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Age-related declines in car following performance under simulated fog conditions

Rui Ni[1], **Julie J. Kang**, and **George J. Andersen**
Department of Psychology University of California, Riverside Riverside, CA 92521 USA

Abstract

The present study examined age-related differences in car following performance when contrast of the driving scene was reduced by simulated fog. Older (mean age of 72.6) and younger (mean age of 21.1) drivers were presented with a car following scenario in a simulator in which a lead vehicle (LV) varied speed according to a sum of three sine wave functions. Drivers were shown an initial following distance of 18m and were asked to maintain headway distance by controlling speed to match changes in LV speed. Five simulated fog conditions were examined ranging from a no fog condition (contrast of 0.55) to a high fog condition (contrast of 0.03). Average LV speed varied across trials (40, 60, or 80 km/h). The results indicated age-related declines in car following performance for both headway distance and RMS (root mean square) error in matching speed. The greatest decline occurred at moderate speeds under the highest fog density condition, with older drivers maintaining a headway distance that was 21% closer than younger drivers. At higher speeds older drivers maintained a greater headway distance than younger drivers. These results suggest that older drivers may be at greater risk for a collision under high fog density and moderate speeds.

Keywords

Aging; driving; car following; fog; driving safety

Driving simulators allow for the investigation and study of driving situations that are a potential safety risk to the driver. For example, driving simulation studies have examined the ability of drivers to detect impending collisions. Such an issue cannot be studied under real world conditions because of the potential accident risk to the driver should a collision occur. Thus, an important benefit of driving simulation studies is that it allows researchers to understand the perceptual or cognitive limitations of the driver by examining conditions that under real world driving that would introduce risk to the driver. The present study examined a driving scenario that is likely to introduce considerable risk to the driver under real world conditions---older drivers performing a car following task under foggy conditions.

An important and consistent finding regarding driving safety is that accident risk increases for older driver populations (Langford & Koppel, 2006; Evans, 2004; Owsley et al., 1991). A detailed analysis of this issue was presented by Evans (2004) who examined data from the

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Address for correspondence: George J. Andersen Department of Psychology, University of California, Riverside Riverside, CA 92521 Phone: (951) 827- 4383 andersen@ucr.edu.

[1] Present address is Department of Psychology,Wichita State University, 1845 North Fairmount, Wichita, KS, 67260-0034.

FARS (Fatality Analysis Reporting System). The results indicated a steady increase in accident fatalities and rate of severe crashes for older drivers beginning at age 60. This increased rate occurred for both men and women and was independent of miles driven.

A number of factors are likely to contribute to the increased risk for older drivers. These factors include age-related changes in sensory processing, perceptual processing, attention, and cognitive ability. Age-related declines in sensory processing include changes in accommodation (Schachar, 2006), contrast sensitivity (Richards, 1977; Derefeldt, Lennerstrand, & Lundh, 1979; Owsley et al., 1983), dark adaptation (McFarland et al., 1980; Domey et al 1960), visual acuity (Chapanis, 1950; Kahn et al, 1977), spatial vision (Sekuler, Hutman, & Owsley, 1980), and dynamic visual acuity (Long & Crambert, 1990). Age-related changes in perceptual processing include declines in motion perception (Trick & Silverman, 1991; Gilmore et al., 1992; Andersen & Atchley, 1995; Betts et al., 2005; Bennett et al., 2007), optical flow (Andersen & Atchley, 1995; Andersen et al., 1999; Andersen & Enriquez, 2006) and depth perception (Norman et al., 2004; 2006). These types of changes have importance for driving safety as declines in motion and depth perception can result in performance decrements in detecting impending collisions during decelerations (Andersen et al., 1999) and of approaching objects (Andersen & Enriquez, 2006). Age-related declines in attention include performance decrements for both focused (e.g., Folk & Hoyer, 1992; Kramer et al., 1999) and divided attention tasks (e.g., Hartley & Little, 1999). One issue that has been extensively studied is the decline in the useful field of view (Scialfa, et al., 1987; Ball, Owsley, & Beard, 1990; for thorough reviews see Sekuler, et al., 1980; Owsley & Sloane, 1990; Hoffman, McDowd, Atchley, & Dubinsky, 2005). Finally, age-related declines in cognitive ability include a consistent result in generalized slowing of cognitive processing (Salthouse & Somberg, 1982a, 1982b).

In the present study we examined age-related differences in sensory and perceptual processing for a task important for driving safety---car following. Failure to correctly respond to changes in lead vehicle (LV) speed can have serious consequences for the safety of the driver. For example, if a driver in a following vehicle fails to respond to a reduction in LV speed then the headway distance between the following and lead vehicle is reduced. This can result in following at a distance that is too close (i.e., does not allow for sufficient response time should the LV suddenly decelerate) leading to an increased risk of a crash.

