DRIVING WITH HEMIANOPIA: A SIMULATOR STUDY INVESTIGATING A VIBROTACTILE ADVANCED DRIVER ASSISTANCE SYSTEM

A thesis presented to the graduate faculty of New England College of Optometry in partial fulfillment of the requirements for the degree of Master of Science

Yustina Kang

March 2024

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ABSTRACT

DRIVING WITH HEMIANOPIA: A SIMULATOR STUDY INVESTIGATING A VIBROTACTILE ADVANCED DRIVER ASSISTANCE SYSTEM

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New England College of Optometry, 2024

Schepens Eye Research Institute

Purpose: Drivers with homonymous visual field loss (HVFL) may have delayed responses to hazards from the blind side and pose safety risks. Warnings that indicate hazard direction may be helpful for directing gaze to blind-side hazards and mitigate collision risk for drivers with HVFL. Using a driving simulator, we tested the hypothesis that responses to blind-side hazards would be faster with directional than non-directional warnings.

Methods: 14 participants with HVFL (35-61y) and 12 age-similar normal vision controls completed 2 drives with directional warnings (vibration on left/right for a hazard on left/right), 2 with non-directional warnings (vibrated simultaneously on both sides), and 2 without warnings. Per drive, 10 pedestrian hazards crossed the road from the left or right in front of the driver's vehicle, requiring a braking response to avoid a collision. Warnings were triggered when situations became dangerous (time-to-collision < 3s).

Results: In drives with warnings, HVFL participants received warnings for the majority of pedestrian hazards (80% overall). With directional warnings, blind-side pedestrians were

fixated faster (1.66s vs. 1.99s, $P = .03$) and were more likely to be fixated before braking (86% vs. 74%) than with nondirectional warnings. Both warnings reduced blind-side collision rates (15% without vs. <1% with warnings). Most HVFL participants (79%) preferred directional over non-directional warnings. Participants with normal vision received warnings for only 33% of events, and their gaze and driving behaviors did not differ between warning conditions.

Conclusions: Both types of warnings were equally efficacious in improving driving safety by reducing collision rates for blind side hazards for HVFL participants. However, directional warnings were strongly preferred, and blind side hazards were fixated more quickly with directional warnings.

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INTRODUCTION

1. Homonymous visual field loss

When the retrochiasmal visual pathway is damaged unilaterally, bilateral homonymous vision loss respecting the vertical midline of the visual field results, affecting the contralateral visual field. The most common homonymous visual field loss (HVFL) is homonymous hemianopia (Chokron et al., 2016), the loss of one-half of the visual field on the same side in each eye. The defect is both bilateral and homonymous because it affects the information projected onto the temporal hemiretina of the contralesional eye and the nasal hemiretina of the ipsilesional eye (Holmes 1918). Stroke, traumatic brain injury, tumors, and brain surgery are the most common causes of HVFL (Zhang et al., 2006). The most common locations of lesions resulting in HVFL are the occipital lobe (45%), followed by damage to the optic radiations (32%) (Zhang et al., 2006), and the remainder by lesions of the optic tract (10%), lateral geniculate nucleus (1.3%) or a combination of several areas (11%) (Goodwin 2014).

HVFL can be total or partial, with a visual field defect ranging from total loss of one hemifield (homonymous hemianopia) to loss of one quadrant (homonymous quadrantanopia) or small areas of paracentral field loss (Zhang et al., 2006). Patients with HVFL such as complete hemianopia may have macular sparing (a small area of residual field around the macula), which often occurs with occipital lesions, specifically infarctions of the posterior cerebral artery (Zhang et al., 2006). While most HVFL is associated with good visual acuity, a visual field defect can have debilitating consequences, causing difficulties in avoiding

obstacles while walking and reduced detection of pedestrians in the blind field when driving (Woutersen et al., 2020; Wood et al., 2009).

1.1 Clinical Evaluation

In the clinic, HVFL is usually documented using perimetry. Goldmann perimetry can be used to quantify neurological visual field loss. However, it is not widely available and requires a skilled technician compared with automated perimetry (Goodwin 2014). Humphrey visual fields are widely used to quantify field loss; however, they suffer from sizeable test-retest variability and can miss HVFL more than half of the time compared to Goldmann perimetry (Wall et al., 2002). Confrontation visual field testing is not sensitive in detecting visual field loss but may be used when it is the only available form of testing and is sufficient to detect hemianopia and quadrantanopia. Perimetry is important for documenting the areas of visual field loss but fails to measure the ability of a patient to compensate for their field loss because patients are required to maintain fixation on a central target throughout the perimetry test.

1.2 Driving with HVFL

Many people with HVFL do not meet the visual field requirements for a driver's license and are required to give up driving. In 22 states in the USA, people with HVFL do not meet the minimum horizontal visual field requirement for driving (e.g., 120 degrees in Massachusetts). However, in some states in the US (Alaska, California, Colorado, Delaware, Idaho, Indiana, Louisiana, Montana, Nevada, New Hampshire, New Jersey, South Dakota, Texas, and West Virginia) where there is no visual field requirement, drivers with HVFL can drive (Peli 2009). In countries such as the Netherlands, Belgium, the UK, and Canada,

patients with HVFL may receive driving licenses after completing a specialized on-road test to demonstrate their fitness to drive (Peli 2009; Kooijman et al., 2004)

Studies have reported conflicting results regarding the driving performance of individuals with HFVL. Some studies found little difference in driving performance between drivers with HVFL and those with full fields (Wood et al., 2009; Schulte et al., 1999), indicating that some drivers with HFVL may compensate well for their deficit. Moreover, some studies reported relatively high pass rates (>70%) for drivers with HVFL in on-road tests (Dow 2011; Wood et al., 2009), suggesting that some drivers with HVFL may be safe to drive. However, results of other on-road and driving simulator studies suggest that HVFL may impair some aspects of visual and motor operation while driving, including steering stability, lane position, speed, traffic-gap judgment, and the ability to respond promptly to hazards that occur on the side of the field loss (Houston et al., 2018; Bowers 2016; Alberti et al., 2017, Niehorster et al., 2013, Tant et al., 2012).

In general, the driving performance of people with HVFL is not predicted by the magnitude of the field loss (Bowers 2016, Kasneci et al., 2014); therefore, individuals must undergo individual assessments to determine eligibility for driving with a field impairment (Elgin et al., 2010; Bowers 2016). For example, in Quebec, a driver with an HVFL who demonstrates safe driving in a specialized road test may qualify for an exemption from the minimum (120°) visual field requirement. In a retrospective study of the outcomes of these specialized road tests for drivers with field loss, Dow (2011) concluded that the actual minimum visual field requirement might be unimportant as long as the driver can demonstrate safe driving in a road test.

Crash rates are an important measure of driving safety. However, there is relatively little data about crash rates of drivers with HVFL. Johnson and Keltner (1983) conducted a retrospective study on driving performance to determine whether there was a relationship between binocular and monocular visual field loss and driving performance. For drivers with significant binocular visual field deficits, they reported twice the rate of accidents and violations than age matched controls with normal visual fields. However, they did not provide a separate analysis of data for drivers with HVFL. McGwin et al. (2016) reviewed motor vehicle collision rates of drivers with hemianopia and quadrantanopia field defects. Participants with field defects (all currently licensed drivers) had an overall higher rate of motor vehicle collisions; their overall rate was 2.45 times higher, and their at-fault rate was 2.64 times higher than drivers with normal vision. These data suggest that drivers with HVFL may be at higher risk for collisions.

1.3 Detecting hazards when driving with HVFL

A visual field defect can severely compromise driving safety, such as difficulty detecting a sudden pedestrian or vehicle appearance (Owsley et al., 2015; Kunimatsu-Sanuki et al., 2017). A series of driving simulator studies demonstrated that, although some individuals with HVFL had good detection of blindside pedestrian hazards, others had difficulty detecting and reacting to pedestrians on the side of their field loss (Alberti et al., 2014; Bowers et al., 2014, Bowers et al. 2009). Bowers et al. (2009) found that, on average, participants with HVFL had lower detection rates than controls for pedestrians in the blind field, and older participants with HVFL had lower detection rates than younger participants with HVFL, demonstrating a declining ability to compensate for field loss with age.

Furthermore, Papageorgiou et al. (2012) reported a higher number of collisions for people with HVFL on the blind versus seeing side in a driving simulator.

1.3.1 Compensating by scanning

People with HVFL could compensate for their field loss by scanning toward the blind side. In a driving simulator study, those with HVFL made more head scans towards the blindside than those with normal vision to the same side; however, the scans tended to be of equal or smaller magnitude (Bowers et al., 2014). Furthermore, other studies have reported less systematic and accurate visual search by people with HVFL (Zihl 1995), and saccades that were longer in latency and shorter in amplitude (Fayel et al., 2014). As a compensatory strategy to bring more of the visual scene into their seeing field, some people with HVFL shift their gaze towards and spend most of their time looking into their blind hemifield (Wood et al., 2011; Bowers et al., 2014). In general, more scans and/or larger scans toward the blind side are associated with better detection and responses to blind side hazards (Alberti et al., 2017). However, some people with HVFL do not compensate well by scanning, as evidenced by low blind side detection rates (Alberti et al., 2014; Bowers et al. 2014; Papageorgiou et al., 2012; Bowers et al., 2009)

So why might people with HVFL fail to scan when there is a hazard on the blind side, or make scans that do not extend far enough into the blind hemifield to see the hazard?

