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Time-to-Contact Estimation Errors among Older Drivers with Useful Field of View Impairments

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Abstract

Previous research indicates that useful field of view (UFOV) decline affects older driver performance. In particular, elderly drivers have difficulty estimating oncoming vehicle time-to-contact (TTC). The objective of this study was to evaluate how UFOV impairments affect TTC estimates in elderly drivers deciding when to make a left turn across oncoming traffic. TTC estimates were obtained from 64 middle-aged (n = 17, age = 46 ± 6 years) and older (n = 37, age = 75 ± 6 years) licensed drivers with a range of UFOV abilities using interactive scenarios in a fixed-base driving simulator. Each driver was situated in an intersection to turn left across oncoming

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traffic approaching and disappearing at differing distances (1.5, 3, or 5 sec) and speeds (45, 55, or 65 mph). Drivers judged when each oncoming vehicle would collide with them if they were to turn left. Findings showed that TTC estimates across all drivers, on average, were most accurate for oncoming vehicles travelling at the highest velocities and least accurate for those travelling at the slowest velocities. Drivers with the worst UFOV scores had the least accurate TTC estimates, especially for slower oncoming vehicles. Results suggest age-related UFOV decline impairs older driver judgment of TTC with oncoming vehicles in safety-critical left-turn situations. Our results are compatible with national statistics on older driver crash proclivity at intersections.

Keywords

Driver Behavior; Designing for the Elderly; Simulation and Virtual Reality; Sensory and Perceptual Processes; Displays and Controls

1. Introduction

Drivers aged 65 years or older are more prone to intersection and left-turn crashes than any other age group (Chandraratna & Stamatiadis, 2003; Mayhew, Simpson, & Ferguson, 2006). Older drivers are also more likely to be judged at fault in crashes at intersections, where drivers are challenged by environmental complexity, time pressure, and mental workload (Cantin, Lavallière, Simoneau, & Teasdale, 2009; Caird, Edwards, Creaser, & Horrey, 2005). Driver ability to detect oncoming vehicles is affected by divided attention (Dewar, 2002), visual clutter (Bao & Boyle, 2008; Ho, Scialfa, Caird, & Graw, 2001; Romoser & Fisher, 2009; Schall et al., 2010), threats from the periphery (Ball & Owsley, 1991), and social pressure (Chen et al., 2015). Misinterpretation of perceptual cues leading to time-to-contact (TTC) estimation errors with oncoming traffic has also been suggested as a risk factor for intersection crashes (Horswill, Helman, Ardiles, & Wann, 2005; Marmeleira, Ferreira, Godinho, & Fernandes, 2007).

While each of these factors may contribute to crash risk in older drivers, previous research has also shown that older adults typically underestimate TTC (i.e., perceive objects as arriving relatively sooner) more often than younger adults (Hancock & Manser, 1997; Schiff, Oldak, & Shah, 1992). This behavior would decrease their risk for crashes (Scialfa, Kline, Lyman, & Kosnik, 1987). DeLucia et al. (2003) postulated that the higher rate of crashes for older drivers may, therefore, not be caused by (mis)estimation of TTC. Rather, they suggest that judgments about when a collision would occur must be preceded by judgments about whether a collision would occur. Their findings indicated that older drivers were 15% less accurate than younger drivers when judging whether a collision would occur. Age related differences were examined through a simple reaction time, mental rotation, and clock task (no significant correlations between judgments about collision and performance were found on the mental rotation and clock tasks).

DeLucia et al. (2003) noted that abilities important to judgments about potential collision subject to age-related decline include useful field of view (UFOV; Kline & Scialfa, 1997), sensitivity to motion (Sekuler, Hutman, & Owsley, 1980), perception of angular movement and movement in depth (Henderson & Burg, 1974), and the ability to extract information from optic flow (Warren et al., 1989). To explain their findings, they suggested that older drivers may need redundant information sources (e.g., optical expansion [optic flow] coupled with ground-intercept information). Thus, when ground-intercept information was missing and/or insufficient drivers did not extract depth information effectively.

The aforementioned research did not evaluate UFOV, however, which is often associated with increased crash risk for older drivers (Ball & Owsley, 1993; Anstey, Wood, Lord, & Walker, 2005; Clay, Wadley, Edwards, Roth, et al., 2005; Sims, McGwin, Allman, Ball, & Owsley, 2000). Sanders (1970) defined the UFOV as the area where information can be perceived during a brief glance without head or eye movement. By reducing perception of safety critical cues from the panorama, UFOV loss has the potential to increase errors for incurring threats, leading to unsafe traffic entry decisions. Driver judgments of personal threat posed by oncoming vehicles in an opposing stream of traffic (i.e., through a measure of depth perception) can be assessed through verbal report, perceptual matching (i.e., adjusting a target to match another referent object), and open- and closed-loop action based tasks (a closed-loop task involves feedback whereas an open-loop task does not; Loomis & Knapp, 2003).