Previous research on car following (e.g. Chandler, Herman, & Montroll, 1958; Helly, 1959; see Brackstone and McDonald, 1999 for a review) has assumed that drivers have precise information regarding headway distance and speed of the lead and following vehicle. A limitation of this research is that drivers do not have access to this precise information. Instead, drivers have access to visual information which is used to estimate distance and speed information. Recently Andersen and Sauer (2007) presented and tested a new model for car following, referred to as the DVA (driving by visual angle) model, based on the visual information available to a driver. The DVA model consists of two components---one component provides information for distance perception (based on visual angle of the LV) and the second component provides information useful for speed perception (based on instantaneous changes in LV visual angle). The results of their study indicate that the DVA model, as compared to other car following models based on precise headway distance and LV speed, could better predict driver performance in both simulator and real world driving conditions. In a related study Andersen and Sauer (2005) showed that information of the driving scene was also used in car following. They presented drivers with an active car following task in which LV speed varied according to a complex waveform. The results indicated greater accuracy in driving performance when the surrounding scene was visible as compared to conditions when it was not visible. They argued that the surrounding scene information is useful for specifying edge rate information, which is used to estimate the speed of the driver's vehicle.

In the present study we examined two hypotheses concerning age-related changes in car following performance. Previous studies have shown age-related differences in the use of scene information to judge distance and layout of a scene (Bian & Andersen, 2008). This finding suggests that older drivers, as compared to younger drivers, will have decrements in perceived distance to the LV. We will refer to this hypothesis as the aging and distance perception hypothesis. Previous studies have also found age-related declines in judging speed of the driver's vehicle (Andersen et al., 1999) and of approaching objects (Schiff et al., 1992; Scialfa et al., 1991). This finding suggests that older drivers, as compared to younger drivers, will have decrements in perceived speed and relative speed change between the lead and following vehicle. We will refer to this hypothesis as the aging and speed perception hypothesis.

In addition to examining age-related differences in car following performance, the present study examined a set of environmental conditions likely to be problematic for older drivers---the presence of fog. Fog reduces the overall contrast and visibility of the driving scene, with the magnitude of reduced visibility increasing as a function of distance. As a result, the ability to see detail of the driving scene is reduced as a function of the distance between the driver and objects in the scene. Epidemiology studies of older driver crash rates have found increased risk of a crash for older drivers under reduced visibility conditions due to weather or dusk/nighttime conditions (Langford & Koppel, 2006; McGwin & Brown, 1999; Massie, Campbell & Williams, 1995; Stutts & Martell, 1992). Recently Kang and colleagues (Kang et al., 2008) found reduced car following performance for college age drives under simulated fog conditions. As discussed earlier, it is well documented in the literature that contrast sensitivity is reduced with increased age (Richards, 1977; Derefeldt, Lennerstrand, & Lundh, 1979; Owsley et al., 1983). Indeed, studies have found that for photopic vision (daylight conditions) there is a 41% reduction of contrast sensitivity for 70 year old subjects as compared to 20 year old subjects in detecting mid to high level spatial frequency targets (Owsley et al., 1983). These results suggest that older drivers are likely to have poorer car following performance than younger drivers because of reduced visibility of the LV under high fog conditions.

Previous research (Broughton et al. 2007; Kang et al., 2008) has found decreased car following performance (failure to maintain following distance) under simulated fog conditions. Two factors may impact car following performance under foggy conditions. First, the reduced visibility of the scene may result in a compression of the overall perceived depth of the driving scene. This situation is likely to occur as the reduction in contrast of the surrounding scene will remove information important for perceived scene depth such as texture gradients and linear perspective (Andersen and Braunstein, 1998). If the perceived depth is compressed then we expect smaller headway distance at high fog density conditions. Second, reduced visibility of the scene may result in increased difficulty in estimating speed. Previous research has found that edge rate information (the rate at which local edges cross a fixed reference point in the visual field) is important for determining the perceived speed of vehicle motion (Larish and Flach, 1990) and is used by drivers for tasks such as braking (Andersen, Cisneros, Atchley and Saidpour, 1999; Andersen and Sauer, 2004). If the reduced visibility of the scene from fog diminishes edge rate information, because of decreased visibility of edges in the driving scene, then we predict greater error in tracking changes in LV speed.

In the present study we investigated the effects of fog on car following performance when optical variables (i.e., visual angle and change in visual angle of the LV) were constant. Drivers were presented with a driving simulation scene of a straight roadway in an urban setting. A single LV was present in the scene. The duration of each trial was 60 seconds. During the first 5 seconds of the trial the LV travelled at a constant speed and headway distance was 18 m. Drivers were instructed that the headway distance during this phase of the trial was the desired headway distance. Following 5 seconds a tone sounded to indicate to the driver that the LV speed would vary. During the remaining 55 seconds of the trial the LV varied speed according to the sum of three non-harmonic sine-wave frequencies. This signal does not repeat and thus prevents the driver from anticipating changes in LV speed.

Car following performance was assessed using a variety of measures that examine both overall performance for a single trial and specific aspects of performance in response to the sum of sine functions (see Jagacinski and Flach, 2003, for a detailed discussion of quantitative analyses in control theory). We will refer to these analyses as global and local measures of performance. Global measures of performance were derived by calculating, on each trial, the average distance headway (between driver and lead vehicle), variance of distance headway (a measure of overall error in maintaining the predetermined following distance), and RMS (root mean square) error in matching LV speed.

