which showed that there were significant main effects of Trial type, $F(1, 6) = 106.22$, $p < 0.01$, and Eccentricity, $F(2, 12) = 6.22$, $p < 0.05$, but there was no interaction between them, $F(2, 12) = 2.26$. Multiple comparisons for the effect of Eccentricity by Ryan's method (Ryan, 1960) showed a significant difference between the eccentricities of 2.5 and 7.5 deg ($p < 0.05$) but not between those of any other pair.

Figure 4 shows the mean RTs for each direction of the target presentation (visual field) for each eccentricity. It is noteworthy that the right direction of the target presentation from the gaze position was defined as 0 deg. Each direction was defined with a 45-deg step from 0 deg in a counterclockwise direction. Therefore, the values of 90, 180, and 270 deg in the figure indicate the upper, left, and lower directions, respectively. As shown in the figure, the RTs increased with increasing eccentricity. Regarding the effect of the visual field, the RTs were slower in the upper and upper left directions than in the other directions. The RTs tended to be slower in the left direction than in the right direction.

A 3 (Eccentricity) × 8 (Visual field) ANOVA showed significant main effects of Eccentricity, $F(2, 12) = 12.69$, $p < 0.01$, and Visual field, $F(7, 42) = 15.85$, $p < 0.01$, with a significant interaction between them, $F(14, 84) = 2.59$, $p < 0.05$. Multiple comparisons for the effect of Eccentricity showed significant differences between all pairs of eccentricities (all $p < 0.05$). Multiple comparisons for the effect of Visual field showed that the RTs were significantly slower in the upper and upper left directions than in the other directions (all $p < 0.05$). The RTs were slower in the left direction than in the right, lower right, and lower directions ($p < 0.05$). The RTs were slower in the lower left direction than in the right direction ($p < 0.05$). A subsequent analysis of the interaction showed that the effects of eccentricity were somewhat different across directions, all $F(2, 12) > 6.23$ and $p < 0.01$.

3.2 Number of Saccades

Figure 5 shows the mean number of saccades for each visual field for each eccentricity. As shown in the figure, the number of saccades increased with increasing eccentricity and was higher in the upper direction than in the lower direction. A 3 (Eccentricity) × 8 (Visual field) ANOVA showed the significant main effects of Eccentricity, $F(2, 12) = 12.87$, $p < 0.01$, and Visual field, $F(7, 42) = 3.78$, $p < 0.05$). There was significant interaction between them, $F(14, 84) = 1.91$, $p < 0.05$. Multiple comparisons for the effect of Eccentricity by Ryan's method showed significant differences between all pairs of eccentricities (all $p < 0.05$). Multiple comparisons for the effect of Visual field showed that the number of saccades was significantly smaller in the lower direction than in the other directions except for the lower right and lower left (all $p < 0.05$). A subsequent analysis of the interaction

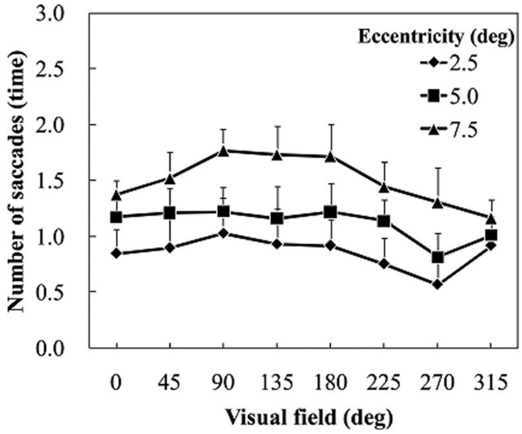

Figure 5. Mean number of saccades for each visual field for each eccentricity. Vertical bars indicate standard errors of the mean.

showed a significant simple main effect of visual field only at 7.5 deg, F (7, 126) = 5.67, $p < 0.01$. Multiple comparisons for the effect of Visual field showed that the number of saccades was smaller in the lower direction than in all other directions except for the right and lower right directions (all $p < 0.05$). The number of saccades was also smaller in the lower right direction than in the upper and upper left directions (all $p < 0.05$).