1.3.2 Lack of guidance from peripheral vision

In subjects with normal vision, large areas of a scene are perceived and spatially represented in peripheral vision (Patterson et al., 2019), and input from the peripheral visual field guides saccades to relevant objects, excluding empty space or irrelevant areas (Zihl

1999). As patients with HVFL lack peripheral visual input to guide their saccades on the side of the field loss, they must explore all parts of the visual scene on that side to increase their possibilities of detecting an object of interest (Chédru et al., 1973).

To see an object in the blind hemifield, someone with an HVFL must scan as far into the blind hemifield as the object's location to bring the object of interest into the seeing area of their visual field. They lack visual cues from their peripheral vision that would tell them when and how far to scan into the blind hemifield and must remember to scan when a hazard is present, which may be entirely by chance. Peripheral objects that appear at larger eccentricities in the blind hemifield might be detected less frequently or with longer response times than objects appearing at smaller eccentricities because larger scans are needed for detection (Bowers et al., 2009). Under high attentional load when driving, someone with HVFL might fail to remember to scan, and when they do remember, the scan toward the affected side might be delayed relative to the appearance of the hazard, reducing the time to respond by braking or steering (Bowers 2016). Therefore, providing a cue to direct their attention to a dangerous situation might be an effective strategy to improve their driving safety. In this study, we evaluate directional vibrotactile hazard warning cues for drivers with HVFL.

2. Hazard warning systems

Driving in urban environments with multiple distractions and possible hazards, including pedestrians, bicycles, and other vehicles, can be overwhelming to even normal-sighted drivers (Hölzl et al., 2021), let alone drivers with visual field loss. Advanced Driver Assistance Systems (ADAS) technologies are increasingly used to support drivers in many

different situations and increase safety by alerting drivers about dangerous conditions (Bao et al., 2016). These systems monitor several parameters, and when thresholds are exceeded, drivers are informed (Biondi et al., 2017). Various types of warnings, including visual, auditory, tactile, and multisensory, have been shown to be beneficial in guiding drivers' attention quickly to the source of potential danger (Meng and Spence 2015).

2.1 Tactile Warning Systems

Vibrotactile warning signals are increasingly being used as information channels in cars to warn the driver (Gaffary and Lécuyer 2018). In the event of a potential crash, drivers respond faster to tactile warning signals than auditory or visual signals (Prewett et al., 2012) as tactile feedback is quicker to process and requires less cognitive resources than visual or auditory (Meng and Spence 2015). Vibrotactile stimuli are advantageous in that they are difficult to ignore (Erp 2001), can be conveyed privately to the driver (Meng and Spence 2015), and tactile perception is less important for driving than either vision or auditory perception. Furthermore, tactile cues were found to be similarly effective regardless of driver workload (Fels et al., 2006).

Vibrotactile warnings can provide useful information despite limited field-of-view and noisy environments and quickly draw the driver's attention when important events occur, either as collision warnings or directional cues. Unlike auditory cues, tactile cues are not affected by the background noise in the driving environment (auditory signals can be lost in background noise like radio music, engine noise, navigation directions, or conversations). Visual warnings are restricted to the driver's field of view and are not always effective in catching a driver's attention as a high degree of visual attention is already required during

driving (Gaffary and Lécuyer 2018). Moreover, a visual cue in the blind field of a driver with an HVFL would not be seen. Unlike auditory and visual signals, vibrations are processed in multiple locations throughout the body, such as the Meissner and Pacinian mechanoreceptors (Merchel and Altinsoy 2020) and are more likely to be sensed.

Vibrotactile warnings are more effective in warning drivers about emergency safety issues than visual or auditory warnings (Politis et al., 2014). Considering our skin constitutes roughly 18% of our body mass, the tactile warning signal can be implemented in various ways through surfaces of the car that the driver is already in contact with (Spence and Ho 2008), including the steering wheel, which is implemented in current cars, seatbelt, or the car seat itself (Gaffary and Lécuyer 2018). The seat can be used to stimulate a large area of the body (Meng and Spence 2015), and as the driver constantly maintains tactile contact with the seat, warnings presented on the seat are highly likely to be perceived.

Several studies have shown that participants respond faster to vibrotactile warnings than to visual or auditory warnings (Ho et al., 2006; Halabi et al., 2014; Fitch et al., 2007; Prewett et al., 2012), and vibrotactile warnings led to more correct localizations of hazardous situations (Halabi et al., 2014, Prewett et al., 2012). Mohebbi et al. (2009) compared tactile and auditory rear-end collision warnings and found tactile warnings to be more effective in the presence of any level of complexity of cell phone conversation, with a shorter warning onset to brake initiation for both simple and complex conversations. Huang et al. (2019) compared the effects of unimodal, bimodal, and trimodal cues on takeover response times. The study found that reaction times for cue combinations that contained tactile signals were 0.25 seconds faster than cues that did not contain a tactile signal. When two vibrators were added to the right and left sides of a steering wheel to reduce navigation errors (making a

wrong turn or taking the wrong exit), Ege, Cetin, and Basdogan (2011) found that participants made 3.7 times fewer errors with combined tactile and auditory feedback compared to auditory feedback alone. Halabi et al. (2014) compared auditory and vibrotactile navigation signals and found that participants responded correctly to vibration mode navigation more often than auditory. Moreover, participants thought vibration feedback provided a more natural experience and required less attention and intuitive response than auditory feedback.

2.2 Tactile Directional Cues

Most drivers spend the majority of time looking in the forward direction when driving with occasional scans to the left and right. As discussed above, drivers with normal vision can use peripheral visual field to guide saccades to potential hazards on the left and right, but drivers with HVFL lack cues from peripheral vision on the side of the field loss. Therefore, providing a directional warning cue may help shift their gaze and attention to a potential hazard in the blind field. A warning that contains directional information allows the driver to pay attention more easily and effectively than a warning without directional information (Dettmann and Bullinger 2017) and was further found to reduce reaction times in normally sighted drivers. The addition of a directional component to an auditory warning helped drivers react more quickly in hazardous situations (Zhang et al., 2015). In contrast, when drivers receive nondirectional information, they must continue observing surrounding traffic until they find the hazard, as they cannot determine where it is coming from, increasing reaction times.

When the warning and the hazard are in the same direction, reaction times are much quicker (Liu and Jhuang 2012), and individuals both respond more quickly and make fewer errors (Change et al., 2008; Chang et al., 2009; Liu and Jhuang 2012). Fitch et al. (2007) found that directional cues improved localization from 32% to 84% and reduced mean localization reaction times by 257ms. The study also found that tactile directional cues had a 92% directional accuracy rate, and tactile cues are superior to auditory alerts for spatial cueing. They also found no evidence that vehicle and whole-body vibrations decrease tactile perception. Spence and Ho (2008) found spatial vibrotactile cues to be particularly effective in diverting drivers' attention to potential hazards on the road, and Hogema et al. (2010) found high localization accuracy with tactile warning signals. Based on this review of prior studies, vibrotactile spatial signals, warning signals for alerting or redirecting attention, may be a practical and effective method to convey directions and spatial information to drivers with HVFL.

2.3 Tactile directional cues for drivers with HVFL

A pilot study by Hölzl et al. (2021) evaluated a simple directional vibrotactile warning for drivers with HVFL in a driving simulator and found that the warning improved their safety. However, a major limitation of the study was the use of a fixed trigger distance for the warning signal; the warning was always triggered at a 45m distance for pedestrians crossing from the right, and 72m for pedestrians crossing from the left. The warning was triggered irrespective of the participant's speed and the criticality of the situation. The warning was purposefully given early to allow sufficient time for the driver to initiate a safe response. However, the feedback from the participants suggested that the warning was often

triggered earlier than necessary which could have led to participants ignoring the warning or receiving too many unnecessary warnings.

In studies of drivers with normal vision, a warning that contains directional information allowed the driver to locate the hazard more easily than a warning without directional information and was found to reduce reaction times (Dettman et al., 2017; Zhang et al., 2015). In contrast, when drivers receive nondirectional warnings (does not indicate whether the hazard is on the right or left), they may have to look to both the left and right until they find the hazard, increasing reaction times.

3. The current study

The overall goal of my thesis project was to evaluate vibrotactile hazard warnings as an assistance device for drivers with HVFL. I used the safe, controlled, and repeatable environment of a driving simulator to evaluate the effects of the warnings on gaze behaviors and driving responses to pedestrian hazards. The pilot study by Hölzl et al. (2021) demonstrated that vibrotactile warnings can be used to improve safety of driving responses to pedestrian hazards, but the warnings were given very early and did not take account of the criticality of the situation. I addressed these limitations by using a warning which was only triggered when the risk of collision with a pedestrian exceeded a pre-defined threshold based on time-to-collision that takes account of the distance to the collision point and the speeds at which the participant's vehicle and the pedestrian were moving. A warning was only given when the collision risk exceeded the threshold, which was more representative of how a collision warning system would operate in real world driving.

