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Age-related difference in steering control under reduced visibility conditions ☆

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ABSTRACT

The current study investigated age-related differences in a steering control task under low visibility conditions. Younger and older drivers were presented with displays simulating forward vehicle motion through a 3D scene of random dots on a ground plane. The lateral position of the vehicle was perturbed by a simulated side wind gust according to a sum of sinusoidal functions. The drivers' task was to steer the vehicle to maintain a straight path. The visibility of the driving scene was reduced by reducing the quantity and the quality of the optical flow field. We found that performance decreased when visibility was reduced for both older and younger drivers, with better performance for younger drivers as compared with older drivers. An age-related interaction was also found with deteriorated optical flow information. These results suggest that under reduced visibility conditions, older drivers may have increased accident risks due to decreased ability to successfully steer the vehicle.

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1. Introduction

Older drivers are involved in more accidents per mile driven than any other age groups except for teenagers [31]. The increased accident risks for older drivers result partly from age-related deficits in visual functions [15,4,5,23,36]. Such age-related declines have been found in a variety of visual functions, such as contrast sensitivity [41,13,37], dark adaptation [27,14], motion perception [43,17,2,10,9], optical flow [2,5], and depth perception [34,35].

Although visual acuity decreases with increased age [11,19], it is not a good predictor for crash risk [46]. Instead, it has been found that dynamic acuity [25], contrast sensitivity, and useful field of view (UFOV, which consists of three subtests of processing speed, divided attention, and selective attention [8]) are better predictor variables of crash risk. For example, McGwin et al. [29] found older drivers have difficulties driving in specific conditions that are related to contrast sensitivity. In one recent study assessing the hazard perception ability of older drivers [18], it was found that UFOV and contrast sensitivity accounted for the individual differences in hazard perception ability in traffic conflict scenarios.

The driving difficulties associated with contrast sensitivity could occur in certain difficult driving conditions such as driving at night or under inclement weather conditions (e.g. in fog or rain). Indeed, nighttime driving is often much more dangerous than daytime driving [31], especially for drivers aged 65 or older [30]. A number of studies have found increased crash rates for older drivers under reduced visibility conditions due to weather or dusk/nighttime conditions [1,23,28,26,42]. Moreover, driving simulation studies have found evidence of decreased driving performance under reduced visibility conditions. Recent studies have shown that fog decreased the judged car following distance for younger drivers [20]. More importantly, reduced driving performance in fog was more pronounced for older drivers in the car following task [33] and detecting collision events on linear trajectories [32].

It has been suggested that an important perceptual task during driving is to derive heading direction from visual information and then steer the vehicle [22]. Failure to accurately detect changes in the path of motion and make corrections to the vehicle's path of motion could have serious consequences for driver safety. In the current study, we examined age-related differences in steering control under reduced visibility conditions. One source of information that has been extensively studied for the perception and control of steering is optical flow—the perspective transformation of the optic array [16]. Research on optical flow has demonstrated the usefulness of this information for the perception of heading [44], the perception of self-motion [3], and the perception of egospeed [24].

It is well documented in the literature that contrast sensitivity is reduced with increased age [37]. Overall contrast of the driving scene is greatly reduced when driving at night or in fog. Previous research has demonstrated age-related decrements in the perception of motion and in the use of optical flow information for the perception of 2D shape [6] and 3D shape [2]. These results com-

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bined suggest that because of the reduced visibility of the optical flow field older drivers are likely to have more difficulties in steering control than younger drivers under low contrast conditions. However, few studies have examined the effect of low visibility on steering control performance. Specifically, it is not clear how reduced contrast would affect the processing of optical flow information for older drivers when performing a steering control task. In the current study, we examined age-related differences in steering control when the optical flow information deteriorates under low visibility conditions.