3.3 Eye movement distances

Figure 6 presents the mean eye movement distances for each visual field for each eccentricity. The eye movement distances increased with increasing eccentricity and were larger in the upper directions (including diagonal directions) than in all other directions at 7.5 deg. A 3 (Eccentricity) × 8 (Visual field) ANOVA showed significant main effects of Eccentricity, F (2, 12) = 16.44, $p < 0.01$, and Visual field, F (7, 42) = 2.99, $p < 0.05$. There was a significant interaction between them, F (14, 84) = 3.80, $p < 0.01$. Multiple comparisons for the effect of Eccentricity showed that the eye movement distances were significantly longer at 7.5 deg than at 2.5 and 5.0 deg (both $p < 0.05$). Multiple comparisons for the effect of Visual field showed no significant difference between any pair of directions. A subsequent analysis for the interaction showed a significant simple main effect of the visual field only at 7.5 deg, F (7, 126) = 9.36, $p < 0.01$. Multiple comparisons for the effect of Visual field showed that the eye movement distances were longer in the upper right, upper, and upper left directions than in the right, lower right, and lower left directions (all $p < 0.05$). The eye movement distances were also longer in the upper left direction than in the lower direction ($p < 0.05$).

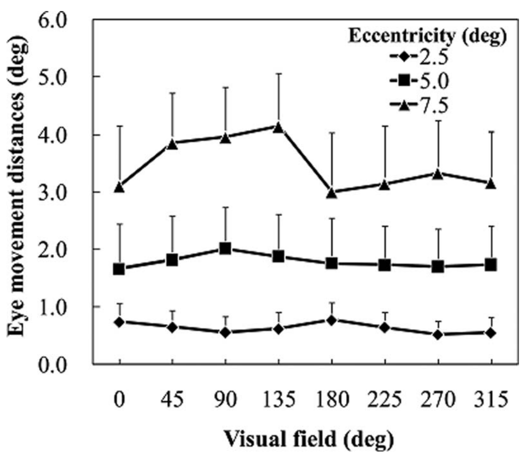

Figure 6. Mean eye movement distances for each visual field for each eccentricity. Vertical bars indicate standard errors of the mean.

4 Discussion

In the present experiment, in order to examine the spatial distribution of the UFOV in driving, the RTs and eye movements to a peripheral target were measured during simulated driving. The results showed that RTs increased with increasing eccentricity. This result was consistent with that of psychophysical studies measuring RTs during stationary fixation in laboratory settings (e.g., Carrasco, Evert, Chang, & Katz, 1995; Carrasco & Frieder, 1997). The number of saccades and eye movement distances increased with increasing eccentricity, suggesting that the participants may have compensated for the poor sensitivity of the retina at the periphery (e.g., Millodot, 1965) by moving their eyes toward the target stimulus before the response, resulting in longer RTs. Regarding the effects of the direction of target presentation in the visual field, RTs were slower for the upper and upper left directions than for all other directions. In addition, the number of saccades showed a tendency toward higher saccades in the upper directions than in the lower directions. The results of the eye movement distance showed a tendency toward longer distances in the upper directions than in all other directions, particularly at the 7.5-deg eccentricity. According to the definition of UFOV, these results suggest that the UFOV in driving is narrower in the upper directions than in the other directions. This finding is consistent with that of psychophysical studies that suggest asymmetries in the spatial distribution of the UFOV between the vertical and horizontal directions (Carrasco et al., 2001, 2002; Corbett & Carrasco, 2011; Ikeda & Takeuchi, 1975; Kumada et al., 1995) and between the upper and lower directions (Carrasco et al., 2001, 2002; Corbett & Carrasco, 2011; Liu et al., 2006). The present results also showed slower RTs in the left than in the right directions, suggesting that the UFOV is narrower in the left than in the right directions. It should be noted that there was no difference in the number of saccades or in the eye movement distances between the right and left directions.