Local measures of performance were derived, on each trial, using a fast Fourier transform (FFT) and examining gain, phase angle, and squared coherence. Gain is a measure of the amplitude of the response relative to the input signal at a particular frequency and is informative about the response sensitivity of the driver. Gain values greater than 1 indicate that the control response is larger than the input, and thus indicate that the driver is responding with greater control than necessary. Gain values less than 1 indicate that the control response is smaller than the input, and thus indicate that the driver is not responding with a sufficiently large control response at that frequency. Phase angle is a measure of the time lag between the input and the control response, expressed in degrees relative to a 180 degree cycle of the sine wave. It provides information regarding the response lag to changes in LV speed at a particular frequency. Squared coherence is a measure of squared correlation between the input and response at a particular frequency and provides a measure of the variance accounted for in tracking performance. Squared coherence is defined as the ratio of the squared cross-amplitude values (of signal and response frequencies) to the product of the spectrum density estimates (of signal and response frequencies).

These measures assessed performance changes based on distance information and speed information. Specifically, mean and variance of distance headway are based on distance perception whereas RMS speed error, gain, phase angle, and squared coherence are based on speed perception. If the age and distance perception hypothesis is correct, then we expect age-related declines in measures based on distance perception. If the age and speed perception hypothesis is correct, then we expect age-related declines in measures based on speed perception. In addition, if older drivers have greater difficulty in detecting and responding to speed changes then we predict age-related declines will be greater as the overall speed of the LV is increased.

An important issue in car following is how to quantify a safe following distance. Time headway (THW) is a measure used to assess safe car following performance and is derived by the ratio of headway distance and velocity of the driver vehicle. This measure indicates the time between two vehicles passing the same point traveling in the same direction and is used as an indication of a safe margin between the driver and lead vehicle. In the present study we required drivers to maintain a fixed distance of 18m across the three speed conditions. Thus, THW would vary as a function of speed. This analysis allows one to determine changes in safe driving performance as a function of fog density. For example, consider car following at a specific constant speed. If drivers have difficulty in maintaining a safe margin as a function of fog then increased fog density should result in a decrease in THW. If older drivers have greater difficulty than younger drivers under foggy conditions in determining distance and speed then they may follow at a closer distance resulting in a decrease in THW---an indication of increased crash risk.

EXPERIMENT

Drivers

Eight college students (age mean and standard deviation of 21.0 and 2.6, respectively) and eight older subjects (age mean and standard deviation of 72.6 and 4.6, respectively) were recruited for the study and were paid for their participation. Prior to the experiment, all drivers were screened using visual and cognitive tests including Snellen static acuity, contrast sensitivity, WAIS-KBIT, and perceptual encoding (see Table 1). All reported normal or corrected-to-normal vision and were currently licensed drivers. All drivers had experience driving in fog and reported driving at least 3 days per week.

Design

Four independent variables were examined: Age (younger and older drivers), simulated fog (simulated fog density of 0.0, 0.04, 0.08, 0.12, and 0.16), average LV speed (40 km/h, 60 km/h, and 80 km/h), and frequency of speed change (0.033, 0.083, 0.117 Hz). Age was run as a between subjects variable. All other variables were run as within subjects variables.

Apparatus—The displays were presented on Dell 670 Workstation. A Logitech Wingman Formula GP system, including acceleration and brake pedals, was used for closed loop control of the simulator. The displays were presented on a 35 deg by 47 deg visual angle monitor. Viewing distance was 60 cm. The display update was 60 Hz.

Driving Simulation Scenario—The roadway consisted of three traffic lanes (representing a 3 lane one way road) with the driver and LV located in the center lane (see Figure 1). The LV was a white colored sedan (6.3 deg visual angle at a headway distance of 18m). We used a white colored vehicle because of all vehicle colors it should be the most difficult to see under foggy conditions. The Michaelson contrast of the rear tires and vehicle body, under the 0.0 fog density condition, was 0.55. Average luminance (measured using a Photo Research PR-524 LiteMate™ photometer and based on luminance measures of 20 random locations in the display) of the driving scene was 24.7 cd/m^2. A black and white gravel texture pattern was used to simulate asphalt. Dashed lines (2 meters in length positioned every 2 meters along the roadway) were used to simulate lane markers. The city buildings and LV were produced by digitally photographing real buildings and vehicle and using the digital images as texture maps for the roadway scenes. The images were digitally altered to increase the realism of the simulator scene (e.g., remove specular highlights, add shading) and were scaled to be appropriate with the geometry of the simulation. Lane width was 3.8m.

Drivers were presented with a car following scenario in which the LV varied its speed according to a sum of 3 equal-energy sinusoids (i.e. the peak accelerations and decelerations of each sine wave in the signal were equivalent). The corresponding amplitudes for these sinusoids were: 9.722, 3.889, and 2.778 km/h. The range of speeds produced by the sum of sines function was +/− 12.3 km/h about the mean speed. At the beginning of each trial run, drivers were given 10 seconds of driving at a constant speed 18 meters behind the constant speed LV to establish a perception of the desired distance to be maintained. The three sinusoids were out of phase with one another. The initial phase of the high and middle frequency was selected randomly with the phase value of the low frequency selected to produce a sum of zero. This manipulation ensured that the speed profile of the LV, following the 5 sec of constant speed, would vary from trial to trial with a smooth speed transition following the period of constant speed.