In designing the current study, comparing three different types of cues, including tactile, auditory and visual, as well as comparing multimodal cues was considered. However, trying to evaluate all possible combinations was beyond the scope of an MS thesis. After completing a review of the literature on different warning types (see above section on hazard warnings), I decided to focus on vibrotactile warnings given that prior studies suggest they were more effective than auditory or visual warnings (at least for drivers without vision impairment). I was interested in how directional versus nondirectional cues would affect the driving behavior of drivers with HVFL, and therefore the safety of their driving. Given the lack of peripheral vision on the blind side, I expected that directional cues would be more helpful than nondirectional cues in warning drivers with HVFL about hazards on their blind side

4. Study hypotheses / Research questions

The goal of this study was to explore the effects of two different vibrotactile pedestrian hazard warnings, 1) directional warnings which provide information about the direction (left or right) from which the pedestrian hazard is approaching and 2) nondirectional warnings which provide a warning but without information about whether the pedestrian was from the left/right on drivers with HVFL and age-matched controls. Within the controlled environment of a driving simulator, the effects of the warnings on gaze patterns and driving responses to pedestrian hazards were evaluated. Questionnaires were used to quantify the opinions of HVFL and normal vision drivers regarding the helpfulness of these warning systems and the interest in integrating these systems into real life driving.

For drivers with HVFL, I expected that the directional hazard warning would have a greater beneficial effect on responses to pedestrians crossing from the blind than the seeing side and be of more benefit than the nondirectional hazard warning. This includes a faster time to fixation and a faster time to first brake with the directional than the nondirectional warning.

For age-matched normal vision participants, I hypothesized that there would be a smaller overall effect of the warnings than for HVFL participants, with no difference in the magnitude of the effect for pedestrians from the left and right (because they have peripheral vision on both the left and right sides), and no difference between directional and nondirectional cues.

Given the lack of studies directly comparing the use of directional and nondirectional warning signals for drivers with vision loss, we expect this work to result in new insights on the effectiveness of providing directional warning signals to improve the safety of drivers and surrounding traffic.

METHODOLOGY

1. Participants

This was a driving simulator study conducted at the Schepens Eye Research Institute. The study followed protocols approved by the institutional review board (IRB) at the Schepens Eye Research Institute. Sixteen participants with homonymous visual field loss (HVFL) and sixteen age-matched controls were recruited.

Participants with HVFL were recruited from a database of subjects who had participated in prior studies in Dr. Bowers' lab and from referrals by low vision practitioners. HVFL participants met the following criteria: (1) a HVFL (hemianopia or quadranopia) for at least three months, confirmed by Goldmann perimetry (kinetic V4e target); (2) no visual neglect screened using Bells test (Vanier et al. 1990) and Schenkenberg line bisection test (Schenkenberg et al. 1980); (3) visual acuity of at least 20/40 in each eye with habitual correction; (4) no physical impairment that could prevent the use of the standard vehicle controls (pedals, steering wheel) in the driving simulator; and (5) prior driving experience. The cognitive status of participants with HVFL was quantified with the Montreal Cognitive Assessment test (MoCA Nasreddine et al. 2005). A total of sixteen participants with HVFL were recruited. One subject was excluded because they did not have any prior driving experience. Data from one subject was excluded because of errors in eye-tracking data. Thus, the final data set included 14 participants with HVFL. Only two participants with HVFL were current drivers (because people with hemianopia do not meet the visual field extent criteria for driving in Massachusetts); however, the remainder were all very interested in driving, if permitted.

Participants with normal vision were recruited from a database of subjects who had participated in prior studies and through recruitment emails to the faculty and students at the New England College of Optometry and faculty at Schepens Eye Research Institute. They were recruited to provide a similar age and gender distribution to the participants with HVFL. Criteria included: (1) current driver; (2) visual acuity of at least 20/40 in each eye with habitual correction; (3) no peripheral visual field loss (4) no adverse history of ocular disease (self-reported) which could affect visual acuity or visual fields; and (5) no physical impairment that could prevent the use of the standard vehicle controls (pedals, steering wheel) in the driving simulator. A total of 18 participants with normal vision were recruited for the study. Six participants could not complete the study due to motion sickness and were excluded, for a total of 12 normal vision participants included in the data analysis.

All participants completed a questionnaire to document demographic information (age, gender, onset of visual field loss, cause of visual field loss) and driving experience (year participants started driving, whether they are still driving or when they stopped driving). For participants who were current drivers, additional questions addressed driving exposure (trips per week and miles driven per year), driving behaviors (typical speed and destinations, driving conditions or locations participants avoid), self-reported violations, and crashes.

Driving Simulator and Virtual Scenarios

Participants drove in a custom-built, fixed-base driving simulator (Figure 1). The simulator elements included the driver seat, pedals, steering wheel, eye tracking system, vibrotactile assistance system, monitors, and computer. The ClubSport Pedals V3, consisting of an accelerator, brake pedal, and steering wheel, were products from Fanatec (Landshut, Germany). Three 34" curved monitors (Samsung C34F70, 3440 x 1440 pixels, 4ms response time, 21:9 aspect ratio) provided a 155-degree horizontal field of view. Rear-view mirrors and a speedometer were displayed on the screens. A Tobii 4C eye tracker (Tobii Eye Tracker 4C, Sweden) installed underneath the center screen recorded gaze positions on that screen at 90 Hz. The gaze tracking data was synced with the driving performance data through the simulator software.



Figure 1. Driving Simulator

2. Pedestrian Crossing Scenarios



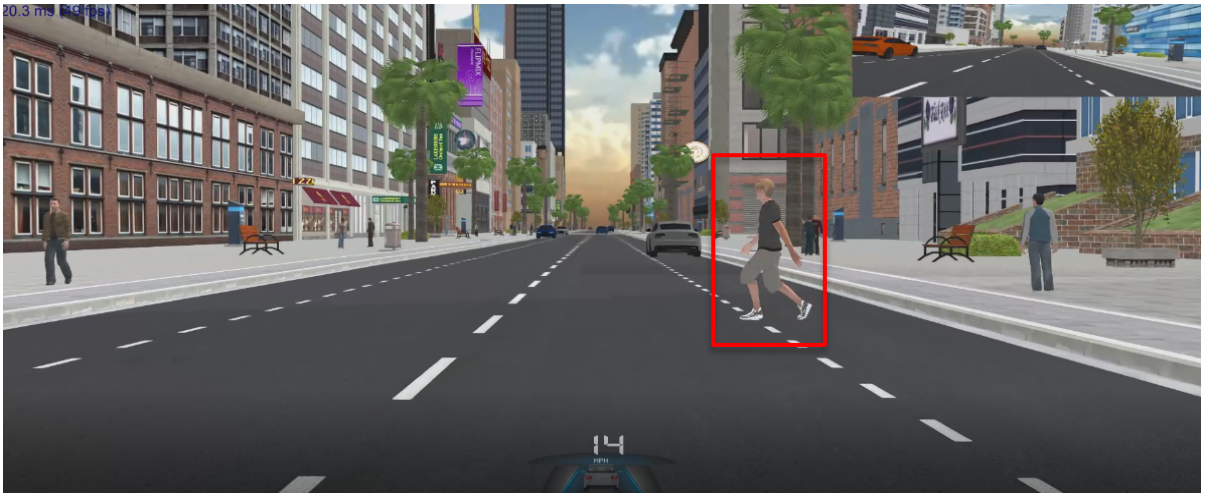




Figure 2. Pedestrian Crossing Scenarios

Screenshots of the virtual world showing a pedestrian crossing scenario. The pedestrian first appears from behind a tree on the right and crosses the street in front of the participant's vehicle. Top: Pedestrian has appeared from behind the tree and is walking toward the road. Middle: Pedestrian has started to cross the road and is about to enter the driver's travel lane. Bottom: Pedestrian has crossed the driver's travel lane.

The virtual world and scenarios were developed using Unity. For this study, six experimental drives were created within a city environment, each lasting about 10-15 minutes. The city drives were on two-lane roads, and one-way streets with oncoming and passing traffic (cars, trucks, buses), with scenery including shops and businesses typical of a city environment as well as trees and benches (Figure 2). A variety of pedestrians populated the environment, walking on the sidewalks, standing in groups, and some also crossing the street.

Ten pedestrian crossing events were scripted in each drive, with an equal number of crossings from the left and right. The crossing situations occurred on a straight section of the road and were not near traffic intersections or turns (Figure 2). In each event, the pedestrian was initially hidden from the participant by a tree or phone booth and only started to move once the participant's car reached the trigger zone. When triggered, the pedestrian was at an eccentricity of 10-15 degrees relative to the heading direction of the car. This range of eccentricities provided variety for the crossing situations and was within the range of eccentricities where participants with HVFL had impaired blind-side detection performance in a prior driving simulator study (Bowers et al., 2009). Once the pedestrian started moving, it crossed the street perpendicular to the road at a constant speed of 2.5 m/s and the participant needed to brake to avoid a collision.

3. Vibrotactile Assistance System

The assistance system consisted of a seat cover (444mm x 380mm x 35mm) with six vibration motors embedded within the foam cushion placed centrally on the driver's seat with three motors on the left and three on the right side (Holzl et al., 2021). For the directional warnings, the motors on either the left or right side vibrated (the side of vibration indicated the direction from which the pedestrian hazard was approaching). For the nondirectional warnings, the motors vibrated on both sides simultaneously. When a predetermined warning threshold was exceeded, the system provided a 500ms vibration (Summers et al., 1997) to warn the driver of the potential hazard.