Driver judgments of potential risks appear to be distance dependent, especially for older drivers (Yan, Radwan, & Guo, 2007). Cutting (2003) divided perceptual space into a near (personal space; about 1.5 m), medium (action space; 1.5 – 30 m), and far-field (vista space: supported only by pictorial cues; 30 m to infinity). Gabbard, Fitch, and Kim (2014) found that observers underestimate distances in the medium-field in the context of augmented reality (AR) applications and recommended that designers establish a margin or buffer to mitigate this effect. Swan et al. (2006) tested AR depth estimation using a perceptual matching task and suggested a linear relationship between distance and depth judgment variability and error. They also observed an inflection from underestimating to overestimating distance at roughly 23 m. Context, apparent risk, advancing age, and cognitive decline associated with UFOV loss may alter this bias.

In a related study that evaluated the potential benefits of AR cues for improving decision making during a gap estimation left-turn task for drivers with age-related cognitive decline (Rusch et al., 2014), UFOV was observed to play an important role in elderly driver behavior whereas their responses were adjusted to become consistent with cueing and comparable to unimpaired drivers. To better understand the safety of responses, the current study was conducted to obtain further information on baseline TTC in this cohort of drivers (i.e., without the assistance from environmental [ground-intercept information] and/or superimposed cues [AR]).

The study examined the effects of UFOV ability on older driver TTC estimation error and TTC estimation error variation using an open-loop action-based task. We hypothesized that drivers with the worst (greatest) UFOV scores would have the least accurate judgments for the arrival of oncoming vehicles and that TTC estimation error and variation would depend on oncoming vehicle speed and distance (referred to as “actual TTC” from this point forward). Patterns of safety-critical distance and speed dependent judgment can inform design of interventions aimed at improving the safety and mobility of aging drivers with perceptual or cognitive dysfunction.

2. Methods

2.1 Participants

Sixty-four drivers were recruited from the general community to participate in this study. The drivers comprised three groups: 17 middle-aged, 30 older-UFOV unimpaired, and 17 older-UFOV impaired (Table 1). All participants had a valid US driver's license, normal corrected vision (on near and far visual acuity and contrast sensitivity tests) and no neurological disease. One participant completed only 2 out of 36 trials (they did not appear to understand the task) and thus all data from this individual was excluded.

2.2 Useful Field of View Assessment

The UFOV was measured using the Visual Attention Analyzer Model 3000 (Vision Resources, Chicago, IL; Ball and Owsley, 1993; Edwards et al., 2005). Consistent with previous studies (Schall et al., 2013; Rusch et al., 2013, 2014), four UFOV subtests measuring (a) processing speed, (b) divided attention, (c) selective attention, and (d) selective attention with a simultaneous same-different discrimination at fixation were summed to calculate a total UFOV score. Each subtest UFOV score represents the threshold in milliseconds at which the individual correctly responds to 75% of the trials (Ball and Owsley, 1992). UFOV impairment was defined by scores of at least 350 on Subtest (c) or 500 on Subtest (d).

2.3 Driving Task

This experiment was conducted using the Simulator for Interdisciplinary Research in Ergonomics and Neuroscience (SIREN) (see Rusch et al., 2014 for details on simulator). Participants performed a driving task where asked to react to oncoming vehicles. The driver vehicle was positioned at the center of the intersection past the painted stop strip in all scenarios. This is the point where drivers tend to position themselves prior to commencing across the opposing lane of traffic. The oncoming vehicle (full-sized red Grand Prix) and road geometry (i.e., number of lanes, lane width, etc.) were the same for each scenario (Figure 1). In contrast to Rusch et al., no ground-intercept information (e.g., construction and/or objects along the opposite lane) was made available that would have provided reference points as a redundant information source (in addition to changes in the angular expansion rates of the vehicle; cf. DeLucia et al., 2003).

Participants responded to thirty-six vehicles that approached traveling at various constant velocities (45, 55, and 65 mph) and disappeared at different actual TTCs (cf. the "disappearing paradigm" by Schiff and Detwiler, 1979; for 1.5, 3, and 5 seconds; Figure 1; Table 2). In this 3x3 factorial within-person design, every participant performed 4 repetitions of each combination. Each participant was instructed to apply the high beams at the moment in which he or she predicted that an oncoming vehicle would collide with his or her vehicle (cf. Caird & Hancock, 1994).