Simulated Fog—To simulate realistic effects of fog the computer simulation used the formula

$$L(s,\theta) = L_o F_{ex}(s) + L_{in}(S,\theta), \tag{1}$$

Where L_o represents the light reflected from the object, F_{ex} (s) is the amount of light that reaches the driver divided by the amount of light decay that occurs with distance (F_{ex} (s) can be replaced with e^{-bms} to represent the decay factor for fog using a Mei-scattering criterion), and L_{in} (S, θ)represents the scattering of light from fog. This function is the industry standard for simulating fog in computer graphics and visualization (Klassen, 1987; Nishita, 1998; Hoffman and Preetham, 2003) and produces a contrast gradient that varies exponentially as a function of distance. The specific fog values in the simulation, using this equation, were 0.0, 0.04, 0.08, 0.12, and 0.16. These values were selected to represent a range of conditions from high visibility (0.0 fog condition) to low visibility (0.16 fog condition). The low visibility condition was selected based on informal observations indicating that under this condition the visibility of the LV was considerably reduced at the desired following distance of 18 m.

To provide metrics that can be used to replicate the same simulated fog conditions we calculated the variation in contrast as a function of fog density. Contrast was determined by measuring luminance differences between the rear tire of the LV (the darkest region of the view of the LV) and the bumper of the LV (the lightest region of the view of the LV). The measurements were taken with the LV at a simulated distance of 18 meters (the desired following distance). Contrast values were derived using the Michaelson contrast formula: Contrast = $(\text{luminance}_{max} - \text{luminance}_{min})/ (\text{luminance}_{max} + \text{luminance}_{min.})$. The contrast values for the 0.0, 0.04, 0.08, 0.12, and 0.16 simulated fog density levels were 0.55, 0.25, 0.12, 0.06, and 0.03. The LV was visible to all drivers under the simulated fog conditions at the predetermined driving distance.

Procedure: Drivers were seated in the simulator and instructed to maintain their initial separation from the LV despite changes in speed of the LV. Each trial consisted of two phases. During the first phase (which lasted 5 seconds) the driver's vehicle was positioned 18 meters behind the LV with a speed that matched the LV speed (40, 60, or 80 km/h). Control input (acceleration/deceleration) was not allowed during this phase and drivers were instructed that the headway distance during this phase was the desired headway distance. Following the first phase a tone sounded indicating the start of the second phase of the trial. During this phase control input was allowed and LV speed varied according to the sum of sine wave functions. Drivers were instructed that the LV speed would change and to maintain the following distance indicated during the first phase by using the acceleration and brake pedals. Drivers were given 15 minutes of practice in the simulator with changes in LV speed (determined by a single sine wave of 0.033 Hz) to become familiar with the control dynamics of the simulator. Following the practice session drivers were given two trials of each combination of speed and fog density for a total of 30 trials. Trial duration was 1 minute. Drivers were given a brief break following 15 trials. The duration of the experimental session was 1 hour.

Feedback for the car following task was used by activating a horn sound if the headway (distance between the driver and LV) exceeded 24 meters. The purpose of the horn was to ensure that the driver closely attended the car following task, and was intended to simulate an impatient driver behind the driver's vehicle. The horn sound was used as feedback for both practice and experimental trials.

RESULTS

Two types of performance were assessed. Global driving performance was determined by deriving measures of mean following distance, variance of following distance, and RMS (root mean squared) speed error (driver speed relative to LV speed). Local performance measures were determined by analyzing the speed of the driver's vehicle using a fast Fourier transform (FFT) and deriving control gain (output/input), phase angle, and squared coherence values for each frequency.

Mean Distance Headway

The mean distance headway (distance between driver and lead vehicle in meters) was calculated for each driver in each condition and analyzed in a 2 (age) by 5 (fog density) by 3 (speed) ANOVA. The main effect of fog on distance headway was significant, $F(4,56) = 5.53$, $p<.05$. The mean distance headway for the 0.0, 0.04, 0.08, 0.12, and 0.16 simulated fog density levels were 19.3, 20.1, 19.3, 18.2, and 17.9 m, respectively. Post hoc tests (Tukey HSD test) indicated significant differences ($p< .05$) between the 0.04 and 0.12, and between the 0.04 and 0.16 fog density conditions.

The main effect of speed was significant, $F(2,28) = 17.4$, $p <.05$. Mean distance headway for the 40, 60, and 80 km/h speeds were 17.7, 19.2, and 20.0 m, respectively. Post hoc tests indicted significant differences between the 40 km/h and 60 km/h, and between the 40 km/h and 80 km/h speed conditions. The interaction between age group and fog was significant, $F(4,56) = 2.91$, $p<.05$, and is shown in Figure 2. According to this result, older drivers maintained a slightly greater headway distance for the no fog (0.0 fog density) condition. However, at higher fog density levels older drivers maintained a closer headway distance than younger drivers.

The interaction between speed and fog density was significant ($F(8, 112) = 2.58$, $p< .05$) as well as the interaction of age, speed and fog density ($F(8,112) = 3.09$, $p<.05$; see Figure 3). According to this result, older drivers consistently maintained a closer following distance than younger drivers as a result of increased fog density and increased speed. The largest age-related difference in distance headway occurred at the intermediate speed (60 km/h) and highest fog density condition. However, a notable exception was the highest fog density condition and highest speed. For this condition older drivers had a greater following distance than younger drivers. This result is likely due to a change in strategy employed by older drivers. Specifically, older drivers increased following distance at high speeds to minimize the likelihood of a collision because of difficulty in perceiving changes in the visual angle of the LV due to reduced contrast.