The deterioration of optical flow information simulated low visibility driving conditions, e.g. caused by nighttime driving or driving in fog. The reduced visibility can affect the optical flow information in two ways. First, the quantity of optical flow, number of visible dots, is reduced. Second, the quality of optical flow, the contrast of visible dots, is also reduced. Two hypotheses concerning age related differences were examined in the study. Previous research has demonstrated age-related decrements in the perception of motion and in the use of optical flow information for the perception of 2D and 3D shape. We propose that older drivers, as compared to younger drivers, will show a decreased steering performance with reduced quantity of optical flow. We will refer to this hypothesis as the quantity hypothesis. To test this hypothesis, we manipulated the number of dots in the scene (resulting in a decreased quantity of optical flow). If the quantity hypothesis is correct, then age-related differences in steering performance should be more pronounced with smaller as compared to greater amount of dots.

The second hypothesis concerns the contrast of dots in the scene. Previous research has shown age-related decrements in contrast sensitivity. We believe that older drivers may have difficulty processing optical flow with reduced contrast. As a result, older drivers, as compared to younger drivers, may have reduced accuracy in steering control when the optical flow contrast is reduced. We will refer to this hypothesis as the quality hypothesis. To examine this hypothesis we presented optical flow in different contrasts. If older drivers have greater difficulty in using low contrast optical flow information then we predict that older drivers, as compared to younger drivers, will have more steering error when the dots array is presented in low contrast.

2. Experiment

2.1. Methods

2.1.1. Drivers

The drivers were 22 younger (mean age = 20.9) and 17 older (mean age = 78.1) individuals. All drivers were screened for basic cognitive and perceptual ability. All drivers had a minimum of 2 years of driving experience, had normal or corrected to normal vision, and were naïve to the purpose of the experiment. Driver's visual attention was measured using the Useful Field of View (UFOV) task, which comprises a processing speed, divided attention, and selective attention score.

2.1.2. Apparatus

The displays were presented on a 46-inch flat screen LCD monitor with a pixel resolution of 1920 by 1080 at a refresh rate of 60 Hz, controlled by a Windows XP Professional Operating System. The visual angle was approximately 25° by 15°. Drivers viewed the displays binocularly at a distance of approximately 215 cm from the screen. A Logitech Driving Force GT steering wheel system was used for steering control. Spring effect, damper effect, and centering spring strength were set at 50% in the Logitech system. Angular displacement of the steering wheel was linearly related to the horizontal displacement in the simulation. Drivers were seated in a fixed-base driver's seat with adjustable steering wheel positioning with an eye height of approximately 115 cm. Drivers viewed the displays in a darkened room and were given at least 5 min for dark-adaptation prior to the experiment.

2.1.3. Stimuli

The displays simulated driving through a 3D array of dots located on a ground plane (as shown in Fig. 1). The simulated speed was 72 km/h (45 M/h). The dimensions of the space were 400 m (width) by 150 m (depth), with the simulated eye position of the driver at 1.6 m above the ground. The horizontal position of the dots pattern was perturbed according to a sum of 3 prime sine-wave functions (as shown in Fig. 2). Amplitudes and frequencies were selected to provide equal energy in the Fourier domain. The three frequencies used were 0.083, 0.161, and 0.216 Hz. The amplitudes for these frequencies were 17.51, 6.74, and 9.02 m, respectively. The first two phases of the sine-wave function were randomized across trials. The last phase was determined such that the output of the sum of the three sine-wave functions was zero at the beginning of each trial. The scene consisted either of 25 or 125 randomly positioned dots to form the ground plane. The dots were randomly positioned at the beginning of each trial, and then the viewpoint moved forward. Dots that moved out of the viewport would be randomly repositioned at the far end of the ground plane.

The background had an average luminance of 16 cd/m^2. Luminance of the dots was 21.65, 24.00, and 26.67 cd/m^2, which generated a Michelson contrast of 0.15, 0.20, and 0.25, for the low, medium, and high contrast condition, respectively. All drivers reported during debriefing that they were able to see the dots in all conditions.

2.1.4. Design

The independent variables for the steering control task were dot number in the optic flow field (25 or 125), contrast level (low, medium, and high), and age group (younger and older). Age group was treated as a between-subjects variable. All other variables were treated as within-subject variables. Two repetitions for each of the six conditions generated 12 trials for each driver. The order of the trials for each driver was randomized individually.