Lee (1980) described vision as a constantly changing optic array or flow field which must be described in spatio-temporal terms. In this left-turn scenario, the approaching vehicle is offset relative to the viewpoint of the observer. The expansion of the front of the vehicle on the retina is not symmetrical and the cues for approach speed are not exactly the same as those used in the early TTC experiments (e.g., head on as in following a lead vehicle). Thus, from this point forward the trajectory path between the driver and oncoming vehicles will be referred to as *angular velocity* (not optic flow) with relevant references to visual angle, angular subtense, and angular expansion.

Caird and Hancock (1994) reported that the rate of expansion of an object in an optic array is a function of distance where objects further down the road expand proportionately less than objects that are close. Previous research has shown that drivers are sensitive to changes in expansion rates of 0.003 rad/s (Hoffmann & Mortimer, 1994) or changes of about 7% (Regan & Hamstra, 1993). The visual angle of the approaching vehicle in this study subtended an approximated range from 0.44° (when actual TTC was 5 s and velocity was 65 mph) to 1.33° (actual TTC=1.5 s and velocity=45 mph) for the horizontal width of vehicle front and 0.36° to 1.09° for the vertical height of vehicle (respectively). Changes in the vehicle side (expansion rate) were minimal for actual TTC greater than 1.5 seconds (i.e., there was no meaningful change in visual angle to report). The full range of visual angles and expansion rates are presented in Figure 1.

Chan et al. (2005) suggested it takes about three seconds (four when pedestrians are present) to complete tasks needed to complete a left-turn: (1) waiting on lead vehicles before entering the intersection, (2) arriving at the intersection, (3) gap estimation to decide when to turn, (4) making the left-turn, and (5) entering the next lane of traffic. The environmental complexity poses a mental work load challenge in this sequence, particularly for drivers with cognitive slowing and UFOV impairment. Gap selection is affected by driver UFOV impairment and approaching vehicle speed (Rusch et al., 2014) and impaired drivers exhibit more conservative behavior (requiring more time in gap selection). In the current study, testing in the mid-field (≤1.5 sec) would have minimized the effects in analysis because older drivers rarely select short gaps (revealed through pilot testing). Therefore, to explore a diverse range of this group’s behavior, the design incorporated disappearing points in the far-field range (≥30 m; Figure 1; Table 2).

2.4 Statistical Analysis

The primary dependent variables included TTC estimation error and TTC estimation error variation. TTC estimation error was derived by taking the difference between the driver estimated TTC and the actual TTC. Estimated TTC was the driver’s prediction (in seconds) of when an oncoming vehicle (with variable speeds) would collide with his or her vehicle. Actual TTC was the minimum value of TTC when the oncoming vehicle disappeared, and defined by the Society of Automotive Engineers (SAE Recommended Practice J2944: the “minimum duration [time interval in seconds] required for one vehicle to strike another”, p. 121).

Likelihood-based methods were used to fit generalized linear mixed models to the data. We tested for differences on TTC estimation error between order, actual TTC (1.5, 3, 5 sec), velocity (45, 55, 65 mph), gender, age (continuous), UFOV score (continuous), and for interactions between UFOV score with velocity and actual TTC. Trials were categorized into three blocks to test for an order effect (12 trials per block, Table 3). Because the task was open-loop (not involving feedback which would have contributed to improvement) this order factor was considered a nuisance variable.

Follow up pair-wise comparisons were performed to evaluate statistically significant two-way interactions using the Tukey procedure. Slopes were estimated for covariates, along with linear combinations of slopes when an interaction between covariates and factors was significant. Data points which fell outside the general clusters in Figure 2 were examined as potential outliers. One trial (outlier) was removed from the dataset because the driver clearly had an extended delay in response due to difficulties activating the high beam lever (all other responses for this individual appeared acceptable so they were not excluded). Other outliers were examined in a preliminary review and analysis and results indicated that exclusion did not change any of the major response patterns. Further, a sensitivity analysis was performed using data collected from a follow up task and results did not show any anomalies (Rusch et al., 2014).

Speed of processing (SOP), or the speed with which an individual performs a cognitive activity, is a fundamental aspect of cognitive aging (Salthouse, 1996). A SOP composite score for older drivers was derived using results of the Trail Making Test Part A, Grooved Pegboard Test, and UFOV task modeled to represent UFOV related skills as in a previous study (Schall et al., 2013). Differences in outcomes related to SOP were marginal compared with models which included UFOV alone, however, and data on the Trail Making and Grooved Pegboard Test were not collected for the middle-aged group because they typically do not exhibit impairments in these areas. For these reasons, UFOV (and not the SOP composite) was used in all presented analyses.

Preliminary analysis also indicated that separating by age and UFOV impairment (i.e., middle-age unimpaired, old unimpaired, old impaired) had no statistically significant effect when comparing differences among individual conditions within the unimpaired group (i.e., middle-aged unimpaired and old unimpaired drivers performed the same; further supported by the insignificant findings found for age, $p>0.05$, Table 3). Therefore, all data were merged into two categories using UFOV unimpaired and impaired for stratification (not factoring age) when plotting and interpreting significant three-way interactions (Figure 2).