Why did the UFOV in driving differ across the visual field? One possibility is the driver's anticipation skills. In this study, each participant had a driver's license and practiced driving in the simulator before the experiment (see Section 2). Based on their knowledge and experience, the participants may have anticipated locations where relevant information was likely to appear and thus changed the spatial distribution of the UFOV. Indeed, there is evidence that a driver's visual search depends on his or her anticipation, which in turn depends on his or her experience (Hills, 1980; Theeuwes, 1996; Theeuwes & Hagenzieker, 1993). Regarding the narrow UFOV in the upper direction, because there would be few objects to be perceived in the upper direction during driving, the participants may have narrowed their UFOV in that direction, as compared with that in the other directions. This anticipation hypothesis could also explain the differences between the horizontal directions in the present experiment. In Japan, drivers are required to drive on the left side of the road. Consequently, Japanese drivers would be expected to spread their UFOV greater to the right side than the left side in order to maintain a view of the entire road. Thus, according to this explanation, drivers who always drive on the right side of the road would spread their UFOV greater to the left side than the right side. This point should be explored in future studies by examining the UFOV of drivers who drive on different sides of the road (e.g., Japanese drivers vs. American drivers).

Another possibility is the visual constraints (e.g., Carrasco et al., 2002; Corbett & Carrasco, 2011). Many physiological studies have shown differences that may affect retinal sensitivity across the directions of the visual field. For example, there are more ganglion cells in the retina (Perry & Cowey, 1985) and the decline of cone cell density is slower in the horizontal directions than in the vertical directions (Curcio, Sloan, Packer, Hendrickson, & Kalina, 1987; Perry & Cowey, 1985). Regarding the differences in the vertical directions, research has shown that the number of ganglion and cone cells is higher in the superior direction (lower visual field) than in the inferior direction (upper visual field) on the retina (Curcio et al., 1987; Curcio & Allen, 1990). If we assume that visual sensitivity is determined by the number of ganglion cells and/or photoreceptors, then these physiological differences would be able to account for the present results. However, one problem with this explanation is that it cannot explain the differences between the horizontal directions. Although studies have reported more ganglion and cone cells in the nasal direction than in the temporal direction from the fovea (Curcio et al., 1987; Perry & Cowey, 1985), the participants of the present study viewed the stimulus binocularly. It should be noted that the anticipation explanation and the physiological explanation are not mutually exclusive.

One may argue that, although the contrast between the target stimulus and the background (i.e., gray disk) was constant across conditions, the contrast between the gray disk and adjacent areas of the display would affect the RTs. Unfortunately, we could not test this point, because the images of the display during the experiment could not be stored. However, to examine the potential effects of the contrast between the gray disk and the adjacent areas, we measured the luminance of the display areas for four directions (upper, lower, right, and left) for three eccentricities (2.5, 5.0, and 7.5 deg) from the center of the display. We selected four straight road sections to measure the luminance of each location because changes in the scenes were relatively small and there were few objects in the road. We selected a scene where a car reached the middle of the road section and then calculated the contrast between the gray disk and the adjacent areas by using the Michelson definition [(Lmax−Lmin)/(Lmax + Lmin)]. At the 2.5-deg areas from the center of the display, the contrast was 0.54, 0.42, 0.39, and 0.47 for the upper, lower, right, and left directions, respectively. At the 5.0-deg areas, the contrast was 0.17, 0.44, 0.41, and 0.51 for the respective directions. At the 7.5-deg areas, the contrast was 0.07, 0.47, 0.39, and 0.50 for the respective directions. In the upper direction, the contrast decreased with increasing distance from the center, but did not change much with distance in the other directions. The contrast was smaller in the upper directions than in the other directions, particularly at 5.0 and 7.5 deg. Therefore, if we assume that the participants maintained their fixations around the center of the display, the contrast effects could account for the slower RTs in the upper direction, particularly at the large eccentricities (i.e., 5.0 and 7.5 deg). However, the contrast effects cannot explain the slower RTs in the upper direction at the 2.5-deg eccentricity. They are also unable to account for the differences between the right and left directions. It is thus unlikely that the contrast effects accounted for all the variations in RT in the present study. This point should be further examined in future studies.