2.2. Procedure

Drivers first completed the visual acuity and contrast sensitivity measurements, and then proceeded to complete the UFOV tasks. After completing the visual tasks, drivers were moved to the sim-

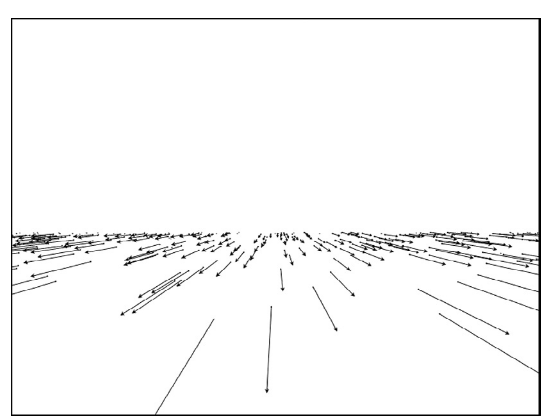

Fig. 1. Low contrast optic flow showing straight ahead moving direction. In the actual experiment, the contrast was reversed so that white dots were displayed on a black background.

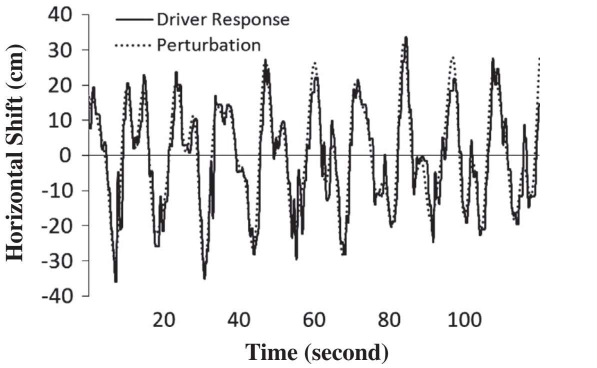

Fig. 2. Example of steering response and perturbation from a single trial. The dotted line depicts the simulated perturbation from 3 sine-wave functions while the solid line depicts the reversed driver response for the purpose of comparison. The sum of the perturbation and the driver response specifies the driver travel path.

ulator to complete the steering control task. The driver's seat and steering wheel position were adjusted to suit their comfort.

Drivers were told that the display was comparable to driving down a straight roadway with lateral wind gusts perturbing their position on the roadway. In addition, they were told that their task was to correct their position on the roadway such that they maintained driving along a straight path. Each trial began with a 10-s straight path period, in which input from steering wheel and perturbation were disabled. This was done to set up the perception of straight path for the drivers. At the end of the 10 s, a beep sounded to notify the drivers that they need to steer the wheel to null out the perturbation. At the end of each trial, a blank screen indicated that a break can be taken. When the driver was ready for the next trial, they were instructed to press the shift lever to advance. Drivers were given at least two practice trials in which display was in maximum contrast (black background and white dots) and amplitude of the sine-wave functions were decreased by 50%. Once the drivers understood the task they were given the experimental trials.

3. Results

Steering performance was assessed by calculating RMS (root means square) steering error in relation to perturbation forces for each driver on each trial in each condition. A higher RMS score represents a greater deviation from the straight driving path indicating poorer driving performance. It was observed in some trials, due to the accumulation of displacement over a boundless driving space, drivers could not return to the original straight path after a certain amount of time. Therefore, an algorithm was developed to distinguish periods of a trial in which a participant became "lost". For each trial, an overall RMS score was computed for all data points. Then, for each individual data point, a RMS score was computed for a 31-frame period (15 preceding, current data point, and 15 proceeding). The data point was deleted if the current RMS score was greater than the overall RMS score (about 37% data was dropped for both younger and older drivers). A final RMS score was computed for the remaining data points. Scores were averaged across repetitions, resulting in six scores (one for each condition) for each participant.

