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THE EFFECTS OF COMBINING REDUCED LUMINANCE AND INCREASED BLUR ON OLDER DRIVER SPEED AND VISUAL ACUITY

Nathan Klein
Clemson University, knathan@clemson.edu

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Nathan D. Klein
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Dr. Johnell Brooks, Committee Chair
Dr. Benjamin Stephens
Dr. Richard Tyrrell

ABSTRACT

Drivers may be at more risk to themselves and other roadway users when vision is blurred or when luminance levels are reduced. Past research has investigated these visual conditions separately, finding that each degrades acuity without severely impairing steering ability. However, it is unknown how reduced luminance in combination with increased blur will affect driving performance. This study sought to quantify this combined effect on older adults' comfortable driving speed and visual acuity by testing 10 participants in a driving simulator. The majority of the luminance and blur conditions are comparable to those the driving population may realistically encounter. Participants were asked to drive the speed at which they feel comfortable and could stay within their lane without using the speedometer. To ensure participants followed the instructions to stay in their lane, a percentage-of-time-in-lane measure was used to confirm no differences in steering performance existed across conditions. The older adult drivers only slowed down during the extreme blur condition; however, visual acuity was impaired by each manipulation. Interestingly, after the training conditions requiring a speed above 50 mph, drivers were given the opportunity to choose their speed and dramatically slowed down. This unexpected finding illustrates an important difference in what aging drivers choose to do in comparison with what they can do. This finding has important applied implications.

DEDICATION

I dedicate this work to my wife LeAnne and daughter Kaya who have been unbelievable sources of motivation as well as my most tempting reasons to procrastinate. Without their love and support, I would not be the person I am today.

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INTRODUCTION

The research reported here investigates luminance, blur, and their impact on driving speed and visual acuity for older adults. Reduced light levels will be combined with increased levels of blur to challenge these individuals in a driving simulator task as well as a test of visual acuity. This study extends the current literature and the implications of selective degradation on vision and driving. With the number of older drivers increasing, it is important to understand if low light levels and blur degrade their vision and driving performance.

According to a recent report by the Center of Sustainable Systems (2005), automobile travel is the most common form of transportation in the United States (U.S.), accounting for 90% of the miles traveled in 1997. Furthermore, the U.S., which comprises only 5% of the world's population, has 25% of the world's vehicles, and their use is on the rise. Between 1990 and 2000, the average number of miles driven annually grew 3.3%, whereas the population grew by only 1.3% annually. In 2003, people in the United States traveled 4.43 trillion miles in automobiles. As expected, the more travel and traffic, the greater opportunity for crashes. Estimates for 2004 indicated a crash every 5 seconds, an injury every 11, and a death every 11 minutes in a motor vehicle (NHTSA, 2006a).

Steering and Speeding

According to the National Highway Transportation and Safety Administration (NHTSA, 2006a), the two factors associated with most fatal crashes are failure to remain in the proper lane and driving too fast for conditions. In 2004, 24% of all fatal crashes were attributed to drivers failing to stay in their lanes, resulting in 13,954 deaths. The second most significant factor, speeding, accounted for 20.13% of all fatal crashes, killing 11,818 people (NHTSA, 2006b). According to NHTSA (2006b) speeding is dangerous because it decreases the driver's ability to steer safely around curves or objects in the roadway, extends the distance needed to stop a vehicle, and increases the distance a vehicle travels while the driver reacts to a dangerous situation. In 2005, 13,113 lives were lost in speeding-related crashes, and it is estimated that speeding costs the U.S. $1,281 per second, totaling $40.4 billion a year. In addition, speeding has also been shown to be related to age. It has been documented that younger drivers are the more likely to speed. The relative proportion of speeding related crashes to all crashes has been found to decrease with increasing driver age. (NHTSA, 2006b)

Speeding and road type. Of these speeding related fatalities, 86% occurred on roads other than interstate highways (NHTSA, 2006b). Of these, rural roads have been found to be more dangerous than urban streets at speeds of 55 and 60 miles per hour (mph), 2004, for example, having 4 times more fatal crashes, 15,130 compared to 4,468 fatalities (NHTSA, 2006a, 2006b). These rural roads account for more than half of all fatal crashes.

Speed, speeding, and speed limits. However, a review of the literature related to driver speed, speeding, and speed limits revealed that the notion that "speed kills", based on the hypothesis that as speeds increase, the time for the driver to react decreases while the forces in a crash increase is a complicated and controversial concept (Bowie & Walz, 1994; Garber & Graham, 1990; Moore, Dolinis, & Woodward, 1995). This simplistic concept, though, is interpreted differently by such experts as public policy makers, public health officials, engineers, and psychologists.

Those involved in setting public policy are responsible for justifying and enforcing speed limits. Speed limits have been and continue to be used to conserve fuel, reduce noise and emissions, and most importantly, promote road safety (Wilmot & Khanal, 1999). According to Wilmot and Khanal (1999), the use of speed limits to improve road safety is contingent on two assumptions: 1) speed limits actually reduce speeds and 2) reduced speeds actually lead to improved safety. In their study examining the effects of speed limits, they found that changes in speed limits were not matched by equal changes in average speed, regardless of whether the speed limit was raised or lowered. Rather, they determined that, generally, motorists do not adhere to speed limits, instead choosing speeds they perceive as acceptably safe. These conclusions support an earlier survey conducted by Denton (1969), which found that 80% of the drivers questioned agreed that speed limits serve a useful purpose while only 10 % actually abided by them.