In this study, the Time-to-collision (TTC) was used as the timing threshold for triggering hazard warnings. TTC is a warning criterion that has been widely used in many automobile collision avoidance systems or driver assistance systems (Mahmud et al., 2017). TTC is defined as “the time until a collision between the vehicle and pedestrian would occur if they continued their present course at their present speeds” (Hydén, 1996). Studies have demonstrated the benefits of utilizing TTC thresholds as a warning criterion for pedestrian warning systems (Bargman et al., 2017; Cicchino 2017; Rakha et al., 2008) and various warning thresholds have been identified through different studies for normally sighted drivers (Abe and Richardson 2005; Large et al., 2019; Yang et al., 2019). Different TTC threshold values can be set for various conflict situations and range widely from 0.9 to 4 seconds (Mahmud et al., 2017) with a lower TTC indicating a more dangerous situation. In this study, the TTC was calculated in real-time based on the time (in seconds) that would have been required to stop the vehicle before reaching the collision zone with the pedestrian assuming they continued their present course at their present speeds. We set a TTC of 3

seconds as a warning threshold based on a previous study exploring the use of different warning timing thresholds for visually impaired drivers (Xu et al., 2022). This TTC provided participants with HVFL sufficient time to respond to the warning to avoid a collision.

4. Study Procedures

Participants were provided with a consent form and the nature and possible consequences of the experiment were explained before the consent form was signed. Participants were told that their participation in the study was completely voluntary and that they could withdraw at any point in the study. Visual acuity and contrast sensitivity were measured using FrACT software (Bach 1996), a computerized test presented on a computer monitor. The participants were tested with appropriate correction and at 4m. For participants with HVFL, the area of field loss was quantified using Goldmann perimetry (kinetic V4e target), binocularly, and the line bisection test, Bells test, and MoCA were performed. In addition, a demographic and driving history questionnaire was administered to document age, onset of visual field loss and cause, age of first driver's license, whether or not they were current drivers, and driving history or current driving habits.

At the start of driving simulator session, the seat and pedal positions were adjusted for each participant. The eye tracker was then calibrated using in-built Tobii calibration procedures and verified using custom-developed gaze validation software (a 9-point validation, covering the full extent of the center screen). Participants then completed a short acclimation drive to get used to the driving simulator, starting on straight roads without other traffic and progressing to practicing driving within the city and making turns. After acclimation, they completed one practice drive and two experimental drives for each of the

three warning types: no warnings, tactile directional warning, and tactile nondirectional warning. The practice drive for each warning type was always completed immediately before the two experimental drives for that condition, with the order of the experimental drives counterbalanced within each condition. The order of conditions was counterbalanced across participants and administered in two blocks: a block of drives without warnings and a block of drives with warnings (directional and non-directional warnings were counterbalanced within this block). Participants either started or ended with the block of drives without warnings. Controls completed the drives in the same order as the participants with HVFL to whom they were matched.

The practice drive for each warning type was similar to the experimental drive for that condition, including the corresponding warning type, pedestrian crossing situations, and traffic on the road. For drives with warnings, the method of operation was explained, and participants experienced what the warning felt like before starting to drive. After completing a practice drive for each condition, the participants completed the main experimental drives.

Participants were instructed to follow the normal rules of the road, although other traffic and pedestrians would not necessarily follow the standard rules of the road, and to avoid collisions. They were informed of the 30-mph speed limit with a 35-mph speed cap. Pre-recorded, spoken audio cues triggered by the car's position in the virtual world were used to direct the driver to turn left or right along the pre-determined routes. Before each drive with hazard warnings, the participants were reminded that, as with all driver assistance systems in real life, the warning system would only provide a warning when a situation started to become dangerous (so if the participant responded quickly to a situation, they might not receive a warning). Additionally, they were reminded that the warning system

might not always work perfectly (and might fail to give a warning when a situation was getting dangerous).

5. Driving performance and gaze behavior measures

Driving performance and gaze data were collected using simulator software at 50 Hz. Following data collection, data was processed in MATLAB (Mathworks, R2017a). The main measures included: time to first fixation, time to first brake, collision rate, and number of scans, derived using Matlab software developed in-house (Swan et al., 2021).

Time to first fixation was defined as the time from when the pedestrian first appeared to when the participant first fixated on the pedestrian (Figure 3). *The time to first brake* was defined as the time from when the pedestrian first appeared to when the participant first pressed the brake pedal (Figure 3). The collision rate was computed as the number of crash events as a percentage of the total number of pedestrian events. Collision events were defined as physical contact that occurred between two road users: crossing pedestrians and the driver in the virtual environment. These events occurred when the pedestrian crossed the street before the participant could brake or the participant was not able to identify the crossing pedestrian and kept driving.

The number of scans was defined as the total number of gaze scans to the left or right side respectively, defined as the series of saccades starting at the 0-degree eccentricity (looking straight ahead) and taking gaze to the most eccentric position to either the left (negative eccentricities) or right (positive eccentricities) (see Figure 3). The number of scans for each event was calculated from when the pedestrian first appeared to when the pedestrian left the collision zone.

In addition, we analyzed the proportion of events for which the pedestrian was fixated before the brake was pressed (i.e., when the time to first fixation was shorter than the time to first brake), and the direction of the first gaze movement after a warning was received (whether it was to the blind or seeing side for HVFL participants, and whether it was in the direction of the crossing pedestrian; Figure 3.

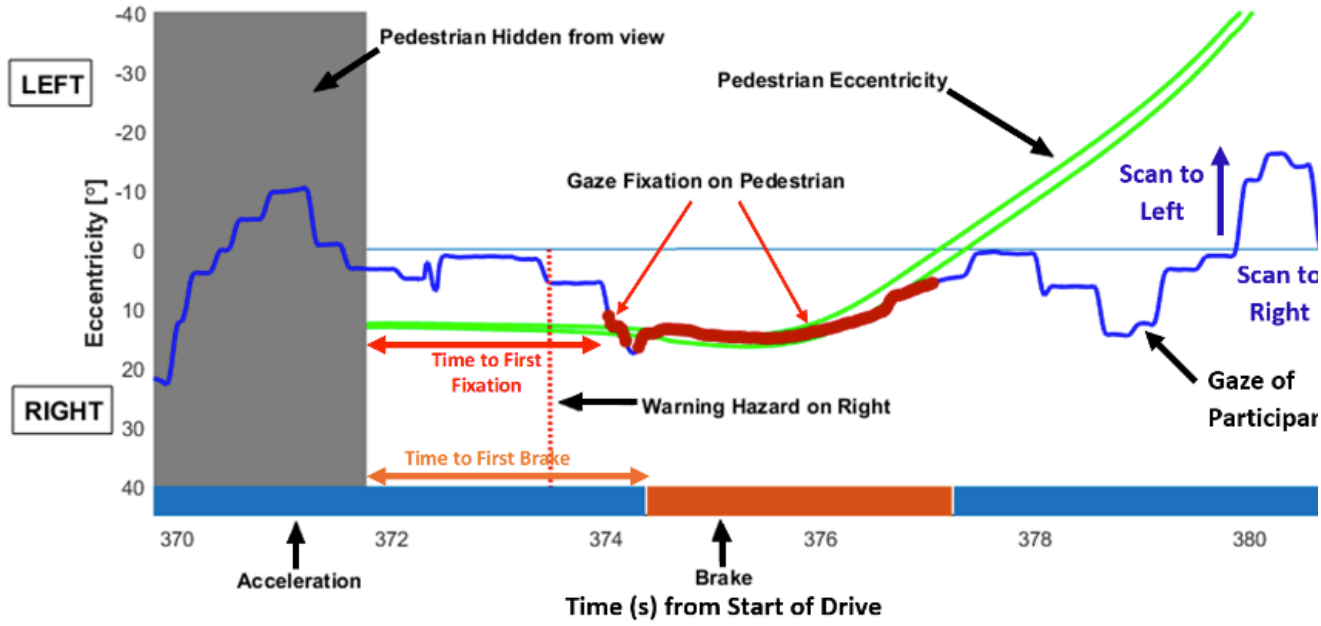


Figure 3. Pedestrian Crossing Event Summary

Lateral gaze and pedestrian eccentricity for an event in which a pedestrian crossed from the right side of the road in a drive with directional warnings for a participant with right hemianopia. The pedestrian appeared in the blind hemifield while the participant was looking slightly to the right (but not far enough to the right see the pedestrian). After the participant received a warning for a hazard on the right, they made a scan which took gaze further to the right so they could see the pedestrian and they fixated on the pedestrian while it crossed the road. They braked soon after fixating the pedestrian leading to a safe street crossing.

6. Participants' Feedback

Participants' opinions and preferences for directional tactile and nondirectional tactile warnings were evaluated using a questionnaire administered before and after driving in the simulator. The pre-questionnaire consisted of a description of the two warning systems and participants were asked about which warning system they might prefer based on the description provided. The post-questionnaire focused on the participant's experiences with the two warning systems when driving in the simulator. Questions asked the participant about the helpfulness of the warning system, whether the warning system influenced their driving behavior, and whether they would want a similar kind of system in their own car. Additionally, the participants were asked which system (directional or nondirectional warnings) they might prefer based on their experiences in the driving simulator.

7. Statistical Analyses

Statistical analyses were performed using R Version 1.1.463. For normal vision participants there were no differences in performance measures between pedestrians approaching from the right and left sides. Therefore, to simplify analyses, data were pooled across right and left sides for participants with normal vision, and pedestrian approach direction was categorized as HVFL_Blind side, HVFL_Seeing side, and Normal Vision. We applied a linear mixed-effects analysis for continuous measures (e.g. time to first fixation, time to first brake response) and a generalized linear mixed-effects model for non-continuous measures (e.g. number of scans) (Bates et al 2015). All models included warning type (directional, nondirectional and no warnings) and pedestrian approach direction (HVFL_Blind side, HVFL_Seeing side, and Normal Vision) as main factors. Event number

and participant identifier were included as random factors in the model. A Mann-Whitney U test was performed to analyze whether there were any group differences in participant characteristics. A significance level of $P = .05$ was used.