To interpret and understand differences in overestimation (unsafe response), percentages and frequencies were isolated for comparison (Figure 3). Percentages in this figure were calculated using the ratio of the subject's frequency count of overestimates in comparison to the total number of over- and under-estimates (2173) multiplied by 100. Negative values (below zero) represent "underestimate" while positive values are "overestimates". Values were also grouped by impairment status as well as approaching vehicle velocity for comparisons.

TTC estimation error variation is defined as the variation (standard deviation) of TTC estimation error (in seconds). Larger TTC estimation error variation values indicate more variability in prediction. The same model (except for order) and testing methods were used to analyze the data.

3. Results

3.1 Time-to-Contact Error Estimation

Table 3 presents the results from a linear mixed model that evaluated driver UFOV score in relationship to TTC estimation error. Drivers had the smallest TTC estimation error for trials in blocks two and three compared to block one (diminishing in small increments over time, Table 4). Additionally, they typically had the smallest error when oncoming vehicles were traveling at the fastest velocities (Figure 2C and 2F) and disappearing at the closest locations (65 mph at 1.5 sec, LSM=0.53, SE=0.10, CI [0.33, 0.74], $p<0.05$ for 7 out of 8 comparisons, Table 5; lower left corner of each plot). Conversely, the largest errors were found for the slowest travelling vehicles (Figure 2A and 2D; Table 4). These findings were supported by an interaction between actual TTC and oncoming vehicle velocity where participants had the largest TTC estimation errors for the slowest vehicles at the furthest distances (45 mph at 5 sec, LSM=2.16, SE=0.11, CI [1.95, 2.36], $p<0.01$ for all comparisons, Table 5). For gender, a trend was found that females (LSM=1.25 sec, SE=0.13, 95% CI [0.98, 1.52]) responded an average of 0.33 seconds more conservatively than men (Mean=0.92 sec, SE=0.12, 95% CI [0.68, 1.15]; $p=0.05$; d=2.61).

3.2 Outcomes associated with UFOV

For UFOV, participants with the poorest (highest) scores were the most conservative and least accurate in their estimations compared to those with the best (lowest) UFOV scores (slope=0.0018 (0.0004); CI [0.0010, 0.0025]). The three-way interaction between UFOV, Actual TTC, and velocity was interpreted using the plots in Figure 2.

Drivers with the poorest (highest) UFOV score had the most inaccurate estimations (largest error) when making judgments about the arrival of vehicles that disappeared at the furthest distance (upper right corner of Figures 2D, 2E, 2F; Table 5). Conversely, driver error for the fastest vehicles which disappeared at the furthest distances was smallest (most accurate) for drivers with no UFOV impairment. The upper right corner of Figure 2C illustrates this finding where the regression line is closer to its identity function than in any other plot. The plots also show that UFOV impaired drivers underestimated TTC more often than UFOV unimpaired drivers, especially for vehicles travelling at the slowest velocity.

The aforementioned observations are supported by the statistically significant interactions between UFOV and actual TTC ($p<0.01$) and actual TTC and oncoming vehicle velocity ($p<0.01$). Specifically, for the interaction between UFOV and actual TTC, slopes were smallest for vehicles disappearing closest to the driver and largest for those which disappeared at 5 seconds (difference in slopes between 1.5 and 5 sec= -0.0014, $p<0.01$, d=3.57, CI [−0.0019, −0.0009]; difference in slopes between 3 and 5 sec= −0.0010, $p<0.01$, d=2.58, CI [−0.0015, −0.0005]; Table 5).

Figure 3 shows a breakdown of the percentages for under-versus overestimations to illustrate the ratio of responses between unimpaired and impaired drivers. Drivers appeared to make the most overestimations for vehicles travelling 65 mph with an Actual TTC of 5 sec (total=5.94%; followed by 65 mph at 3 sec=4.24% and 55 mph at 3 sec=4.00%). Additionally, differences in overestimations between velocity categories were most evident for an Actual TTC of 5 seconds. For the unimpaired group, differences ranged from 0.87 to 3.42 (45 mph=0.75%; 55 mph=1.62%; 65 mph=4.17%). The impaired group differences ranged between 0.35 and 1.58 (45 mph=0.18%; 55 mph=0.53%; 65 mph=1.76%).

3.3 Time-to-Contact Error Estimation Variation

Results from a linear mixed model (inclusive of all factors tested for TTC estimation error with the exception of order) evaluating the effect of driver UFOV score in relationship to TTC estimation error variation indicated that there was a main effect of actual TTC ($F(2, 117) = 20.54$, $p<0.01$) where variation was significantly different at all levels (1.5 sec= 0.30(0.03), 95% CI [0.25, 0.35]; 3 sec= 0.40(0.03), 95% CI [0.35, 0.46]; 5 sec=0.72(0.03), 95% CI [0.66, 0.77]; all $p<0.01$).