In examining whether reduced speeds increase road safety, Fildes and Lee (1993) suggest that rather than considering crashes as a whole, a distinction should be made between the likelihood of being involved in one and its consequences, with various researchers claiming that higher speeds increase crash severity but not necessarily crash frequency (Shinar, 1998). The initial research in this area is found in the review of the National Maximum Speed Limit (NMSL) of 55 mph by the Transportation Research Board (Committee for the Study of the Benefits and Costs…, 1984), which found that overall, the NMSL saved approximately 3,000 to 5,000 lives annually even after accounting for other variables that may have contributed to safety benefits such as reduced exposure and discretionary driving. Later research by Joksch (1993) resulted in a power function that can be used to determine the relationship between impact speed and fatality risk. In exploring the relationship between speed and frequency, Taylor et al. (2000) reported that a reduction in speed by one mph can reduce collision frequencies between two and seven percent, while Waller (2002) reports that the probability of a fatal injury increases disproportionately relative to incremental speed increases. Her example involved an increase in speed from 40 to 50 mph which causes the probability of a serious or fatal injury to double. An additional problem according to other researchers is that roads with higher speeds will affect safety on roads with lower speeds. These indirect effects, known as the speed spillover hypothesis, argue that motorists will get into the habit of driving at faster speeds and carry this behavior over to other roads (Kamerud, 1988; Houston, 1999).

Regardless of higher speeds and their relationships with crash severity and frequency, there is evidence that lowering speed limits may not necessarily make roads safer (Solomon, 1964; Bohlin, 1967; Munden, 1967; Nilsson, 1981). For example, if a portion of drivers do not comply with a speed limit because it seems too low, then the variability of individual vehicle speeds in a traffic stream, known as speed dispersion, increases, a situation which can increase the risk for these vehicles traveling in the stream (Shinar, 1998; Wilmot & Khanal, 1999). Contrary to common sense, some research has shown that increases in speed can result in improved safety (Houston, 1999). For instance, the traffic diversion theory hypothesizes that an increase in the speed limit on a safer facility (e.g. freeway) may divert traffic away from less safe highways, producing an overall reduction in the total number of accidents for the same amount of travel (Kamerud, 1988; Lave & Elias, 1994). Public policy makers have learned that dealing with speeds involves assessing driver behaviors and perceptions in order to implement successful solutions based on research, not simply common sense.

At least one group of researchers (Richter et al., 2006) in the public health sector is addressing speed issues and driving as a pathogenic event resulting in injuries and fatalities that must be prevented. Referring to speed as a sickness, (e.g. sick populations, sick systems, sick individuals, or sick roads) that must be targeted and cured, they propose implementing successful remedies from other countries in their review of major studies on reduced and increased speed limits and epidemiologic studies on the effects of speed violations on individual risk. According to their goal and proposal, “Vision Zero – no road deaths – through Killing Speed,” it is unethical to sacrifice human lives to save time by traveling at increased speeds. They estimate that the cost of not accepting delay in the United States may be as high as 20,000 lives per year. In a systematic review of the effect of transport interventions on public health, Morrison, Petticrew, and Thomson (2003) found that health can be improved by changing the way that people use different forms of transportation and traffic calming schemes and by eliminating and redirecting efforts for interventions such as driver improvement and education courses, as they may actually be harmful to health. They recommend putting efforts and resources towards interventions that are supported by data.

Speeding has been addressed as an antisocial behavior by Poulter and McKenna (2007), in their examination of public opinions. They found that speeding rated as the problem of most concern relative to all other antisocial behaviors by all age groups in the population surveyed. Since driving fast is dangerous yet people still do it, Horswill and McKenna (1999) investigated driver speed choice as an everyday risky behavior. They looked at the effects of auditory feedback on speed choice, finding that drivers with quieter internal car noise drove faster than those who received louder car noises. These findings can be applied to road and vehicle designs, which currently attempt to reduce noise from the outside world, probably influencing driver speeds. Another perceptual influence on driver estimates of speed, known as speed adaptation, has been reported to occur when drivers transition from high-speed roadways to roads with lower speed limits (Schmidt & Tiffin, 1969). This factor, linked to accidents in these types of transition areas, causes drivers to feel that they are driving more slowly than they actually are, a phenomenon shown to occur even when drivers have access to a heads up speedometer display. These effects are also resistant to momentary decelerations from the adapted speed, meaning that drivers remain adapted despite these fluctuations (Barch, 1958). Denton (1969) found that drivers typically did not use the speedometer during these types of speed transitions as well as during other types of vehicle maneuvers in which knowledge of speed might be considered important. Despite the misleading perceptual cues that have been observed, 70% of the participants in Denton's study did not consider the speedometer necessary for safe driving. He also found that drivers believed they used their speedometer more than they actually did.

In an investigation of the effects of fog on driving performance (simulated by reduced contrast levels of the visual scene) Snowden, Stimpson, and Ruddle (1998) found that the apparent speed of the vehicle slows for drivers. When asked to drive at a target speed, participants drove faster during the scenarios involving reduced contrast. In addition, when comparing speeds between low and high contrast scenes, subjects tended to assume faster speeds in the lower contrast conditions, perceiving the foggier scenes to be moving more slowly. Snowden, Stimpson, and Ruddle propose that the danger of driving under challenging visual conditions such as fog is that typically drivers do not want to divert their eyes from the roadway to look at their speedometers so they rely on their perception. The danger in this situation is drivers are unaware of their bias to drive faster because they misperceive their actual speed.