So far we have discussed the spatial distribution of the UFOV on the basis of processing speed (i.e., RTs). However, it is difficult to relate the present results to the findings reported in previous studies that directly measured the spatial range of the UFOV (e.g., Ikeda & Takeuchi, 1975). To do this, we calculated the target eccentricity at which the participants would respond before criterion times (500, 600, and 700 ms) by a linear regression of the mean RTs on the eccentricities for each visual field. Figure 7 shows the spatial range of the UFOV evaluated by the mean RTs. As shown in the figure, the UFOV was clearly narrower in the upper directions than in all other directions. This pattern is similar to the findings of Ikeda and Takeuchi (1975) and Kumada et al. (1995).

The present finding of slower RTs when the target stimulus appeared during saccades than when it did not is consistent with that of psychophysical studies on saccadic suppression (e.g., Matin et al., 1972; Volkman, 1962). This result suggests that the saccades in driving may be responsible for the failure to perceive relevant information (e.g., Rensink, O'Regan, & Clark, 1997; Simons & Ambinder, 2005). It should be noted that this result does not mean that drivers should not move their eyes when driving. Drivers need to frequently move their eyes in order to identify objects in front of and/or behind their vehicle. Particularly when trying to identify objects behind their vehicle and preparing for car maneuvering (e.g., changing lanes), drivers would have to move their eyes frequently in order to look into the mirrors. The present results imply that drivers should identify objects with a few (or optimal frequencies of) eye movements.

In the present study, we presented the gaze marker at the current gaze location of the participants before the target stimulus presentation. Since the participants had to drive safely even during the presentation of the gaze marker, our results reflect, at least to some degree, the UFOV in driving. However,

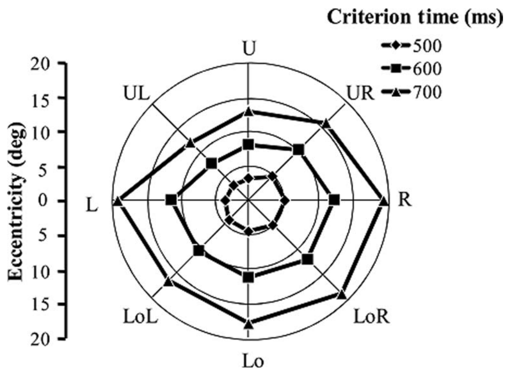

Figure 7. Polar representation of UFOV for eight spatial directions (vertical, horizontal, and diagonal directions) estimated by a linear regression of the mean RTs on the eccentricities. U, R, Lo, and L indicate upper, right, lower, and left, respectively.

the use of a gaze marker could also be a limitation of the present study, because the presentation of the marker could have affected the shape of the UFOV observed in the present study and further studies are needed to explore the potential effects of the marker. There are, at least, four possibilities. First, the presentation of the gaze marker could have distracted the participants from driving. It should be noted that we also used the front display, which is actually smaller than the screen of the simulator (see Section 2). Therefore, the presentation of the marker, as well as the small front display used, could have led to differences between the participants' experiences during the experiment and actual driving.

Second, because there could be small position errors between the gaze marker and the participant's gaze (due to the limitation of the eye-tracking system used), these position errors could have caused small saccades and attentional shifts in a specific direction. To examine this possibility, we calculated the differences in the eye positions between the onsets of the gaze marker and the target stimulus on each trial. Figures 8(a–c) present the data plots from one participant for each eccentricity condition. As can be seen in the figures, there was no systematic shift in eye position toward a specific direction after the gaze marker onset. Figure 8(d) shows the mean and individual values of all the participants. Note that the vertical and horizontal bars in Figure 8(d) indicate the mean standard deviation of all the participants, not the standard error from the mean. The result indicates that the position errors would not shift the participants' gaze to a specific direction after the marker presentation and also suggests that they would not shift the participants' attention, at least in an overt manner. However, the position errors might still have caused attentional shifts to a specific direction in a covert manner.

Third, because the gaze marker could have oscillated continuously, particularly when following the participants' fixational eye movements, these oscillations could have caused attentional shifts. The results of the analyses of eye position differences between the onsets of gaze marker and target stimulus partially support the notion that there was no systematic shift in attention (at least in an overt manner) after the gaze marker onset (Figure 8). Nevertheless, they cannot confirm whether the participants' attention could have been shifted depending on the type of motion.