4. Discussion

This study assessed how UFOV affects TTC estimation in drivers with a range of ages and UFOV impairment. Results indicated that UFOV impairment has a variety of effects on TTC estimation error dependent upon oncoming vehicle distance (actual TTC) and speed, largely in line with predictions. As expected, TTC estimation error, on average, was smallest (most accurate) for oncoming vehicles travelling at the highest velocities and largest for the slowest velocities (consistent with Rusch et al., 2014; Marmeleira et al., 2007; Horswill et al., 2005).

Moreover, as hypothesized, drivers with the poorest UFOV scores had the most inaccurate judgments. Consistent with findings by DeLucia et al. (2003), older drivers with age related impairments had a bias toward underestimation. These results support the previous findings suggesting that testing when a collision would occur will result in conservative behavior and extends it to include UFOV.

Drivers with the poorest UFOV exhibited a greater tendency for TTC underestimation, especially as velocity decreased and the actual TTC level increased compared to the UFOV unimpaired (consistent with findings in Rusch et al., 2014). The pattern suggests that older drivers are more likely to underestimate TTC even in the far-field. It is possible that drivers with healthy functioning depth estimation abilities (likely correlated with UFOV) were able to make adjustments for assessing vehicles further away based upon context (e.g., speed, vehicle size, etc.) and limited resources (i.e., angular velocity alone independent of ground-intercept information; cf. DeLucia et al, 2003).

While the results for the unimpaired group seem positive at first glance, a closer look reveals the opposite. The regressions in Figures 2C and 2F make it appear as though accuracy increased (i.e., coming into alignment with the identity function) for vehicles traveling at 65 mph. However, a safe increase would be coupled with a tight clustering of observations. That is not the case here. Instead, the clustering of observations appears to have a wider spread for actual TTC of 5 sec. Further, these clusters were shifted upwards (associated with more overestimation) and may suggest an unsafe increase, especially for the unimpaired group.

Hoffmann and Mortimer (1996) suggested that a drivers' ability to scale velocity (in overtaking) is limited by a threshold (i.e., detecting change was only possible when the subtended angular velocity of the lead vehicle exceeded about 0.003 rad/s). While there appeared to be sufficient viewing time available for all levels of actual TTC in the current study (minimum of 5.3 seconds and an approximated angular velocity threshold greater than 0.172 degrees [0.003 rad/s; see asymptote on Figure 1]), relatively poor visual cues available for processing the expansion rate of vehicles disappearing at 5 sec may have contributed to higher rates of overestimation, especially for vehicles travelling at the fastest velocity (65 mph). Further, the lack of redundant resources (i.e., ground-intercept detail) likely contributed to inaccuracy, especially for the UFOV impaired group who exhibited minimal overestimation in most cases otherwise (cf. DeLucia et al., 2003). Drivers typically expect slower velocities at intersections thus responses may have also been affected by this.

While the angular velocity for the vehicle side was not taken into account because it did not become visible until about 1.5 s this factor would contribute to the quick rise found in angular subtense plots (Figure 1) and likely to findings associated with higher rates of overestimation for the fastest velocities. That is, when angular expansion information related to the vehicle’s side is not available, the driver only has two-dimensional detail for estimation. Once the vehicle side becomes visible and change is detectable the driver can couple this detail with horizontal and vertical expansion rates (making it three dimensional; 3-d). For vehicles travelling at 55 and 65 mph, viewing time for the added 3-d detail in the closer range (where actual TTC= 1.5 s) was minimal and may have contributed to the higher rate of overestimation (for the unimpaired group) relative to lower rates observed for 45 mph.

Swan et al. (2006) suggested a bias switch from underestimating to overestimating at a distance of approximately 23 meters. The findings suggest a region of opportunity for safety intervention, albeit in a study that used a perceptual matching task that did not factor velocity nor consider effects of personal risk or cognitive decline. The current study tested judgment of dynamic objects (e.g., with various levels of velocity) in addition to individual differences in driver competency (UFOV). Responses varied across velocity and driver group. For example, the UFOV unimpaired group exhibited the largest degree of overestimation responding to vehicles travelling at 65 mph with an actual TTC of 5 sec. In this instance, the bias switch occurs at a much further distance than 23 meters. In contrast, the UFOV impaired group did not exhibit a pronounced bias switch. These findings underscore the need to explore contextual and demographic factors when developing countermeasures, such as AR systems.