Owens, Wood, and Carberry (2002) investigated this phenomenon in an actual vehicle on a closed-road circuit, finding conflicting results. The speedometer was obstructed from view, and fog was simulated by placing from zero to two diffusing plastic filters on the windshield and windows. They found that all measures of perceived speed decreased significantly with reduced visibility and that drivers traveled more slowly in fog. They also found that drivers consistently over estimated their speed under clear and foggy conditions, the amount of overestimation being higher for the foggier conditions.

Driver Age and Crashes

Despite the debate in the speeding literature, data consistently shows that age is a factor in crashes. Based on the latest mortality data, motor vehicle crashes are the leading cause of death for young drivers under the age of 25 (NHTSA, 2006d). Between 9 and 10 drivers in this age group are killed every day in motor vehicle crashes. In 2005, 3,467 young drivers were killed and an additional 281,000 were injured. Also, in the same year young drivers were involved in 12.6% of all fatal crashes. From 1995 to 2005 such driver involvement in fatal crashes rose 4%, reaching 7,460 cases (NHTSA, 2006c). Not only are these drivers involved in more fatal crashes, they are affecting others on the roadways at an increasing rate as well, a factor affected by the increasing number of young licensed drivers rising 6.2% between 1994 and 2004 (NHTSA, 2006d). Currently, 12.5 million young drivers comprise 6.3% of the total population of licensed drivers in the United States.

Drivers over 65, the other age group at the highest risk, are involved in a greater proportion of accidents per mile driven, even though they drive the least (Stamatiadis & Deacon,1995; Cooper, 1990; Evans, 1988). More specifically, Wood and Mallen (2001) found that older drivers received worse performance scores in comparison to younger drivers in sign recognition, lane keeping, and speed control. In addition, older drivers were rated as less safe than younger drivers even when visual problems were controlled. In 2005, 191,000 older individuals were injured in traffic crashes (NHTSA, 2006c). These crashes are not just a risk for older drivers as 73% of these crashes involved other vehicles. In the same year, older drivers accounted for 14.3% of all traffic fatalities, totaling 3,935 deaths. At this rate between 10 and 11 older drivers were killed each day because of traffic crashes (NHTSA, 2006c). This problem is compounded as the number of older adults in society as well as the number of older licensed drivers on the roadways increases. In 2004, the last year data were available, older adults made up 15% of the total number of licensed drivers even though in 2005 they represented only 12% of the total population. Moreover, this age group is a growing driving population: between 1994 and 2004 the number of older licensed drivers increased by 17% whereas the total number of licensed drivers increased by only 13%.

Due to the increasing number of older drivers, the roadway demographics are changing, creating a need for traffic safety specialists to re-examine traditional or prototypical driving models to incorporate current older drivers. Even though medically older drivers are considered to be frailer than younger drivers (Olson & Farber, 2003, chap. 11), their behaviors and activities are evolving, with recent evidence showing new causes for their crashes. For example, in a recent analysis of South Carolina driving statistics, speeding for the first time is documented as a contributor to senior crashes (Wilson, 2006). Additionally, driving under the influence, often due to medication interactions, made the list for the first time providing strong evidence showing that the characteristics of seniors are changing. Today's seniors may be on the roadway for different reasons and at different times than those of past generations.

Luminance

Night Driving. Regardless of the age of the driver, speed, or road type, driving at night is inherently more dangerous than driving during the day, even when factors such as alcohol and fatigue are controlled (Owens & Sivak, 1996). Despite a fatality rate four times higher than during the day, drivers do not sufficiently alter their behavior at night (Owens, Wood, & Owens, 2007; Owens, 2003; Owens, Wood, & Owens, 2007). More specifically, drivers do not slow their driving speed enough to compensate for the reduction of light. According to Johansson and Rumar (1968), safety begins to be compromised at night at speeds of approximately 20 mph (32 km/hr) when using low beam headlights. According to the assured clear distance ahead (ACDA) rule, the total stopping distance needed for a driver to detect and stop for a dark-clad pedestrian has been found to be 1.2 - 3 times greater than the distance at which a driver can react when driving with low beam head lights (Leibowitz, Owens & Tyrrell, 1998). Since the majority of states do not attenuate speed limits for nighttime driving, drivers overdrive their headlights and exceed visibility limits because they do not understand the underlying dangers associated with night driving. Owens, Helmers, and Sivak (1993) have calculated that more than 17,000 (mostly young) lives would be saved each year if the nighttime fatality rate matched the daytime rate.