RESULTS

1. Characteristics of Participants

1.1 HVFL Participants

Sixteen participants with HVFL completed the study. Two subjects were excluded from the analyses: one subject for errors in eye-tracking data, and one subject because they did not meet the inclusion criteria (did not have any prior driving experience). Thus, the final data set included 14 participants with HVFL, four female and ten male (Table 1). The majority of the subjects had visual field loss due to stroke (n=10). The average duration of HVFL was around seven years. There were two current drivers, and the rest were former drivers.

Table 1. HVFL Participant Characteristics

Participant	Age	Gender	VA (logMAR)	Contrast Sensitivity (logCS)	Side of Visual Field Loss	Cause of Visual Field Loss	Duration of HVFL (years)	Driving Status
1	53	Male	-0.17	1.35	Left HH	Stroke	6	Prior
2	26	Male	-0.17	1.87	Left HH	Stroke	4	Prior
4	50	Male	-0.17	1.93	Left HH	Stroke	3	Prior
5	30	Female	-0.17	1.76	Right HH	Brain Tumor	3	Prior
6	55	Male	-0.27	1.76	Left HH	Brain Cyst	18	Prior
7	24	Male	0.13	1.76	Left HH	Brain Tumor	4	Prior
8	75	Female	-0.12	1.76	Left HH	Stroke	3	Prior
9	73	Male	-0.14	1.93	Right HH	Stroke	12	Current
10	54	Male	-0.07	1.31	Left HQ	Stroke	6	Current
11	58	Male	-0.03	1.31	Right HH	TBI	22	Prior
12	38	Female	0.01	1.36	Left HH	Stroke	4	Prior
13	34	Male	0.03	1.36	Right HQ	Stroke	7	Prior
14	83	Female	0.25	1.67	Left HH	Stroke	1	Prior

1.2 Normal Vision Participants

The normal vision participants were recruited to be age and gender-similar to the HVFL participants. A total of 18 participants were recruited for the study. Six participants could not complete the study due to motion sickness and were excluded, for a total of 12 normal vision participants included in the data analysis (Table 2).

1.3 Comparison of HVFL and normal vision groups

There was no significant difference between the HVFL and normal vision groups for age (P = .40), total years of driving experience (P = .35) and visual acuity (P = .29). Mean contrast sensitivity was worse in HVFL participants than normal vision participants. Prior studies have also reported lower contrast sensitivity in the seeing hemifield of people with HVFL than in normal vision participants (Philip et al., 2013). Contrast sensitivity also decreases with age (Hess et al., 1989) and the HVFL participants were slightly, but not significantly, older than the normal vision participants.

Table 2. Participant Characteristics

	HVFL	**Normal Vision**
Number of participants	14	12
Age, years, median (IQR*)	54 (35 to 61)	42 (32 to 51)
Male, n (%)	78% (n=11)	68% (n=8)
Visual acuity, LogMAR, Median (IQR)	-0.07 (-0.17 to 0.01)	-0.16 (-0.25 to 0.07)
Contrast sensitivity, LogCS, Median (IQR)	1.74 (1.36 to 1.76)	1.9 (1.76 to 2.04)
Side of Visual Field Loss, n (%)		
Left	10 (71%)	N/A
Right	4 (29%)	
Cause of Visual Field loss, n (%)		
Stroke	(10, 71%)	N/A
Brain tumor/cyst	(3, 21%)	
TBI	(1, 7%)	
Current Drivers, n (%)	2 (14%)	12 (100%)
Driving experience, years, Median (IQR)	36 (15 to 42)	19 (12 to 29)

***** IQR = interquartile range

2. Overall Behavior of Participants at Pedestrian Crossing Events

Here we give examples of the performance of HVFL participants at pedestrian crossing events. We then report the proportion of pedestrian events where warnings were triggered.

2.1 Examples of Pedestrian Crossing Event Performance for HVFL Participants

The following figures show the behavior of three different HVFL participants at pedestrian crossing events (Figure 4-6). Three scenarios are shown with three different warning types: no warning, directional warning, and nondirectional warning.

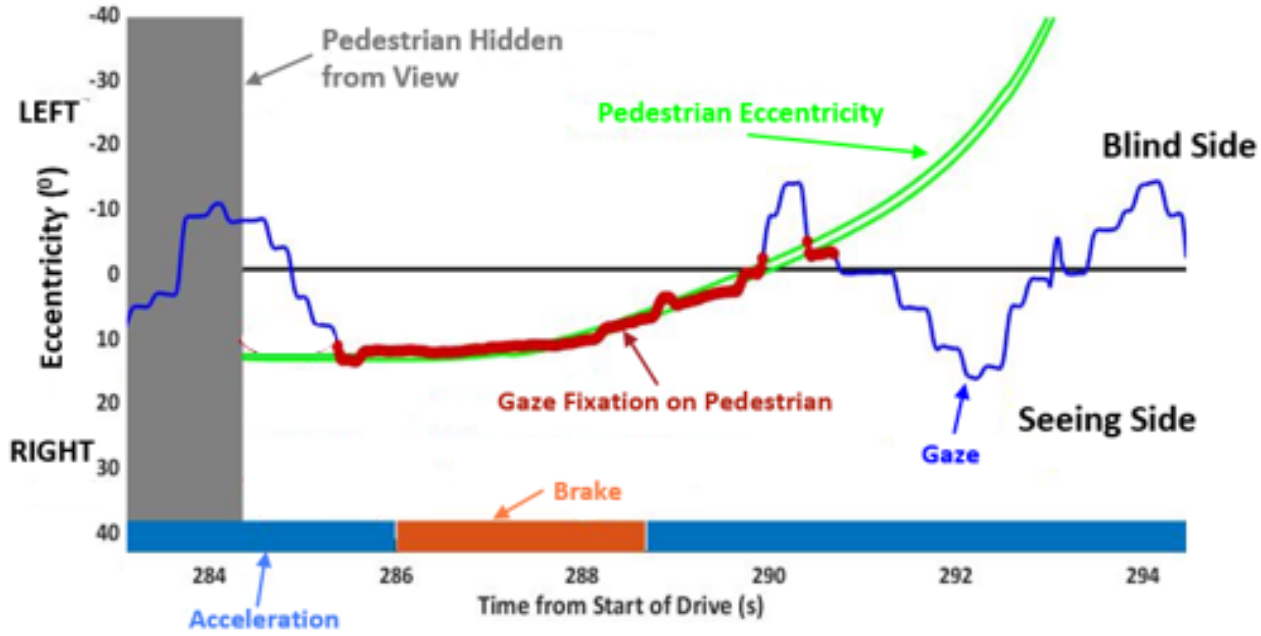


Figure 4. Left HVFL: Seeing side hazard and no warning triggered.

Plot shows data for a participant with left homonymous visual field loss (HVFL) for an event where a pedestrian crosses from the right (seeing) side of the road in a drive in which a warning was not triggered. The x-axis represents the time from the start of the drive in seconds, and the y-axis represents the eccentricity in degrees. The negative eccentricity values represent the left side of the road, and the positive eccentricity values represent the right. The grey shaded area means the pedestrian is not visible to the participant during that time. The green lines show the eccentricity of the pedestrian. The blue line represents the gaze of the participant on the screen. The orange and blue bars on the bottom represent the

brake and acceleration behaviors of the participant. The bold red line represents the participant's fixation directly on the pedestrian. In this event, the pedestrian appeared from the seeing side. The participant quickly saw and fixated the pedestrian and braked soon after the fixation leading to a safe street crossing.

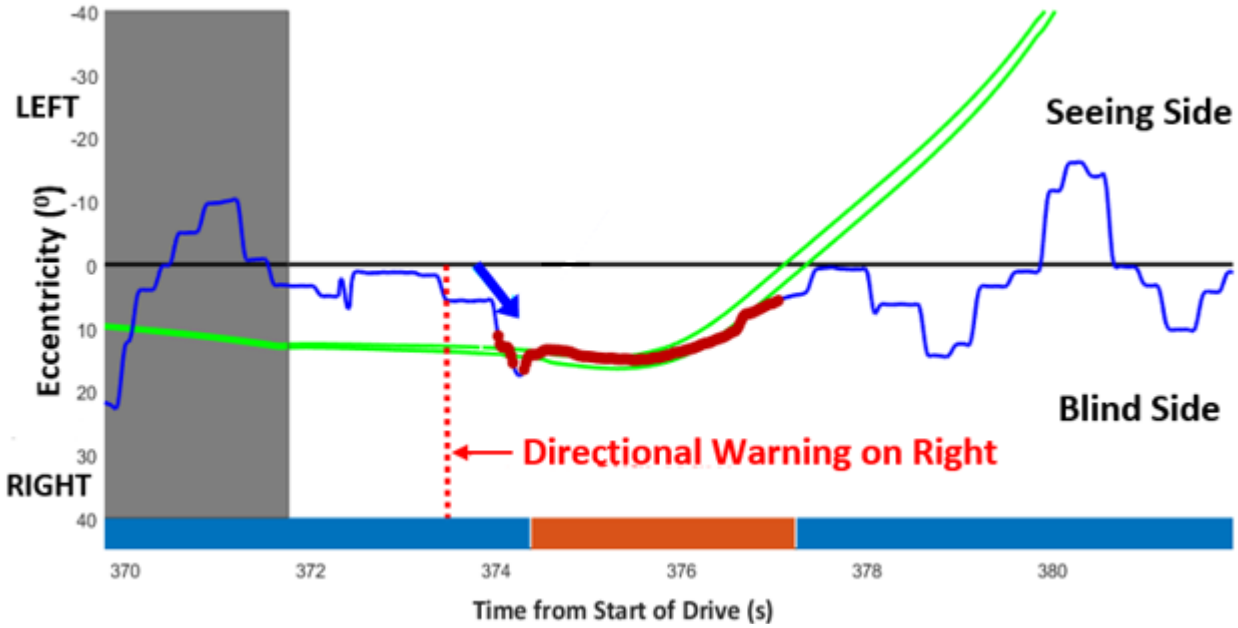


Figure 5. Right HVFL: Blind side hazard and directional warning.