Other interesting observations were found for gender and order. There was a trend that women were more conservative than men (had a larger TTC estimation error), in line with Rusch et al. (2014) and Alexander, Barham, and Black (2002) who observed that women tend to select a larger median gap than men, age notwithstanding. For order, drivers had a slightly higher TTC estimation error in the first block compared to later blocks. A main effect of order in a beneficial direction (e.g., becoming more accurate corresponding to decreasing TTC estimation error) may suggest a general learning or practice effect, whereas a main effect of order in a detrimental direction (e.g., increasing TTC estimation error) may suggest a potential fatigue effect. The decrease in TTC estimation error over time could suggest a practice effect, however because the task was open-loop (with no feedback) and preliminary analysis indicated that exclusion of this factor did not produce a major difference in the model a practice effect does not seem likely. Further, when order was examined in higher-order effects (e.g., with velocity, UFOV, etc.) performance modification appeared to be associated with multiple factors (consistent with Rusch et al.).

For TTC estimation error variation, we hypothesized that drivers would make estimates most consistently (smallest variation) when oncoming vehicles were traveling at the fastest velocities and disappearing at the closest locations. A main effect of actual TTC supported our expectation about variation in relationship to proximity. However, consistent with Rusch et al. (2014), results on this variable were not substantial where neither velocity nor UFOV had evident effects. Findings on this outcome (and others) may have been limited due to the small sample size, especially in the UFOV impaired group.

4.1 Implication, limitations, and future work

Results for TTC estimation error suggest that drivers with the poorest UFOV scores had the most inaccurate judgments of the arrival of oncoming traffic. More interestingly, driver behavior for the UFOV impaired group exhibited a constant underestimation bias even as actual TTC increased (consistent with DeLucia et al., 2003). The underestimation may be related to an inefficient compensation strategy used by impaired drivers (i.e., using a universal depth estimation strategy predominantly dependent on distance). A weakness in this strategy is that it does not factor context (i.e., velocity, vehicle size, angular expansion, etc.) and will not help when making an evaluation as to whether a collision would occur. Further, it imposes more risk when the driver is subject to time or social pressure (e.g., a tailing honking vehicle; Chen et al., 2015) and not able to wait for larger safer gaps. Driver assistance systems may provide a potential countermeasure for such deficiencies.

Admittedly, the current study involved a simple task requiring no driving and limited distraction. Further it only tested estimation for when a collision might occur. Hancock and Manser (1997) completed a similar study and demonstrated that participant TTC estimates were most accurate when an approaching vehicle was naturally occluded (as it passed behind a bush). Future research should assess a multitude of TTC contexts (e.g., whether a collision would occur, more realistic and diverse scenarios, different vehicle sizes and colors, moving observer conditions, etc.) in response to expected and unexpected hazards in simulated and real-world settings.

Limitations of human processing in context, as in this study, can help inform the development of countermeasures to mitigate discrepancies between driver perception and reality and improve driver safety, including among older drivers with cognitive impairments. AR systems, for example, can improve the detection of hazardous targets of low visibility (e.g., pedestrians) without obscuring non-hazardous objects (e.g., recreational sign) in middle-aged (Rusch et al., 2013) and older drivers (Schall et al., 2013). Such applications are commonly evaluated in simulated environments where safety concerns are curtailed and the benefits of iterative testing can be gleaned (Schall Jr. et al., 2010; Gabbard , Fitch, & Kim 2014).

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HIGHLIGHTS

- Speed and distance affected TTC estimates, especially among UFOV impaired.
- Drivers with the poorest UFOV scores had the most inaccurate judgments of TTC.
- Drivers with UFOV impairments exhibited the most underestimation bias.
- Response times were least accurate for vehicles travelling at the slowest speeds.

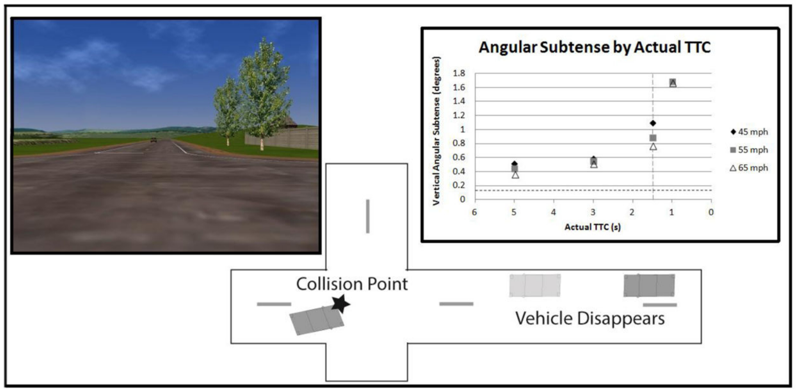

Figure 1.