Civil twilight. The dangers associated with nighttime driving begin during dusk. During this period, called civil twilight, the human visual system undergoes a rapid adaptation to the reduced amount of light in the environment (Owens, Wood, & Owens, 2007; Owens, 2003; Olson & Farber, 1996). For the half hour that the sun's altitude is between 0 degrees at the horizon and -6 degrees below the horizon, luminance levels in the environment range from 300 lux to 3 lux at the dimmest point. This period of civil twilight involves substantial skylight, but the surface of the earth is not lit well enough to see objects on the road without the use of headlights. It is well documented that visual acuity, contrast sensitivity, and useful field of view are sensitive to the changes in light levels during this period of civil twilight (Leibowitz & Owens, 1991; Odom, Tyrrell, Brooks, & Muth, 2005; Owens, Francis, & Leibowitz, 1989; Sturr, Kline, & Taub, 1990). According to Owens (2003), the luminance values associated with the dark end of civil twilight are comparable to the furthest useful distance illuminated by headlights when driving; therefore, this period is comparable to the functional limit of headlights. To complicate the situation, the time needed for individuals to adapt effectively to darkness, or dark adapt, increases with age (Jackson, Owsley, & McGwin, 1999).

Seeing. Despite the challenges associated with adapting from daylight (photopic levels) to nighttime (scotopic levels), the human eye is adept at functioning under a wide range of luminance levels (Blake & Sekuler, 2006, chap. 3; Graham, 1965, p.42-59, 73-75). This ability comes from the physiology of the retina, which is composed of two types of photoreceptor cells, cones and rods. Cones, which are located in the center of the retina at the fovea, function only under photopic conditions. These photoreceptors are responsible for seeing fine details and support such functions as reading and identifying objects. This mode of vision referred to as visual recognition or focal vision, dominates conscious awareness. Rods, which surround the fovea on the retina, are capable of functioning at scotopic levels. While they are not capable of providing the fine resolution that cones do, they are more sensitive to light, able to detect a single photon. In addition, the rods provide peripheral vision and help with guidance, locomotion, and motion perception referred to as ambient or guidance vision, which has little conscious awareness. Since there is a tradeoff between resolution and sensitivity, the rods and cones provide the capability to cope with diverse light levels, allowing for human vision to function well in both day and nighttime. Visual information transmitted from the photoreceptors to the brain is processed in the visual cortex as well as the superior colliculus.

Parallel processes. Schneider (1967, 1969) first found evidence of parallel processes in vision by making selective lesions to these areas of the brain. After making a lesion to the visual cortex of Syrian hamsters, he found that they could no longer discriminate between test patterns consisting of lines and dots but could still navigate the environment. The second group of hamsters, which had their superior colliculus lesioned, could discriminate patterns but could not successfully navigate their environment. The results of this study indicate that the capabilities of these two groups were altered, providing evidence for two pathways for processing visual information in the brain.

At this same time Salvatore (1967) conducted a study of vehicle speed estimation and found that when estimations from the periphery were compared to those of the fovea, peripheral estimates were found to be more accurate. He also determined that increased acceleration results in an increase in error in speed judgment. Overall, participants believed they were traveling slower than they actually were and deceleration was sensed more effectively than acceleration.

Selective degradation. Ten years later Leibowitz and Owens (1977) applied Schneider's findings to nighttime driving, hypothesizing why drivers are comfortable driving the same speeds in both daylight and darkness. Specifically, they hypothesized that under daylight conditions, drivers would have little difficulty using both focal and ambient modes of vision simultaneously. However, as luminance levels are reduced, recognition functions such as acuity, sensitivity to contrast, and the ability to perceive objects would degrade rapidly with the guidance mode remaining unaffected until light levels fall below those normally encountered in typical nighttime driving environments. The Selective Degradation Hypothesis suggests that drivers are overconfident at night because they are unaware of their degraded visual recognition abilities since their ambient visual capabilities are maintained. Specifically, they predicted that steering performance would be dependent on ambient vision, remaining robust at low light levels, whereas acuity measures were predicted to be dependent on focal vision, therefore degrading systematically with decreasing light levels.

Testing the selective degradation hypothesis. Owens and Tyrrell (1999) were the first to investigate the Selective Degradation Hypothesis, completing a series of experiments measuring the effects of reduced luminance on both visual guidance and visual recognition. Recognition vision was assessed through measures of visual acuity, and guidance vision was assessed through measures of steering accuracy using a low-fidelity driving simulator. The participants' task was to maintain position between a series of white posts while traveling at a constant speed. To simulate night driving, neutral density (ND) filters were mounted in trial frames to create luminance levels of 30, 1.0, 0.03, and 0.003 cd/m^2. Participants from three age groups, having mean ages of 24, 38, and 72 years, completed this study. The results were consistent with the predictions of the Selective Degradation Hypothesis: As luminance decreased, so did visual acuity, while steering remained robust. Overall, the steering error was greater for the older participants than the younger. In addition, their steering error increased more than the younger participants' as luminance levels decreased. At the intermediate luminance level of 0.03 cd/m^2, a level comparable to the dark end of civil twilight, the older participants' steering performance was degraded where there were no significant effects for the younger age groups whose performance was not affected until the lowest luminance tested of 0.003 cd/m^2. However, in response to the researchers' subjective questions on their normal driving behavior, the participants indicated they felt comfortable driving at night, appearing to be unaware of their reduced vision.

Brooks, Tyrrell, and Frank (2005) replicated the Owens and Tyrrell (1999) study with young drivers using a higher-fidelity driving simulator. To manipulate luminance, neutral density filters were placed in welding goggles to create four levels, the lower 3 identical to those used by Owens and Tyrrell and the fourth being 16.7 cd/m^2, due to threshold limitations of the simulator's projectors. Luminance was quantified by the luminance of the roadway's dividing lines, which was the maximum luminance in the driving scene. As in the Owens and Tyrrell study, visual acuity was assessed. The driving task consisted of continuously curvy roads with no traffic, with the participants being instructed to maintain a speed of 55 mph. Their speeds were displayed above the hood of the car on the center channel projection screen in addition to being read aloud every 20 seconds or more frequently if requested because this speedometer was difficult to read under low luminance conditions. Whenever participant's speeds fell below 50 mph, the experimenter instructed them to speed up and vice versa when they exceeded 60 mph.