Finally, the participants could have used the gaze marker as a cue for the target stimulus presentation and, consequently, the marker could have affected their attentional strategies. Our analysis suggests that the participants did not shift their eyes to a specific area such as the sky after the marker presentation (Figure 8). Therefore, it is unlikely that the participants moved their gaze to a relatively uniform area to prepare for the target stimulus presentation. However, it is conceivable that the par-

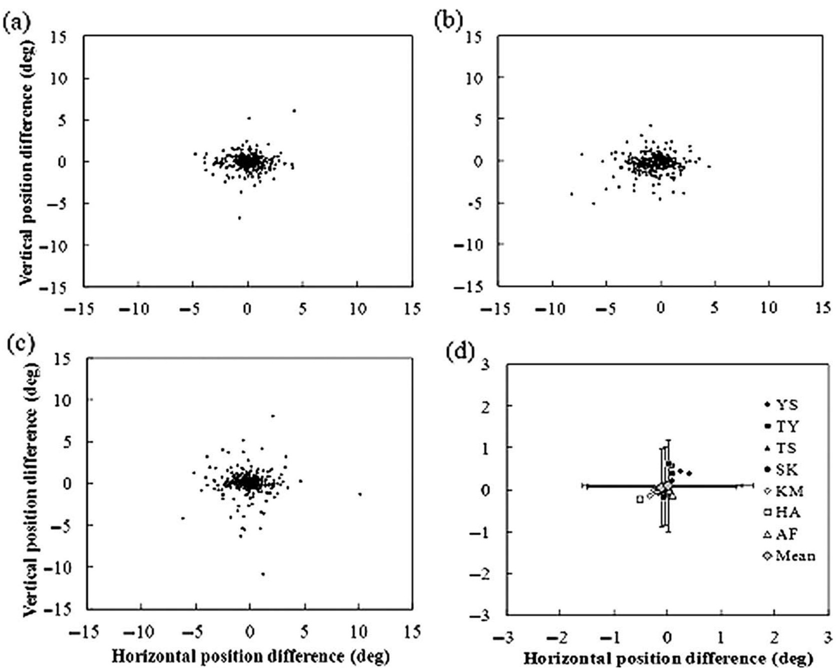

Figure 8. Plots of eye position differences between the onsets of the gaze marker and the target stimulus on each trial at (a) 2.5, (b) 5.0, and (c) 7.5 deg in one participant (HA) and (d) plots of the mean values at the three eccentricities for each participant. Horizontal and vertical bars indicate mean standard deviation of all participants.

ticipants may have shifted their attention in a covert manner after the gaze marker onset to prepare for the target stimulus presentation.

Two more points should be noted concerning the present study. First, it may be argued that the participants' RTs might have been sacrificed for the sake of accuracy in the driving tasks. At this point, we do not have a conclusive answer because we did not measure driving performance. However, as mentioned in the Introduction, the gaze marker was presented at a location where the participants were currently fixated, in order to encourage them to efficiently allocate their attentional resources for the RT task. Therefore, the tradeoff between the driving and RT tasks would be too small to explain the present findings. Second, one may argue that the present study did not evaluate the UFOV during driving because the participants did not perform any central task (e.g., detection and identification of a stimulus presented in the central part of visual field). However, in the present study, the participants were asked to drive safely during simulated driving. Furthermore, the participants were exposed to several dangers of potential accidents (see Section 2). Thus, the participants should have been able to detect and/or identify visual objects in the central part of visual field in order to drive safely. Therefore, we think that the absence of a specific central task does not negate the present findings concerning the UFOV.

5 Conclusion

In conclusion, the present study demonstrated that the spatial distribution of the UFOV in simulated driving differed among the meridians in the visual field. This finding is similar to the results of studies using simplistic settings (e.g., Carrasco et al, 2001, 2002; Ikeda & Takeuchi, 1975; Kumada et al, 1995). However, the presentation of the gaze marker before the target presentation might have affected the shape of the UFOV, and the present findings could have been specific to the conditions in the present study. Further studies without the gaze marker presentation are therefore needed.

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