Headway Distance Variance

The variance of distance headway (distance between driver and lead vehicle) was calculated for each driver in each condition and analyzed in a 2 (age) by 5 (fog density) by 3 (speed) ANOVA. The main effect of age was significant ($F(1,14) = 4.9$, $p<.05$). This result indicated that older drivers had greater headway variance (mean variance of 25.6) compared to younger drivers (mean variance of 10.1). There were no other significant main effects or interactions.

RMS Speed Error

The RMS speed error was derived for each driver in each fog and speed condition and analyzed in a 2 (age) by 5 (fog density) × 3 (speed) ANOVA. There was a significant main effect of age ($F(1,14) = 5.8$, $p<.05$) indicating greater RMS error for older drivers (mean RMS error of 6.17 km/h) as compared to younger drivers (mean RMS error of 4.83 km/h). There was also a main effect of fog ($F(4,56) = 3.2$, $p<.05$). The mean RMS error for the 0.0, 0.04, 0.08, 0.12, and 0.16 fog density levels were 5.17, 5.55, 5.29, 5.50, and 5.98 km/h, respectively. Post hoc analyses indicated a significant difference between the 0.0 and 0.16 fog density conditions. There were no other significant main effects or interactions ($p>.05$).

Speed measure: FFT analyses

The speed of the driver's vehicle was recorded and analyzed using a fast Fourier transform (FFT) with control gain (output/input), phase angle, and squared coherence (the squared correlation between the input and response at a particular frequency) values derived for each frequency. The average gain, phase angle and squared coherence scores were derived for each driver and analyzed in a 2 (age) by 3 (speed) by 3 (frequency) by 5 (fog density) ANOVA.

Control gain

The results for control gain are shown in Figure 4. The main effect of speed was significant, F(2,28) = 25.2, p<.05. The average gain for the 40, 60, and 80 km/h speeds were 0.87, 0.93, and 0.95, respectively. Post hoc comparisons indicated significant differences between the 40 and 60 km/h speeds, and between the 40 and 80 km/h speeds. The main effect of fog was significant, F(4,56) = 3.1, p<.05. The average control gain for the 0.0, 0.04, 0.08, 0.12, and 0.16 fog density conditions were 0.93, 0.92, 0.92, 0.91, and 0.90, respectively. Post hoc comparisons indicated significant differences the 0.0 and 0.16 fog density conditions. The main effect of frequency was significant, F(2,28) = 73.8, p<.05. The average gain for the 0.033, 0.083, 0.117 Hz frequencies were 0.99, 0.91, and 0.85, respectively. Post hoc comparisons indicated significant differences between all pairwise comparisons. Finally, the two way interaction between speed and frequency was significant, F(4,56) = 27.9, p<.05. According to this result, the decrease in control gain with an increase in speed was most pronounced for the 0.117 frequency as compared to the 0.083 and 0.033 Hz frequencies.

There were no other significant main effects or interactions.

Control Phase Angle

The results for control phase angle are shown in Figure 4. The main effect of speed (F(2,28) = 28.3), fog density (F(4,56) = 4.03), and frequency (F(2,28) = 55.5) were significant (p<.05). In addition, the two way interactions between speed and fog (F(8,112) = 2.3), speed and frequency (F(4,56) = 8.9), and fog and frequency (F(8,112) = 2.78) were significant (p<.05). These results are consistent with the results reported in Kang et al., (2008). There was no significant effect of age nor did age interact with any other variables (p>.05).

Squared Coherence

The results for squared coherence are shown in Figure 5. The main effect of age was significant, F(1,14) = 4.5, p<.05. The average squared coherence for the older and younger drivers were 0.89 and 0.94, respectively. The main effect of fog was significant, F(4,56) = 4.6, p<.05. The average squared coherence for the 0.0, 0.04, 0.08, 0.12, and 0.16 fog density conditions were 0.92, 0.91, 0.92, 0.91, and 0.90, respectively. Post hoc comparisons indicated significant differences between 0.0 and 0.16 fog density conditions. This result indicates decreased car following performance under the highest fog density condition examined. There were no significant interactions between age and the other variables, p>.05.

Time Headway

To examine the effects of fog on the safety margin for car following we derived time headway (THW) data. THW varied as a function of the average speed of the LV with THW decreasing at increased average speed of the LV. Thus, we conducted separate 2 (age) × 5 (fog density) for each speed condition. The results for THW are presented in Figure 6. At the slowest speed (40 km/h) the main effect of fog was significant, F(4,56) = 4.83, p<.05. According to this result THW decreased as a function of fog density. The main effect of age [F(1,14) <1] and the interaction of age and fog density [F(4,56)=1.6] were not significant, p>.05. These results indicate that at the lowest average LV speed we did not find any significant differences in car following performance between older and younger drivers.

At the intermediate speed (60 km/h) the main effect of fog density was significant, F(4,56) = 18.5, $p<.01$ as well as the interaction between driver age and fog density, F(4,56) = 5.75, $p<.01$. According to this result, THW decreased for both older and younger drivers with an increase in fog density. However, older drivers had the largest decrease in THW at the highest fog condition. This result indicates that older drivers, as compared to younger drivers, had a significant reduction in the safety margin at the highest fog density level.