Data for a participant with right HVFL for an event where a pedestrian crossed from the right (blind) side of the road in a drive with directional warnings. At the start of the event when the pedestrian appeared, the participant was mostly looking straight ahead or slightly to the right (but not far enough to the right to see the pedestrian). The participant received a directional warning on the right. After receiving the warning, their first scan was in the direction of the hazard. They fixated on the pedestrian and soon after braked leading to a safe street crossing.

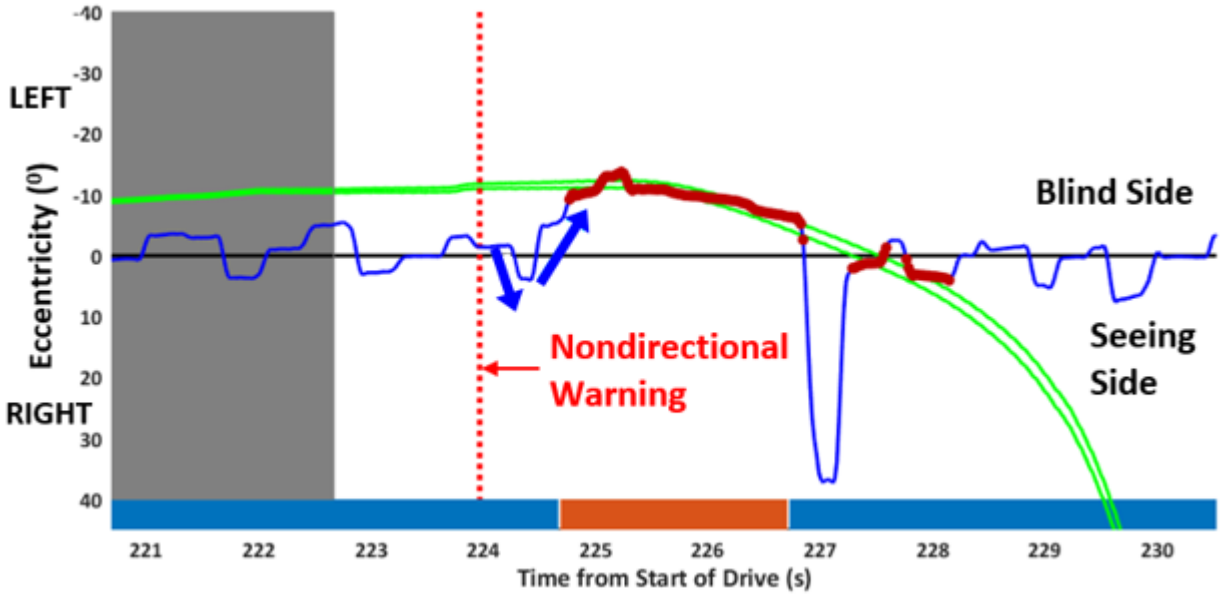


Figure 6. Left HVFL: Blind side hazard and nondirectional warning.

Data for a participant with left HVFL for an event where a pedestrian crossed from the left (blind) side of the road in a drive with nondirectional warnings. When the pedestrian first appeared the participant's gaze was close to straight ahead and they never looked far enough to the left to see it. The participant then received a nondirectional warning. After the warning, they made their first scan away from the hazard, and their second scan towards the hazard. They also braked first before they fixated on the pedestrian.

2.2 Proportion of Events with Warnings

For the HVFL group, the average proportion of events with warnings was greater when pedestrians approached from the blind side (88%) than the seeing side (78%). However, there was little difference in warning rates between drives with directional (83%) and nondirectional (78%) warnings and the proportion of events (81%) where the warning threshold was exceeded in drives without warnings. In contrast, the proportion of events with warnings was only 33% for the normal vision participants.

3. Gaze Behavior on Pedestrian Crossing Events

We evaluated the effect of the warning type (directional, nondirectional, and no warning) and pedestrian approach direction (HVFL_Blind side, HVFL_Seeing side, and Normal Vision) on gaze behaviors during pedestrian crossing events.

3.1 Proportion of Events where Participants Fixate First Before Braking

For pedestrians approaching from the HVFL participants' blind side, the rates of fixating the hazard before braking were higher for drives with directional warnings (86%) than nondirectional (74%), and lowest for drives without warnings (56%) (Figure 7). For pedestrians approaching from the seeing side, rates of fixating before braking were high (about 82%) with no effects of warning type. Participants with normal vision almost always fixated before braking (99%) with no effects of warning type.

For HVFL participants, we further examined what happened in events where a pedestrian approached from the blind side and the warning threshold was exceeded (includes data from drives with and without warnings). When there was a collision, the pedestrian was never fixated; however, when there was no collision, the pedestrian was usually fixated first (86%).

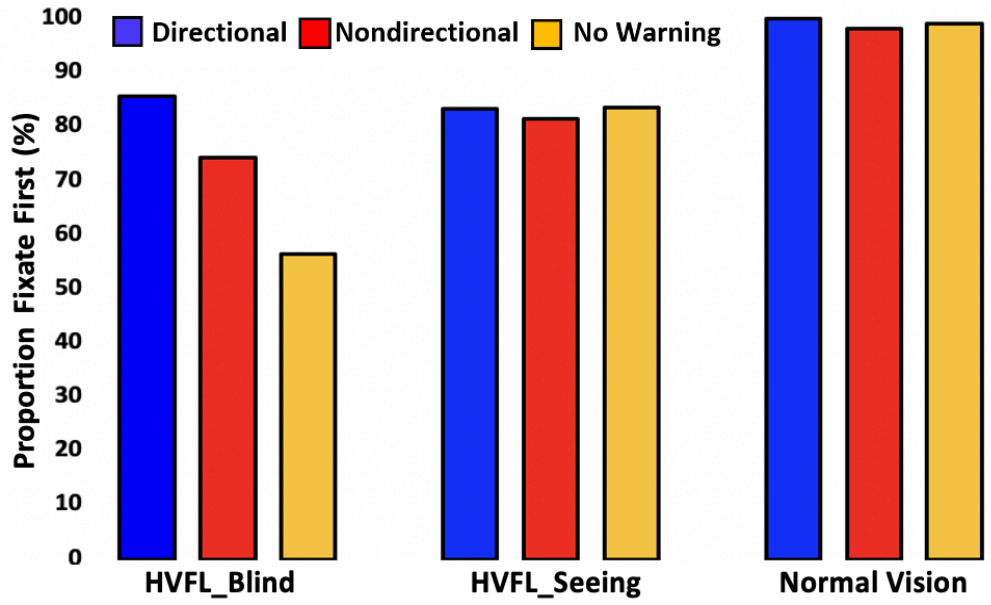


Figure 7. Proportion of events where the pedestrian was fixated before braking for the three warning conditions for HVFL blind side and seeing side and normal vision participants.

3.2 First Gaze Direction After Warning

After receiving a directional warning, HVFL participants made their first scan towards the blind side for 54% of events and towards the seeing side for 46% of events. After a nondirectional warning, the first scan was towards the blind side for 63% vs seeing side 37% of events. Combining data for the two types of warnings, the first scan after the warning was to the blind side more often than to the seeing side (58% vs 42%) overall.

For directional warning events, the first gaze after the warning was in the direction of the pedestrian for 88% of blind side warnings compared to only 25% of seeing side warnings. For nondirectional warning events, the first gaze after the warning was in the direction of the pedestrian for 81% of blind side warnings compared to 37% of seeing side warnings.

3.3 Number of Scans

The number of scans made did not differ significantly between the blind and seeing side for HVFL participants (mean: 3.07 vs 3.17, b=-0.23, SE=0.14, t=-1.7, p=0.08; Figure 8). However, HVFL participants made significantly more scans to the seeing side than normal vision participants (mean: 3.17 vs 2.38, b=0.09, SE=0.04, t=2.2, p=0.03).

There was no significant main effect of warning type and no significant interaction between the pedestrian approaching side and the warning type on the number of scans made.