The primary steering variable for each 5-minute trial was the percentage of time spent entirely within the driver's lane. The drivers were able to maintain the target speed of 55 mph under all conditions (range 54.8 – 55.6 across conditions). As with the Owens and Tyrrell (1999) study, steering performance was robust, ranging between 82-88% of the trial in the lane. Acuity was found to be sensitive to the luminance reductions, decreasing from approximately 20/20 to 20/180. The results from this study support those found by Owens and Tyrrell: More importantly, the Selective Degradation Hypothesis was again supported as steering performance remained robust at low luminance levels while visual acuity did not.

Brooks (2005) conducted a second study using the same driving simulator with the following changes. Participants consisted of three groups with mean ages of 19, 43.5, and 69.5 years and luminance levels were manipulated by placing ND filters in either trial frames or trial lens clips with the periphery occluded to provide a wider visual field than the welding goggles used in the Brooks et al. (2005) study. While the same digital speedometer was used, a voice recording instructed the participants to speed up whenever their speeds dropped below 50 mph, and a voice loop played every two seconds instructing them to slow down when their speeds exceeded 60 mph. In addition, luminance levels were changed slightly to 10, 1.0, 0.1, 0.01, and 0.001 cd/m^2. Based upon the research of Jackson, Owsley, and McGwin (1999), different dark adaptation times were used to ensure that participants of various ages reached a similar level of sensitivity.

Once again, the primary dependent variable was the time spent entirely within one's lane. Across the three age groups, the driver time in lane ranged from 68% to 96%. The only difference among age groups for steering ability occurred under the dimmest luminance condition of 0.001 cd/m^2, with the oldest drivers (59%) performing significantly worse than the youngest drivers (78%).

Driving speed across the age groups ranged between 51 mph to 55 mph. The only group failing to maintain the target speed range was the seniors whose mean speed dropped below 50 mph to 45 mph under the dimmest conditions. More importantly a larger age effect was found in the variability of the drivers' speeds, with seniors varying the most within each trial. In addition it was observed that the seniors felt frustrated and became agitated when being reminded to increase their speeds (J.O. Brooks, personal communication, June 2, 2006).

For all groups, acuity was sensitive to luminance decreases. High contrast visual acuity declined from 20/22 to 20/400 when averaged across the three age groups, with the seniors' acuity being worse than the younger age groups across all conditions. In testing selective degradation, the results from this study are similar to Owens and Tyrrell (1999) and Brooks, Tyrrell, and Frank (2005) with regards to steering performance and acuity, where steering performance remained robust and visual acuity degraded as light levels decreased.

To investigate further the variability in the seniors' speeds and the resulting frustration found in the Brooks experiment (personal communication, June 2, 2006), a follow up study was conducted using the same procedure but eliminating the lower threshold voice loop (Brooks, 2005; Klein et al., 2006). Instead, the participants, representing only 2 age groups, with mean ages of 20 and 72 years, were instructed to drive a comfortable speed although the speed limit remained at 55 mph.

As with the previous simulator studies, steering performance was robust with the participants staying entirely within their lanes 71 to 92% of the time during the trials. When the drivers were able to choose their own speeds, there were no age effects for the time spent in lane. However, overall, the seniors drove significantly slower (M = 40 mph) than the younger drivers (M = 53 mph). This gap between the age groups increased as the luminance levels decreased, with the smallest difference under the maximum luminance condition, 8.1 mph, and the largest difference under the minimum luminance condition, 16.5 mph.

The findings from these four simulator studies are supported by a closed circuit test track study conducted by Owens and Wood (Owens, Wood, & Owens, 2007; Owens, 2003). This study, which occluded the speedometer, assessed driving behavior across four luminance levels by reducing high beam headlight intensities by 75, 87.5 and 97 %. Participants of three different age groups, with mean ages of 22, 47, and 72 years were instructed to drive as they normally would on ordinary rural roads, maintaining a comfortable speed, while steering and performing an object recognition task of 28 signs, four speed bumps, and two pedestrians.

Overall, the older adults drove significantly slower (M = 24.6 mph) than the younger (M = 28.3 mph). When averaged across the age groups, there was a significant reduction in speed as luminance levels were reduced, the total reduction in speed between daylight and high beams was only 2 mph. The 97% reduction from high beams resulted in a speed reduction of only 1.6 mph when averaged across the age groups. As expected, recognition abilities declined with luminance. While the drivers had the option to slow down to a speed which would allow them to read all signs, only one participant did so.

Blur

A natural extension to these studies of luminance and its effect on vision is an investigation of blur and its impact on driving since blur can degrade vision as well. For optimal focal vision, it is necessary to have sufficient light and for this light to be focused sharply. To investigate if increasing blur causes selective degradation in human vision similar to decreasing luminance, researchers have measured the effect of blur on visual recognition and guidance using methods similar to those used to test luminance. Examining the effects of blur on guidance and focal vision is important from both a basic scientific and practical viewpoint. Such a study is equally important to luminance in the area of driving safety.