At the highest speed (80 km/h) the main effect of fog density was significant, F(4,56) = 2.73, $p<.05$ as well as the interaction between driver age and fog density, F(4,56) = 3.12, $p<.05$. According to this result older and younger drivers had a decrease in THW with an increase in fog density with the exception of the highest fog density condition. For younger drivers THW continued to decrease at the highest fog density condition. However, for older drivers THW increased at the highest fog density condition. This result suggests that older drivers increased the following distance to increase the safety margin.

General Discussion

The present study examined two hypotheses concerning age-related differences in car following performance under foggy conditions. According to the aging and distance perception hypothesis, older drivers, as compared to younger drivers, will have decrements in perceived distance to the LV. According to the aging and speed perception hypothesis, older drivers, as compared to younger drivers, will have decrements in perceived speed and relative speed change between the lead and following vehicle. The results of the present study provide evidence in support of both of these hypotheses. With regard to distance information, we found that older drivers, as compared to younger drivers, followed at a closer headway distance with an increase in fog density. In addition, although mean headway distance varied for both younger and older drivers as a function of speed, older drivers showed a greater change as a result of speed. This effect was especially pronounced for the highest fog density conditions examined. We also found greater variance in distance headway for older drivers, as compared to younger drivers. These results provide evidence in support of the age and distance perception hypothesis.

With regard to speed perception the results indicated that older drivers had greater RMS speed error than younger drivers. In addition, older drivers had lower squared coherence scores than younger drivers, indicating that older drivers had poorer performance in tracking local variations in speed at specific frequencies of LV speed. These results provide evidence in support of the age and speed perception hypothesis. The results of the present study, considered together, suggest that older drivers have decreased car following performance as a result of difficulty in judging both speed and distance.

An important finding in the present study was the interaction of age, speed, and fog density for the distance headway measure. Of particular interest were the age-related performance differences for the 60 km/h speed condition under the highest fog density condition (see Figures 3 and 6). Under this condition older drivers, as compared to younger drivers, followed at a very close distance and shorter THW. We believe older drivers followed at a close distance because of reduced visibility due to fog and the increased difficulty to perceive changes in LV speed. This combination of speed and fog density resulted in the greatest difference in performance between younger and older drivers and suggests a serious collision risk for older drivers. We can assess collision risk by deriving the time gap (the amount of time to close the following distance). The shorter the time gap the less time available to the driver to avoid a collision. For the 60 km/h/0.16 fog density condition younger drivers had an average time gap of 1.1 sec.

However older drivers had a time gap of 0.87 sec. This represents a 21% reduction in time available to respond to avoid a collision for older drivers. Given the well documented finding of slower reaction time with age this result suggests that older drivers may be at considerable risk of a collision under high fog density conditions at moderate speeds.

An interesting change in the pattern of results occurred for older drivers at the 80 km/h speed. At this speed under the highest fog density condition examined older drivers maintained a following distance and THW that was much greater than the following distance of younger drivers (see Figures 3 and 6). Unlike the results for the 60 km/h speed (which we believe is due to perceptual difficulty for older drivers) we believe the results for the 80 km/h speed are due to a combination of perceptual difficulty and a strategic shift by older drivers. Specifically, older drivers may be aware of the difficulty in perceiving changes in LV speed under the high fog condition and, because of the decreased THW, adopt a greater following distance to increase the safety margin.

These results of the preset study suggest two human factors applications. The first application concerns car following models. As noted earlier, the DVA model (Andersen & Sauer, 2007) includes components for distance headway and speed. A modification of the DVA model to account for car following under fog conditions should focus on changes in both the distance and speed components. For example, adding a noise parameter for estimating distance and speed change may allow the model to predict car following performance under fog conditions. Age-related differences in car following performance can be incorporated in the model by using a greater magnitude of noise for the distance component. A second application concerns in-vehicle warning systems or adaptive control systems for reduced visibility conditions. The results of the present study indicate that older drivers have greater difficulty, under fog conditions, in maintaining distance headway. This finding suggests that the development of warning systems or adaptive control systems to improve driver safety, particularly for reduced visibility conditions, should focus on distance headway information in minimizing collision risk.

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Figure 1.

Sample image of the driving simulation scene. The fog density level depicted is an intermediate (0.08) level.

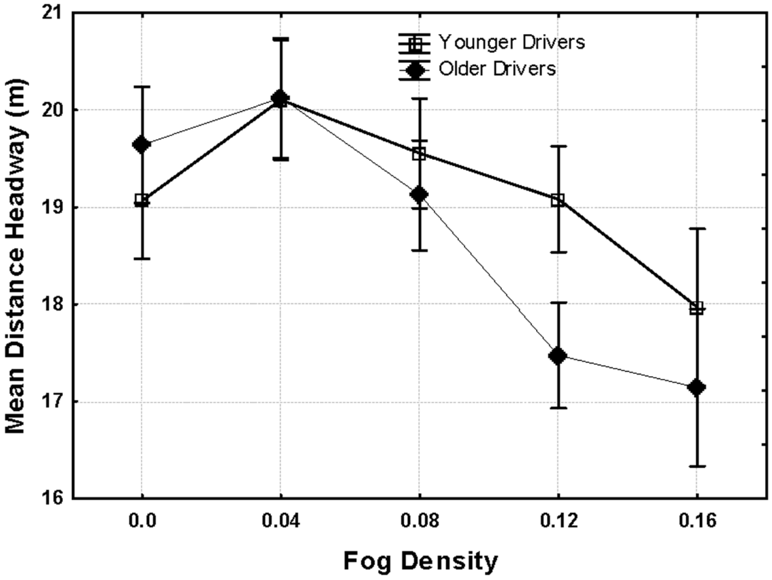

Figure 2.
Mean headway distance as a function of age of drivers and fog density.