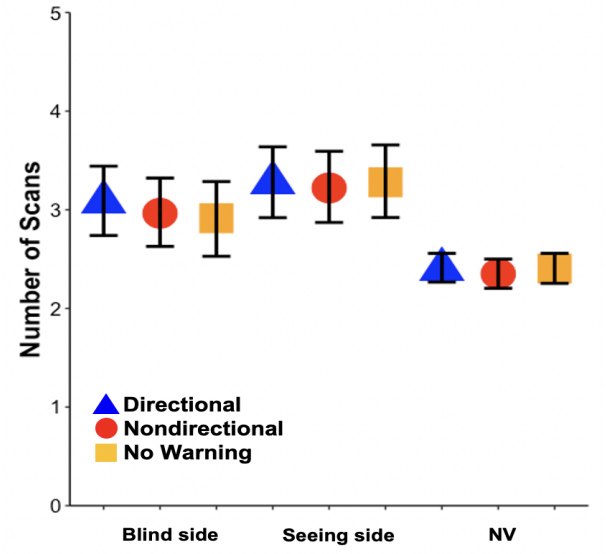


Figure 8. Number of Scans

The mean number of scans for the three warning conditions for HVFL blind side and seeing side and normal vision participants. The type of warning is represented by directional (blue triangle), nondirectional (red circle), and no warning (yellow square). Error bars represent the standard error of the mean.

3.4 Time to First Fixation

There was a main effect of pedestrian approach direction (Figure 9-A). For HVFL participants, the time to first fixation was slower on the blind than the seeing side (mean: 1.69s vs. 1.38s, b = .04, SE = .001, t = 4.13, P < .001). Normal vision participants were

significantly faster to fixate on pedestrian hazards than HVFL participants were on their seeing side (mean: 0.72s vs. 1.38s, b = .14, SE = .02, t=6.9, P < .001). For data pooled across pedestrian approach direction, the time to first fixation did not differ when driving with no warnings versus nondirectional warnings (mean: 1.03s vs. 1.23s, P = .11). However, it was significantly faster with directional warnings than nondirectional warnings (mean: 1.16s vs 1.23s, b = .36, SE = .001, t = 4.27, P < .001).

We also found significant interactions between the pedestrian approach direction and warning type (Figure 9-A). The first fixation times did not differ between HVFL blind and seeing sides when driving without warnings (mean: 1.29s vs. 1.30s) and when driving with directional warnings (mean: 1.66s vs. 1.45s). However, when driving with nondirectional warnings, the first fixation times were significantly longer (by 0.59s) on the blind than the seeing side (mean: 1.99s vs. 1.40s, b = -.008, SE = .002, t = -3.70, interaction P < .001). Additionally, the first fixation times on seeing side pedestrians did not differ between directional and nondirectional warnings (1.45s vs. 1.40s); however, the fixation times on blind side pedestrians were significantly faster (by 0.33s) when driving with directional warnings versus nondirectional warnings (1.66s vs. 1.99s, b = .005, SE = .002, t = 2.18, interaction P = .03).

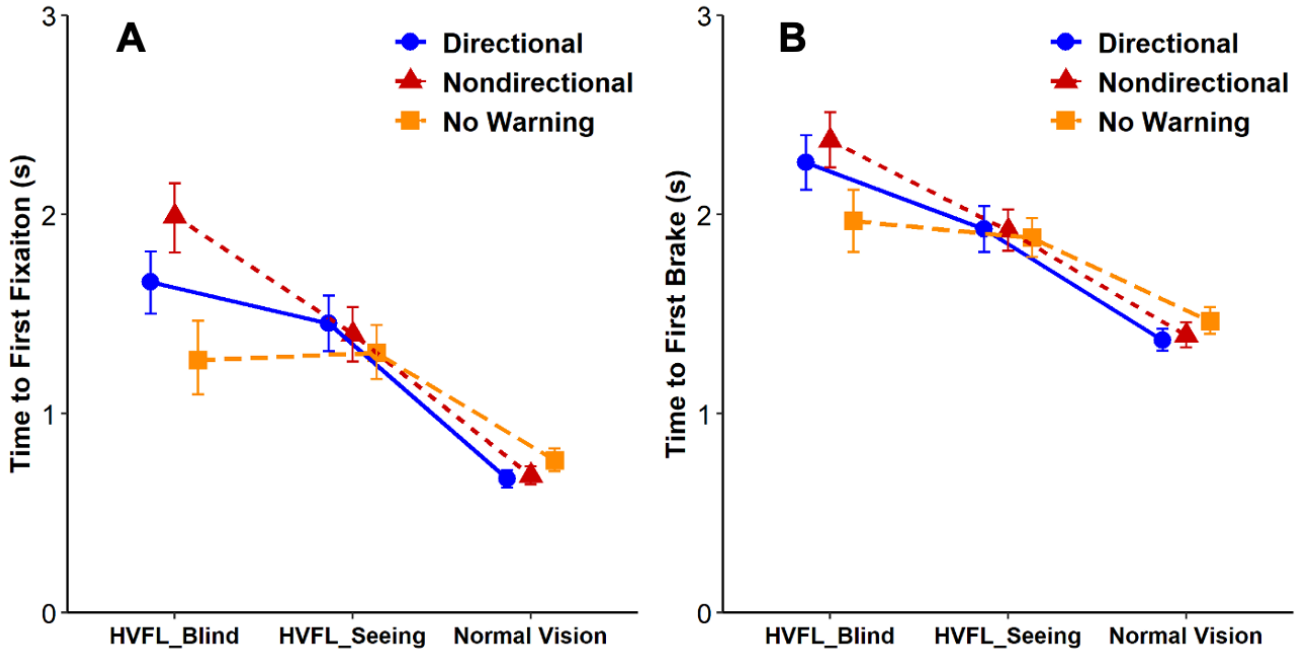


Figure 9. Time to first fixation and first brake

The mean time to first fixation (A) and the mean time to the first brake press (B) for the three warning conditions for HVFL blind side and seeing side and normal vision participants. Error bars represent the standard error of the mean.

4. Driving Responses to Pedestrian Crossing Events

We assessed the effect of warning type (directional, nondirectional, and no warning) and pedestrian approach direction (HVFL_Blind side, HVFL_Seeing side, and Normal Vision) on the time to the first brake press and on collision rates.

4.1 Time to First Brake

There was a main effect of pedestrian approach direction on brake responses (Figure 9-B). Overall, HVFL participants were faster to initiate brake responses when pedestrian hazards approached from the seeing side compared to their blind side (mean: 1.91s vs. 2.23s, $b = -.34$, $SE = .04$, $t = -9.33$, $P < .001$), and normal vision participants were significantly faster to brake than HVFL participants on their seeing side (mean: 1.41s vs. 1.91, $b = -.54$,

SE = .14, t = -3.9, P < .001). There was also a main effect of warning type. For data pooled across pedestrian approach direction, participants were significantly faster to brake when driving without warnings compared to nondirectional warnings (mean: 1.70s vs. 1.82s, b = .09, SE = .03, t= 2.64, P = .008), but brake response times did not differ between drives with directional and nondirectional warnings.

There were significant interactions between pedestrian approach direction and warning type (Figure 9-B). When driving without warnings, the brake times did not differ between HVFL blind and seeing sides (mean: 1.97s vs. 1.88s). However, when driving with nondirectional warnings, the brake times were significantly slower (by 0.45s) for HVFL blind than seeing side (mean: 2.37s, vs 1.92s, b = .23, SE = .08, t= 2.55, interaction P = .01), and when driving with directional warnings, brake times were also significantly slower for HVFL blind than seeing side (mean: 2.26s vs 1.91s, P = .05).

4.2 Collision Rates

There were no collision events on the seeing side for HVFL participants and no collision events for normal vision participants. For HVFL participants when pedestrians approached from the blind side, collision rates were 15.7% without warnings, which reduced to 0.7% with nondirectional warnings and 0% with directional warnings (Figure 10).

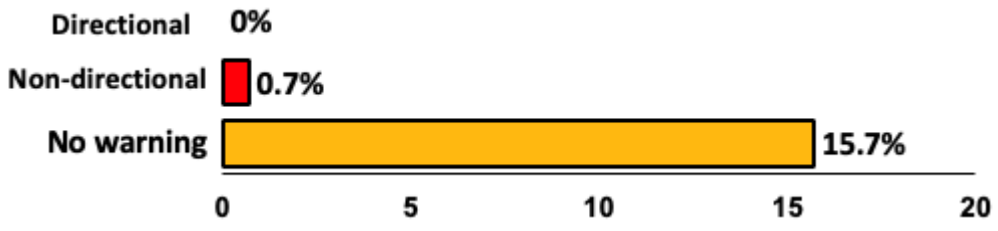


Figure 10. Collision Rates

The bar plot shows the collision rates for blind side events for each type of warning.

5. Participant Feedback

Participants' responses to the questionnaires administered before and after driving in the simulator are summarized in Table 3. The majority of HVFL participants preferred a directional warning system both before (86%) and after driving (79%). Two HVFL participants who initially preferred directional warnings, responded after driving, that they preferred nondirectional warnings. Both these participants reported that they did not use the directional information since they could already tell that a pedestrian was crossing from their blind side if they did not see anything on the seeing side. Another participant who initially preferred nondirectional warnings later had no preference since the directional component had no difference to them because they were "always scanning." In contrast, only 50% of normal vision participants preferred directional warnings in both the pre- and post-questionnaire. The two normal vision participants who initially preferred nondirectional changed their opinions to no preference after driving with the warning systems.