Driving with blur. When evaluating the effects of luminance on steering and acuity, Owens and Tyrrell (1999) also assessed the effects of increased levels of blur using their steering simulation in which participants (Mean age = 38 years for steering and 34.8 years for acuity) steered between white posts at a set speed. Myopic blur levels of 0, 2, 5, and 10 diopters were tested at the maximum luminance condition through simulation with positive lenses mounted in trial frames. With each increase in blur, visual acuity was significantly degraded but with no effect on steering performance.

Brooks, Tyrrell, and Frank's (2005) replication of the Owens and Tyrrell (1999) study included an investigation of the effects of blur on driving and acuity performance using their higher fidelity driving simulator and the same levels of blur plus an additional +1 diopter manipulation. While a significant effect was revealed with increased blur in relation to the percentage of the trial spent entirely within the lane, this decrease was minimal, ranging from a maximum of 95 to a minimum of 88 at 5 diopters blur. However, the effect of blur on visual acuity was more marked, reducing it from 20/20 to 20/178. In both simulator studies, increased blur, like reduced luminance, had a large effect on visual acuity but a minimal effect on steering performance.

The effects of blur on steering performance have been investigated in both the lab and real-world settings using a closed-road course. With blurring lenses, Higgins, Wood, and Tait (1998) manipulated the visual acuity of their participants, all measured at the same levels of 20/20, 20/40, 20/100, and 20/200 for the 4 trials. Steering performance, driving speed, sign reading, and hazard avoidance were assessed, these results indicating that as the amount of blur increased, the ability to read road signs declined as well as the number of hazards avoided; the drivers, however, did not compensate for this acuity reduction by slowing their speeds adequately. On the other hand, blur did not affect their steering abilities as they did not hit more cones during the maneuvering task.

Combining Luminance and Blur

Evidence from simulator and road studies have shown that the effects of both luminance and blur selectively degrade focal vision while ambient vision remains robust, impacting steering capabilities less than activities dependent on acuity. While past research has investigated blur and luminance and their impact on driving, little research has combined these two challenging visual situations. One applied study involving both was conducted by Johnson, Casson, and Zadnik (1992; Johnson & Casson, 1995) to determine the importance of healthy vision for California Department of Corrections officers. In the laboratory portion of this study the combined effects of blur, luminance, and contrast on acuity were measured using Tyrrell and Owens's (1988) Modified Binary Search. Visual acuity measurements were collected for four luminance levels (75.0, 7.5, 0.75 and 0.075 cd/m^2) using different blurring lenses (0, +1, +2, +4, and +6). For the control, the effects of blur and luminance were examined separately, each manipulation steadily reducing visual acuity. In investigating these additive effects of blur and luminance, the authors concluded that, “the resulting visual acuity . . . decreased by an amount significantly greater than for” luminance or blur separately (p. 88). While these data were collected under static conditions in a controlled setting, Johnson et al.’s (1992) second study measured the relationship between reduced luminance and increased blur in a dynamic, applied setting.

Correctional Officers performed a yard surveillance simulation to determine which volunteer inmate held a screwdriver as a weapon under daytime and nighttime conditions. Luminance levels during the daytime simulation ranged between 500 and 3,000 cd/m^2, while the average luminance level for the night yard ranged from 0.2 to 4 cd/m^2. Positive lenses were used in a trial lens frame to blur the officer’s binocular visual acuity to predetermined levels of 20/20, 20/30, 20/40, and 20/60. After a five-second observation period, the officers indicated the location of the target person, subsequently providing a confidence rating of their decision from zero to ten with zero indicating no confidence and ten most confident.

Performance was at 100 % in the 20/20 condition but dropped to 17 % at the 20/30 level. None of the correctional officers could perform either task at the remaining visual acuity levels. The results did not differ as a function of light levels, only blur. Despite similar performance between the day and night simulation tasks, the confidence ratings of the correctional officers are inconsistent with their performance. Under the 20/20 visual acuity condition, the average confidence rating was high (M = 10) for both the day and night simulations. For the rest of the day simulation visual acuity levels, there was a steady decline in confidence through the 20/60 level. However, the confidence ratings of the correctional officers for the night simulation task drop at the 20/30 level remaining low for the duration (near 0).

Current study. While Johnson et al.'s (1992; Johnson & Casson, 1995) study confirmed that blur and luminance degrade visual acuity, it is not known how this combination impacts a dynamic task such as driving that requires both focal and ambient vision. The proposed study was designed to test the effects of both luminance and blur on older adult driving speed and acuity. The methods used replicated and built upon those of Brooks et al. (2005) and Brooks (2005) where steering and vision were assessed under degraded visual conditions. This study focused on more commonly occurring visual degradations than the more extreme manipulations used in the previous studies.

The predictions for this study extend the previous literature based on the selective degradation hypothesis (Leibowitz & Owens, 1977). However, since these predictions are coupled with driver capabilities, they may not be applicable to driver preferences. In other words, previous studies illustrate that drivers are capable of staying in their lane under degraded visual conditions; however, they may not be comfortable doing so. Given that older drivers slowed down when luminance levels became severely degraded, even when they were instructed to drive at a set speed (Brooks, 2005) and that older drivers tend to drive slower than younger drivers when given the choice (Owens, Wood, & Owens, 2007; Klein et al., 2006; Owens, 2003) it is likely that there is a difference between what drivers are capable of doing and what they are comfortable doing. It is anticipated that drivers will significantly decrease their speeds across the combinations of decreased luminance and increased blur while lane keeping performance will remain robust, meaning that the time drivers spend in the lane will not change. Consistent with previous research (Brooks, 2005; Brooks et al., 2005; Johnson, Casson, & Zadnick, 1992; Owens & Tyrrell, 1999), it is expected that visual acuity will decline with increased blur and decreased luminance.