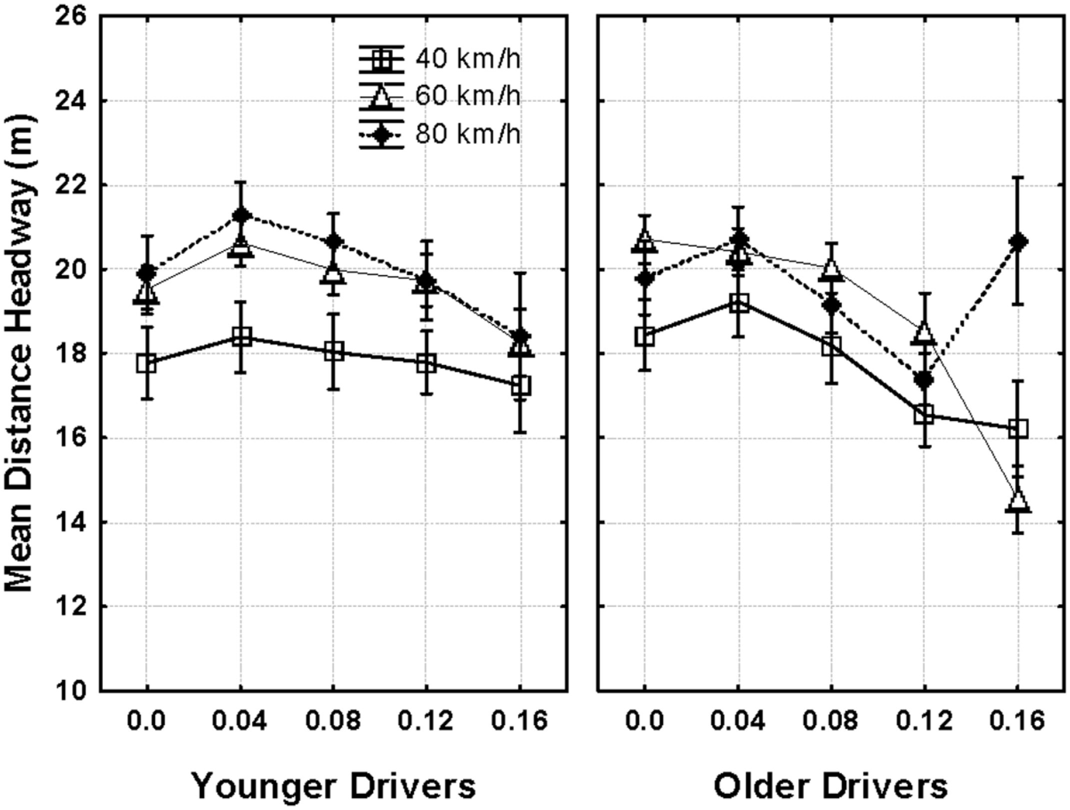

Figure 3.

Mean headway distance as a function of age of drivers, fog density, and speed.

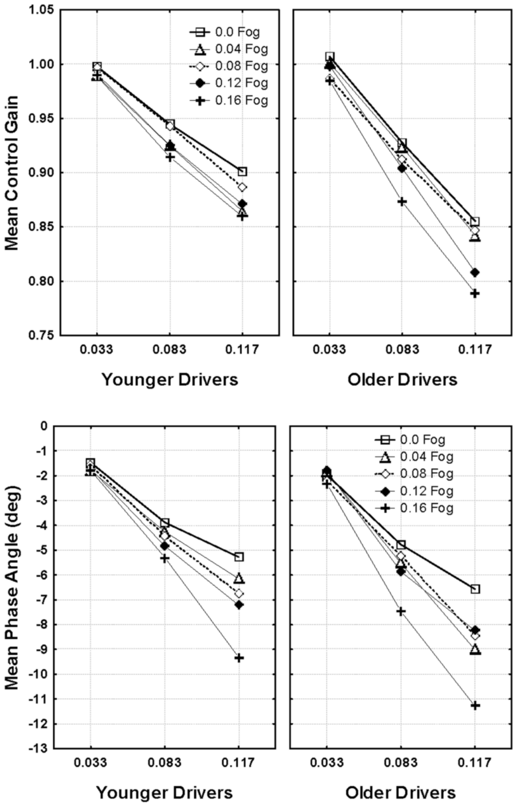

Figure 4.

Bode plot (control gain and phase angle) as a function of driver age group and fog density.