After driving with the warnings, most HVFL participants found the directional information extremely (29%) or very useful (57%), and the majority (86%) reported that they used the directional information. In contrast, only 33% of normal vision participants found the directional information very useful, and only two responded that they used the directional information. HVFL participants who used the directional information stated that they knew which way to look with directional warnings vs. nondirectional warnings; for nondirectional warnings they had to look to see where the hazard was coming from. Other participants thought they reacted quicker to the directional warnings in general. Overall, the warnings were found to be very helpful by 79% of HVFL participants compared to only 33% of normal vision participants. If permitted to drive, all HVFL participants wanted a similar

warning system in their car, compared to only 67% of normal vision participants wanted to own them.

Table 3. Questionnaire responses for the two groups

Question	Answer	HVFL n, %	Normal Vision n, %
Question before driving in the simulator			
Preference for warning type based only on the description	Directional	12 (86%)	6 (50%)
	Nondirectional	1 (7%)	2 (17%)
	No Preference	2 (14%)	4 (33%)
Questions after driving in the simulator			
How useful did you find the directional information?	Extremely Useful	4 (29%)	0%
	Very Useful	8 (57%)	4 (33%)
	Moderately Useful	2 (14%)	4 (33%)
	Slightly Useful	1 (7%)	4 (33%)
Did you actually use the directional information?	Yes	12 (86%)	2 (17%)
	No	2 (14%)	10 (83%)
Which of the two vibrational warning designs did you prefer?	Directional	11 (79%)	6 (50%)
	Nondirectional	2 (14%)	0%
	No Preference	1 (7%)	6 (50%)
Helpfulness of the warnings in general	Very Helpful	11 (79%)	4 (33%)
	Moderately Helpful	2 (14%)	4 (33%)
	Slightly Helpful	1 (7%)	4 (33%)
Would you use a similar kind of warning system in your own car?	Yes	14 (100%)	8 (67%)

DISCUSSION

1. Purpose of the Study

This study aimed to explore the effects of directional and nondirectional vibrotactile hazard warnings on gaze patterns and driving responses to pedestrian hazards within the controlled environment of a driving simulator. The warning system was designed to address difficulties drivers with HVFL have in responding to pedestrian hazards due to the lack of peripheral vision on the side of their vision loss. HVFL participants received warnings for the majority of pedestrian hazards (80% overall) in drives with warnings. Consistent with our hypothesis, directional warnings promoted faster fixations on blind side pedestrians than nondirectional warnings. However, both directional and nondirectional warnings were equally efficacious in improving driving safety by reducing collision rates for blind side hazards from 15% without warnings to less than 1% with warnings (similar to the seeing side). Consistent with the Hölzl et al. study (2021) which evaluated an early prototype of a pedestrian hazard warning system for drivers with HVFL, participants with normal vision received fewer hazard warnings (33%) than participants with HVFL. Furthermore, gaze and driving behaviors of participants with normal vision did not differ between drives with and without warnings.

2. Number of Warnings Received for Pedestrian Crossing Events

Participants with HVFL received more warnings on the blind (88%) than the seeing side (78%), consistent with the lack of vision on the blind side. However, the difference between the blind and seeing sides was not as large as might have been expected given the normal field of vision on the seeing side and the finding that NV drivers received warnings in

only 33% of events. Drivers with HVFL may have given more attention to their blind than seeing side, reducing awareness of pedestrian hazards on the seeing side. Interestingly, the rate of hypothetical warnings in drives without warnings (81%) was within the range of the number of warnings in drives with warnings, suggesting that overall participants with HVFL did not drive more carefully in drives without warnings (or less carefully in drives with warnings).

3. Gaze Behavior and Driving Responses to Pedestrian Crossing Events

When pedestrians approached from the blind side, HVFL participants were more likely to fixate the pedestrian before braking in drives with directional warnings than in drives with nondirectional warnings or without warnings. These findings suggest that the directional information helped guide gaze of the HVFL participants to hazards on the blind side. With nondirectional information, participants still needed to decide in which direction to scan and were more likely to brake before fixating the hazard (though they still fixated the pedestrian first in the majority of events). In contrast, when the pedestrian approached from the seeing side, there were no differences in the rates of fixating before braking for drives with directional, nondirectional, and no warnings. Normal vision participants almost always fixated before they braked, and this did not vary with the type of warning. Interestingly, rates of fixating before braking were higher for the NV participants (99%) than on the seeing side for HVFL participants (82%).

After receiving a directional warning, HVFL participants made a scan to the blind side in just over half of the events and to the seeing side in just under half of the events. In contrast, after receiving a nondirectional warning they were more likely to make their first

scan towards the blind (63%) than seeing side (37%). Again, these findings suggest that the directional warning was helpful in directing gaze to the side of the hazard while with the nondirectional warnings, they seemed to try to compensate by directing their first gaze towards the blind side. Previous studies (Meng and Spence 2015; Bates et al. 2015; Ho et al. 2005) have shown that directional tactile warnings can successfully convey spatial information and direct driver's attention to potentially risky areas; our study demonstrated that these benefits remain effective for drivers with HVFL, particularly in assisting with directing gaze and attention to blind side hazards.

Overall, there were no significant differences in the number of scans to the blind and seeing sides and between drives with and without warnings. We expected an increased number of scans to the blind side given prior studies (Bowers 2016; Xu et al., 2022) that found HVFL drivers made more compensatory scans to the blind than seeing side. Although there was no difference in the number of blind and seeing side scans, HVFL drivers made more scans than the normal vision drivers, suggesting that the HVFL drivers were aware of the need to scan. HVFL participants knew that pedestrian hazards could appear from either the left or the right and were therefore primed to look for them on both sides.

Consistent with prior driving simulator studies of people with HVFL (Bowers et al., 2009; Papageorgiou et al., 2012; Houston et al. 2018) when data were pooled across all warning types, the time to the first fixation on the pedestrian hazard and the time to the brake press response were slower on the blind than on the seeing side. However, for fixation times, there was a highly significant interaction between pedestrian approach direction and warning type. Specifically, in drives with directional warnings, the time to first fixation did not differ

between the blind and seeing sides whereas in the drives with nondirectional warnings, it took 0.6 s longer to the first fixation on the blind than the seeing side. In contrast, the time to brake was significantly longer on the blind than the seeing side when driving with directional and non-directional warnings. In addition, the first fixation times on blind side pedestrians were 0.33s faster when driving with directional warnings compared to nondirectional warnings, but the time to brake did not differ significantly between the two warning types. Thus, the beneficial effect of the directional information in guiding gaze of the participants with HVFL only seems to manifest in fixation behaviors and fixation times, not in the brake response times.

Interestingly, we found no differences in fixation times and no differences in brake response times between the HVFL blind and seeing sides when driving without warnings. This may seem counterintuitive; however, one likely explanation is that when driving without warnings participants with HVFL either scanned early, saw the pedestrian on the blind side and responded quickly (as quickly as on the seeing side), or they did not scan/scanned too late to the blind side, did not see the pedestrian, and had a collision. When there was a collision there was no fixation on the pedestrian and usually no brake response time was recorded. Therefore, in drives without warnings the blind-side events in analyses were mostly those with early response times.

4. Participant Feedback

Overall, the HVFL participants were positive in their feedback about the vibrotactile warnings. The majority preferred the directional over the non-directional warnings both before driving (based only on the verbal description) and after experiencing the warnings in

the simulated driving. The majority of HVFL participants reported that they used the directional information and found it very or extremely useful. As expected, the normal vision participants were less enthusiastic about the warnings; only half of them preferred directional warnings and one-third reported using the directional information. This is likely because the warning timing threshold used in this study (a time-to-collision of 3 seconds) was selected to give drivers with HVFL time to respond but was too early for those with normal vision who had no difficulties in quickly noticing and reacting to the hazards, as demonstrated by the relatively low number of warnings they received.

5. Limitations and Future Directions

Some study limitations need to be considered. First, only two of the HVFL participants were current drivers (because people with hemianopia are not permitted to drive in Massachusetts where the study was conducted). This may have contributed to differences between the HVFL seeing side responses and the responses of normal vision participants who were all current drivers. Lack of current driving experience might also have exaggerated the positive effects of the warnings for the HVFL drivers. However, it could be argued that the results demonstrate the potential of warning systems to assist drivers with HVFL when they first return to driving. Second, while the pedestrian hazard scenarios used a variety of pedestrian models and there were many distractor pedestrians in the virtual world, this study only includes one type of pedestrian behavior. Specifically, the pedestrian walks across the streets without stopping and their crossing behavior remains constant. In real-world driving, pedestrian behaviors are much more diverse. In addition, two of the HVFL participants had driven in the driving simulator in prior studies and were also highly motivated to drive. This

could have influenced their behavior in the study, and they would have been more eager for a better result. In the future, using a larger sample size of HVFL participants including more current drivers with hemianopia would allow us to address this limitation.

Of the two warning systems explored in this study, directional warnings were preferred, and future research should continue to explore different modalities for directional warnings – auditory or visual or multimodal cues - to determine which warning modality would be the most effective for drivers with visual field loss. A simple pedestrian crossing scenario was implemented in this study to study the effects of different warning modalities on detecting pedestrian hazards. In future studies, a variety of pedestrian hazards including more complicated pedestrian behaviors could be explored.

6. Conclusions

In summary, nondirectional warnings were as efficacious as directional in reducing blind side collisions of HVFL participants; however, directional warnings were strongly preferred. Differences in fixation behaviors between the two warning types suggest that participants with HVFL used the directional information (as they self-reported) to guide their gaze to fixate hazards on the blind side. With directional warnings, blind-side pedestrians were fixated faster and were more likely to be fixated first before braking than with nondirectional warnings. However, brake response times did not differ between the two warning types.

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