A three-way mixed design analysis of variance (ANOVA) was conducted to evaluate the effect of dot density, contrast level, and age on driving performance. Younger drivers had significantly less steering error than older drivers ($F(1,37) = 29.81$, $p < .01$). Both older and younger drivers had greater steering error with a reduced number of dots ($F(1,37) = 21.78$, $p < .01$) and reduced contrast of the dots ($F(2,36) = 10.0$, $p < .01$) in the flow field. The density by age interaction effect was significant ($F(1,37) = 13.64$, $p < .01$), and the contrast by age interaction effect was significant ($F(2,36) = 10.77$, $p < .01$). The density by contrast interaction effect was significant, ($F(2,74) = 3.95$, $p < .05$). The three-way interaction among density, contrast, and age was not significant ($F(2,36) = 1.27$, $p = .30$). These results, as illustrated in Fig. 3, showed that older drivers had consistent greater steering error as compared to younger drivers especially when optical flow information decreased in either quantity or quality.

Correlation coefficients were computed between the visual assessment scores and six steering control task conditions. The Holm's sequential Bonferroni approach was used to control for Type I error across the correlations. The results of the correlational analyses between the driving conditions and UFOV scores, contrast sensitivity, and visual acuity are presented in Tables 1–3, respectively. Further analysis showed correlations among the processing speed and divided attention were moderately correlated, $r(39) = .39$, $p < .05$. Divided attention and selective attention were strongly correlated, $r(39) = .76$, $p < .01$.

4. Discussion

In this study, we examined age-related differences in the use of optical flow information when performing a steering control task under reduced visibility conditions. We predicted that when visibility was reduced older drivers would show greater decrements because of decreased contrast sensitivity and decrements in processing optical flow. The results provide evidence supporting both the quantity and quality hypothesis. Specifically, when deteriorated optical flow was presented, either with reduced number of dots or with reduced contrast, older drivers showed greater decrements in steering performance as compared with younger drivers. Considered together, these results suggest that under low visibility conditions older drivers may be subject to an increased accident risk due to a decreased ability to process optical flow information for steering control.

Warren et al. [44] found that drivers were able to judge heading very accurately, even when the amount of optic flow information was limited. They reduced the number of optic flow points, using random-dot displays, and found that participants were still able to perform well when only 10 to 63 dots were presented in the display. However, in this study we found that older drivers had decreased steering control performance when reduced amount of optic flow information was presented, especially under low visibility conditions. More importantly, it was found that the quantity of optical flow information plays a more important role, as compared to the quality of optical flow, in determining steering control performance for older drivers. This result has important practical implications, suggesting that a potential intervention for age-related increased accident risks at night can be implemented by placing more reflectors either at the roadside, on the lane dividers, or on the lane markers, which generates greater amount of optical flow information for steering control. Another practical implication is that age-related deficits in driving under low visibility conditions generate great needs for the development of more advanced in-vehicle display technologies and devices to improve driving safety for older drivers.

Our study had some limitations: We used a low-fidelity driving simulator in our study, in which limited visual information (only optic flow) was presented to the drivers. In real-world driving conditions, even under low visibility conditions, there are more sources of visual information present, such as gaze direction [45], road edges [21], and scene layout. These information sources can be flexibly combined to be used for the perception of heading