The driving task design. Given a constant oncoming vehicle velocity, the angular subtense of the oncoming vehicle slowly increases (horizontal asymptote on the left) at the furthest distances and as that distance decreases the rate of expansion rapidly increases (steep rise at right). The horizontal dashed line represents a 0.003 rad/s (0.172 degree) threshold reported as the point at which drivers are no longer to detect change in angular velocity (Hoffmann & Mortimer, 1996). The vertical dashed line represents a cut-off of 1.5 s in which drivers were never presented with visible visual information beyond this point (points are only included for 55 and 65 mph; there was insufficient data to estimate for 45 mph for actual TTC < 1.5 s). The corresponding horizontal angular subtense (HAS) was proportionate by a factor of 1.2185 (e.g., when actual TTC=5 and velocity=65 mph the HAS=VAS*1.2185=0.44 degree).

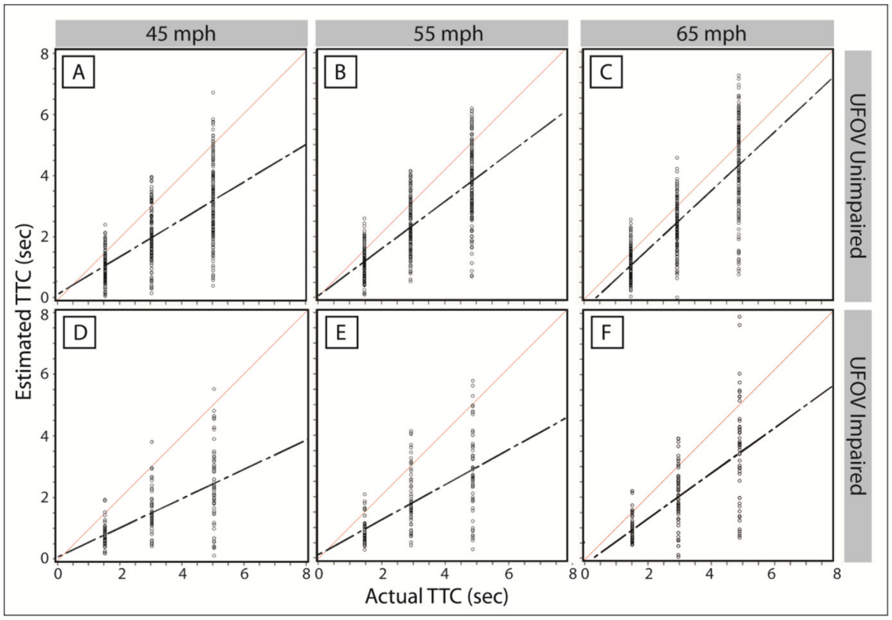

Figure 2.

Time-to-contact estimation based on "Actual TTC" and velocity for UFOV impaired and UFOV unimpaired drivers. Red lines represent the identity function in each plot. Estimated TTC values above the red identity line are over-estimations of Actual TTC and values below the red identity line are under-estimations of Actual TTC.

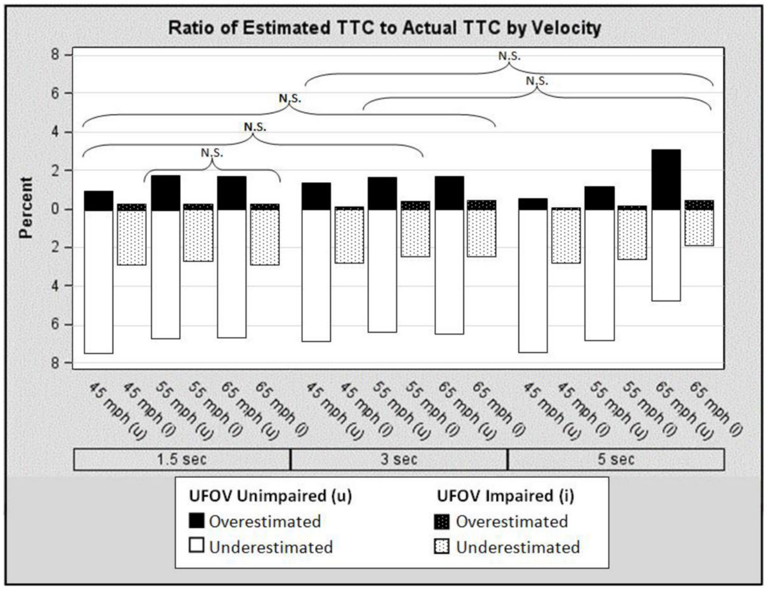

Figure 3.