METHOD

Participants

Ten licensed drivers (four male and six female), between the ages of 65 and 80 (M = 72.5), with an average of 54 years (ranging from 47 to 64 years), of driving experience completed this study. Individuals were screened via self report for a history of migraines, motion sickness, visual pathologies, and cataract extraction. Despite the prescreening, three additional participants were unable to complete the study due to simulator sickness. No one had any previous experience with the Clemson University driving simulator, nor did they have any familiarity with the hypotheses under investigation. Participants were paid $10 per hour and received a small token of appreciation for their time.

Materials

Driving Simulator. Participants drove a fixed-based driving simulator (Drive Safety Inc.). Three forward and one rear visual channel were used (each 50 degree horizontal by 40 degree vertical; 1024 x 768 resolution). Participants sat in a Mitsubishi Galant and used the original steering wheel, gearshift, speedometer, brake pedal, and gas pedal.

The roadway environment consisted of a flat, intentionally curvy, rural, two-lane road with a lane width of three meters and no paved shoulder (see Figure 1). The lanes were divided by two solid yellow center lines while the outer boundaries were marked by a solid white edge line. The winding feature of the roadway was designed to challenge the participants' steering capabilities even under optimal viewing conditions. All the driving scenarios consisted of curves of equal radius made by using one of two Drive Safety tiles (see Figure 1). The curve pattern was varied between each of the ten scenarios to prevent familiarization with the road. There was no other traffic, and the scenery consisted only of trees.

Figure 1. Depiction of a typical scene from the driver's perspective in the simulator. All scenarios consisted of curvy two lane rural roads free of other traffic and pedestrians.

Visual Scene Manipulations. Luminance was reduced by placing neutral density (ND) filters in front of the driver's eyes. These ND filters were mounted to ring inserts placed in either trial frames for participants who did not wear glasses or trial lens clips for participants who wore glasses. Blinders were placed on the sides of all frames to occlude peripheral light and to prevent the use of peripheral vision, thus providing a forward binocular field of view of approximately 65 degrees horizontal by 45 degrees vertical. The ND filters reduced the scene luminance by 0 (control), 1, or 2 log units. When wearing the filters, the luminance of the roadway's dividing lines (the maximum luminance in the scene) was 10, 1.0, or 0.1 cd/m^2 (1, 0, and -1 log cd/m^2, respectively).

These luminance values were selected because they represent the range of luminance levels encountered during civil twilight (Olson & Farber, 1996).

Blur was manipulated by placing positive lenses in front of both eyes using either the trial frames or trial lens clips. Three separate blur lenses were used to simulate myopic blur of 0 (control), +2, and +5 diopters (D). This range of blur includes common refractive errors that typically go unnoticed or untreated in the general population (0 and +2 D) as well as a more extreme case (+5D). Correspondence with several experts about when individuals tend to notice a change in their vision significant enough to take action resulted in a general consensus of at least -.5 to -1 diopter of blur (S.J. Grygier, personal communication, August 10, 2006; R.L. Owens, personal communication, August 15, 2006; R.E. Peyser, personal communication, July 10, 2006; E.P. Stavrou, personal communication, August 7, 2006). Dr. Owens also stressed that there is a large amount of variability among individuals and their sensitivity levels, with some people unaware that their vision is at 20/100 and others complaining about being 20/25. Dr. Grygier reported that a -.5 diopter change has become an implicit standard since most insurance companies will not fund glasses until they are at least .5 diopter strong.

Vision Charts. A high and low contrast Bailey-Lovie far visual acuity chart was used to measure the participants' visual acuity (Bailey-Lovie, 1976; Ferris, Kassoff, Bresnick, & Bailey, 1982). These charts were designed to be used at multiple testing distances by adding a constant corresponding to specific testing distances. This technique was possible because the charts use 14 rows of optotypes with five letters on each row, with the size of the letters decreasing by 0.1 log unit increments. Acuity was quantified using the logarithm of the minimum angle of resolution, logMAR. In addition to acuity contrast sensitivity was measured using a Pelli-Robson Contrast Sensitivity chart (Pelli, Robson, & Wilkins, 1988). The background luminance of these charts were 1 log cd/m^2, the same as the luminance of the roadway's dividing lines, the maximum luminance in the driving scene.

Workload. Workload was assessed using the Rating Scale Mental Effort (RSME) (Zijlstra, 1993), which is a one-dimensional scale with ratings between 0 and 150. Nine descriptive terms indicate different values along the axis of the scale (e.g. rather much effort corresponds to 58 and maximum effort corresponds to 112). Participants were asked to rate the amount of mental effort required to complete each driving scenario.

Procedure

Driving Simulator Training. Participants completed a consent form, a demographic questionnaire, and a motion sickness history questionnaire before being introduced to the vehicle. After the seat position was properly adjusted, the vehicle's controls were shown and described. Participants completed as many training sessions as needed until they were able to complete the task adequately and feel comfortable with the simulator. An outline of the procedure containing the sequence of events and scenario descriptions can be seen in Table 1.