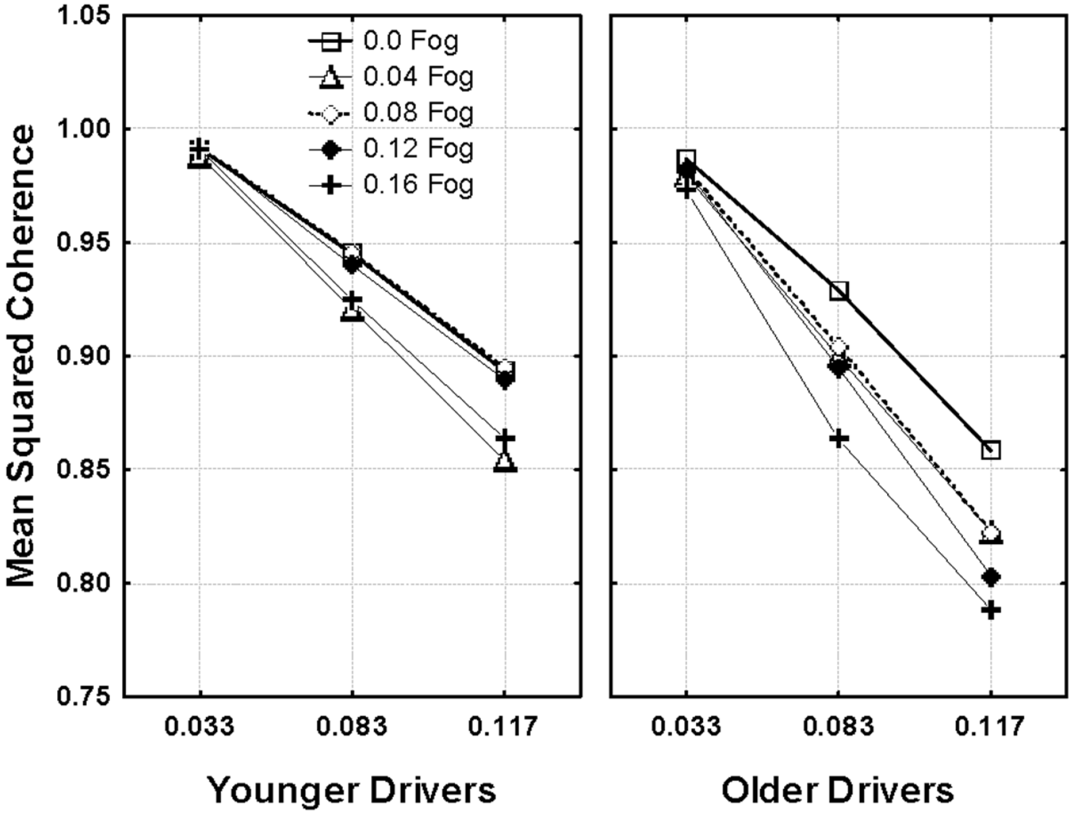

Figure 5.

Mean Squared coherence as a function of driver age group, frequency, and fog density.

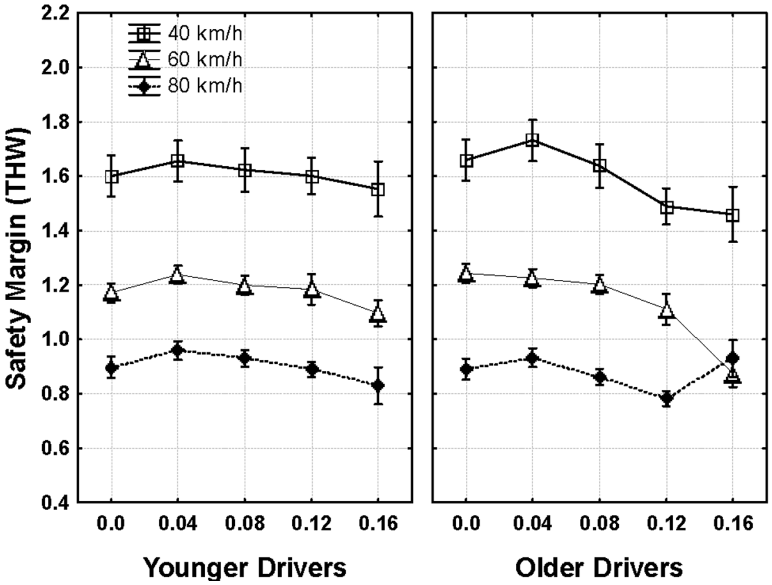

Figure 6.

Safety martin (time headway) as a function of driver age group, fog density and speed.

Table 1

Means and Standard Deviations of Participants' Demographic Information and Results from Perceptual and Cognitive Tests

Variable	Younger		Older	
	M	SD	M	SD
Age (years)[a]	21.1	2.67	72.6	4.62
Years of education[a]	14.0	1.3	16.8	2.1
Snellen Letter Acuity	10/10.8	1.7	10/13	2.3
Log Contrast Sensitivity[a,b]	1.75	0.06	1.62	0.19
Digit Span Forward	11.0	1.7	12.1	2.0
Digit Span Backward	7.6	2.9	8.0	2.1
Perceptual Encoding Manual[a]	92.2	13.3	67.0	12.5
Kaufman Brief Intelligence Test	28.3	4.4	29.9	4.8

[a] Differences between age groups were significant ($p \leq .05$) for both sets of age groups.

[b] Contrast sensitivity was measured using the Pelli Robson test (Pelli, Robson, & Wilkins, 1988).