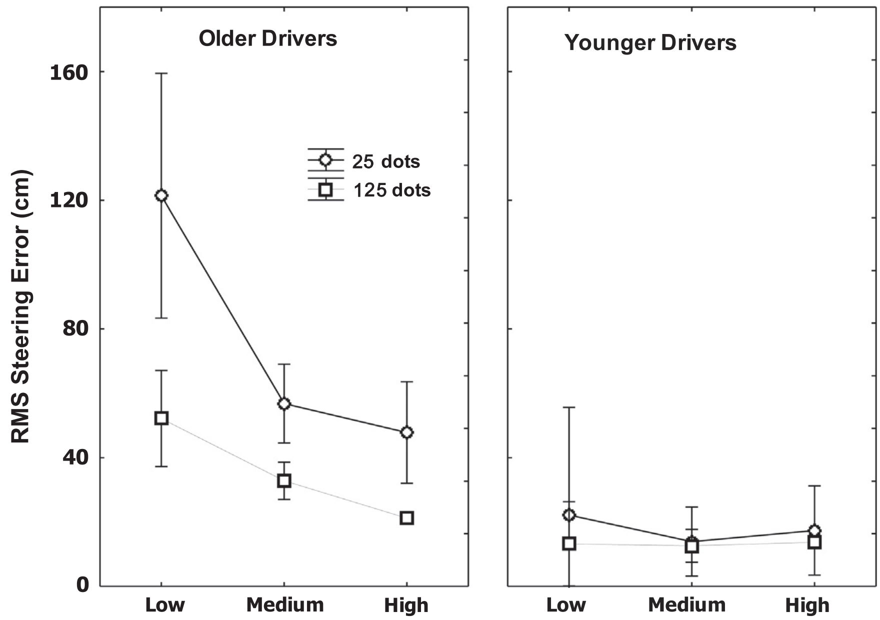

Fig. 3. The combined results of RMS steering error as a function of dots contrast for older and younger drivers.

Table 1
Correlations between UFOV scores and driving conditions.

	Low dot density (25)			High dot density (125)		
	Low contrast	Medium contrast	High contrast	Low contrast	Medium contrast	High contrast
Processing speed	.32*	0.0	.13	0.0	.06	.18
Divided attention	.52**	.50**	.36*	.48**	.32*	.54**
Selective attention	.55**	.55**	.30	.43**	.48**	.71**

Table 2
Correlations between contrast sensitivity and driving conditions.

	Low dot density (25)			High dot density (125)		
	Low contrast	Medium contrast	High contrast	Low contrast	Medium contrast	High contrast
Binocularly	−.14	−.39*	−.13	−.60**	−.33*	−.37*

Table 3
Correlations between visual acuity and driving conditions.

	Low dot density (25)			High dot density (125)		
	Low contrast	Medium contrast	High contrast	Low contrast	Medium contrast	High contrast
Binocularly	−.38*	−.43**	−.24	−.47**	−.43**	−.55**

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

direction in steering control. Thus, how well results from the current study generalize into real-world conditions need further investigation. Another limitation is, as explained in the results section, that drivers sometimes were "lost" during the trial and had difficulties steering back to the original straight path. Thus part of the data has to be removed based on a unified criterion. This "getting lost" behavior could be partially due to the fact that in our study only optical flow information was presented which made the task really difficult for the drivers. A possible solution to this could be to present more sources of visual information in the optical flow field, such as texture ground and posts that were studied by previous research [12]. The "getting lost" behavior might also result from the participants looking at the wrong whose gaze patterns could have changed the way they steered and/or influenced their visual information sampling efficiency from the driving scene. It would be helpful to examine eye-movement patterns during steering control in future studies. Another possible limitation is that the contrast levels in the current study were not the same as those in real-world driving at night conditions. This limitation resulted from the contrast limit of the big screen LCD monitor, which can be solved in the future study by utilizing neutral optic filters.

The current study adds to the growing body of literature showing that the decreased ability in processing perceptual information accompanying aging may lead to increased risk for older drivers (e.g., [33,32]), especially under low visibility conditions which result from driving at night or under inclement weather conditions (e.g., in fog). Under the high visibility condition older drivers had steering performance comparable with younger drivers, which could be partially explained by the compensation strategy employed by the older drivers. However, under high demand conditions when the visibility was low older drivers could not compensate enough for their decreased motor response to the deteriorated visual information. This finding is consistent with that in a recent study by Raw et al. [39], in which they found the "middle-of-the road" compensation for older drivers was impaired when the road was narrow and the speed was high. An important issue for future research is whether this decrement can be minimized or even reversed through training. Andersen et al. [7] found that training with sub-threshold stimuli improved older observers when performing a texture discrimination task. Richards et al. [40] found that older observers could improve their performance in divided attention through repeated training with the UFOV task, and that this improvement was retained for up to 3 months. Similarly, improvements in contrast sensitivity through training were found in a most recent study [38]. An interesting topic for future research would be to investigate whether older drivers can improve their driving performance under low visibility conditions through the use of contrast sensitivity training techniques.

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