Black is overestimation for UFOV unimpaired drivers and speckled black is overestimation for UFOV impaired drivers. White is underestimation for UFOV unimpaired drivers and speckled white is underestimation for UFOV impaired drivers. Tests of significance are based on the ANOVA in Table 3 where UFOV was analyzed as continuous (not discrete). Therefore comparisons are based upon the totals in each velocity category (i.e., unimpaired + impaired). All differences were significant ($p<0.05$) except those labeled ‘N.S.’.

Table 1

Demographic, UFOV scores, and travel frequency by driver category.

	Middle-aged (n=17)	**Older UFOV Unimpaired (n=30)**	**Older UFOV Impaired (n=17)**
Mean (SD)			
Age (years)	46 (6.0)	72 (6.0)	77 (6.0)
UFOV Average	375.2 (139.6)	578.3 (200.8)	1053.5 (241.7)
UFOV Range[1]	171 – 638	262 – 999	686 – 1523
N (%)			
Gender			
Male	10 (58.8)	15 (50.0)	10 (58.8)
Female	7 (41.2)	15 (50.0)	7 (41.2)
Miles per week traveled			
0–50 miles	2 (11.8)	10 (33.3)	5 (29.4)
51–100 miles	7 (41.2)	9 (30.0)	8 (47.1)
101–150 miles	4 (23.5)	4 (13.3)	1 (5.9)
151+ miles	4 (23.5)	7 (23.3)	3 (17.6)

[1] Range values are presented as Minimum – Maximum

Table 2

Disappearing distances and viewing times for different approaching velocities and actual TTC levels

	1.5 sec		3 sec		5 sec	
	Actual TTC	**Viewing time**	**Actual TTC**	**Viewing time**	**Actual TTC**	**Viewing time**
Approaching Velocities						
20.1 m/s (45 mph)	30.2 m	13.53 s	36.9 m	11.87 s	43.7 m	9.87 s
24.6 m/s (55 mph)	60.3 m	10.80 s	73.8 m	9.17 s	87.3 m	7.17 s
29.1 m/s (65 mph)	100.5 m	8.90 s	123.0 m	7.30 s	145.5 m	5.30 s

Table 3

Mixed effects related to UFOV for TTC Estimation Error

Effect	**Numerator Degrees of Freedom (DOF)**	**Denominator DOF**	**F**	***p***
Order	2	1969	22.84	<0.01
Actual TTC (1.5, 3, 5 sec)	2	118	0.14	0.87
Velocity (45, 55, 65 mph)	2	1969	33.43	<0.01
Gender	1	58	3.38	0.07
Age	1	58	1.03	0.31
UFOV	1	58	22.32	<0.01
Actual TTC * Velocity	4	1969	21.34	<0.01
UFOV*Velocity	2	1973	0.01	0.99
UFOV * Actual TTC	2	120	18.23	<0.01
UFOV * Actual TTC * Velocity	4	1974	5.44	<0.01

Table 4

Least square mean (LSM) estimates (seconds) with effect sizes associated with order and velocity for TTC estimation error (TTCE)

	TTCE	**d**	**95% CI**
Order (LSMs by block)			
1 (Trials 1–12)	1.20 (0.09)		1.02, 1.39
2 (Trials 13–24)	1.04 (0.09)		0.86, 1.23
3 (Trials 25–36)	1.00 (0.09)		0.81, 1.18
Differences			
Block 1 – Block 2	0.16*	1.74	0.08, 0.24
Block 1 – Block 3	0.21*	2.28	0.13, 0.28
Block 2 – Block 3	0.05	0.53	−0.03, 0.13
Velocity (LSMs)			
45 mph	1.38 (0.09)		1.19, 1.56
55 mph	1.06 (0.09)		0.88, 1.24
65 mph	0.81 (0.09)		0.63, 0.99
Differences			
45 – 55 mph	0.32*	3.47	0.24, 0.39
45 – 65 mph	0.57*	6.19	0.49, 0.64
55 – 65 mph	0.25*	2.72	0.18, 0.32

*$p \leq 0.01$

Table 5

Least square means (LSM) and slope estimates (seconds) of TTC estimation error for two-way Actual TTC interactions between velocity and UFOV

	1.5 sec	**95% CI**	**3 sec**	**95% CI**	**5 sec**	**95% CI**
LSMs						
45 mph	0.78 (0.10)	0.57, 0.99	1.19 (0.10)	0.99, 1.40	2.16 (0.11)	1.95, 2.36
55 mph	0.61 (0.10)	0.41, 0.82	0.94 (0.11)	0.73, 1.15	1.62 (0.11)	1.41, 1.83
65 mph	0.53 (0.10)	0.33, 0.74	0.82 (0.11)	0.61, 1.02	1.08 (0.11)	0.87, 1.29
Slopes UFOV	0.0012, (0.0004)	0.0004, 0.0019	0.0015, (0.0004)	0.0008, 0.0023	0.0026, (0.0004)	0.0018, 0.0034