Table 1. Sequence of events for scenarios and driving trials.

Order	Driving Session	Scenario		Speedometer Available	Type of Instructions: Drive at…
1	Training	Straight Road		Yes	Speed Limit
2	Training	Curvy Road		Yes	Speed Limit
3	Training	Curvy Road with Frames		Yes	Speed Limit
4	Training	Error Recovery		Yes	Speed Limit
5	**Training Check**	**ND 0**	**Blur 0**	**Yes**	Speed Limit
6	**Baseline**	**ND 0**	**Blur 0**	**No**	Comfortable Speed
		Dark Adaptation			
7 to 9	Exp	ND 2	Blur 0, 2, or 5	No	Comfortable Speed
	Exp	ND 2	Blur 0, 2, or 5	No	Comfortable Speed
	Exp	ND 2	Blur 0, 2, or 5	No	Comfortable Speed
10 to 12	Exp	ND 1	Blur 0, 2, or 5	No	Comfortable Speed
	Exp	ND 1	Blur 0, 2, or 5	No	Comfortable Speed
	Exp	ND 1	Blur 0, 2, or 5	No	Comfortable Speed
13 to 15	Exp/Control	ND 0	Blur 0, 2, or 5	No	Comfortable Speed
	Exp/Control	ND 0	Blur 0, 2, or 5	No	Comfortable Speed
	Exp/Control	ND 0	Blur 0, 2, or 5	No	Comfortable Speed
16	**Training Control**	**ND 0**	**Blur 0**	**Yes**	Speed Limit

The first training session consisted of a straight road. Once drivers were able to drive straight at a speed of 55 mph, they were asked to move around within the lane to explore the boundaries at a speed of their choice. The boundaries were ambiguous due to a lack of kinesthetic and acoustic feedback when one leaves the lane. As a result of this ambiguity, when either edge of the vehicle leaves the lane, a large, red “out of lane” message appeared on the center screen. This message disappeared when the driver returned to within the lane. This session lasted a minimum of two minutes. All driving trials were followed by a mandatory two-minute break.

All other training sessions and experimental trials lasted five minutes. The continuously curvy road was introduced in the second training session. Drivers were asked to move around the lane once they were capable of maintaining their lane position. The red “out of lane” message was again used to identify when drivers left the lane.

Due to the difficulty seniors have controlling the simulated vehicle when steering errors occur; the next session was designed to practice error recovery techniques. For this trial and all subsequent ones, no out of lane message was used, and the drivers had their periphery occluded for the first time by wearing either the trial frames or the lens clips.

The final training session served to ensure participants met a minimum level of competency referred to as the training-check. Participants were instructed to stay within the lane and drive the speed limit of 55 mph. Participants were required to stay in the lane a minimum of 85% of the trial at a minimum average speed of 50 mph. They were not permitted to proceed to the experimental trials until they were able to meet these criteria. Next participants completed the baseline driving session without the use of their speedometer and with instructions to drive at a comfortable speed to safely stay in their lane.

After each practice session and driving trial, to monitor any signs of simulator sickness, participants responded to a motion sickness questionnaire and rated the mental effort that was required to perform the driving task. After these surveys, the participants read the acuity chart and contrast sensitivity charts, initially at a distance of three meters but with the possibility of having them moved to a testing distance of either one meter or 50 centimeters if needed.

Driving trials. Prior to beginning the experimental trials, the participants dark-adapted for 40 minutes consistent with the Brooks (2005) study based on Jackson, Owsley & McGwinn's (1999) findings. While adapting to darkness, the participants sat in the vehicle talking to the experimenter while wearing two comfortable blindfolds, a cloth blindfold and occluded ski goggles. After dark adaptation was complete, the three luminance levels were tested in order from the dimmest to the brightest to avoid having to dark adapt more than once. Within each luminance level, the three blur conditions were randomized for a total of nine five-minute trials. The minimum blur condition that occurred during the maximum luminance block of conditions was used as the control and later compared to performance in the baseline condition. Before the first driving trial after dark adaptation participants had three minutes to re-adjust to the new light level and one minute for each subsequent trial.

Before all experimental trials and the baseline trial, the participants were instructed to stay in the center of the lane and drive the speed limit of 55 mph. The participants were also instructed to drive as they would in the real world, meaning that they should adjust their speed to remain safely in the lane. If participants exceeded 60 mph, an audio clip instructed them to “slow down” every two seconds until their speed dropped below 60 mph. While the speedometer was available during the training sessions, it was not present for the experimental trials in order to eliminate any speed cues in an effort to get a less biased measure of the driver’s comfortable speed. Also, by eliminating the availability of the speedometer a possible confound was avoided since the speedometer’s visibility would have changed due to the reduced luminance and increased blur manipulations, mirroring the change in the visual conditions. Under optimal conditions, pilot testing showed that drivers were not impacted by removing the speedometer (Klein & Brooks, 2006). After the experimental trials, participants completed a final session, referred to as the training control, with the same instructions to drive the speed limit of 55 mph and under the same maximum luminance and minimum blur conditions as in the training-check condition. This training-control condition was used as an additional comparison of performance between the beginning and end of the study to ensure participants were still capable of driving the speed limit regardless of their comfort ability. Overall on average, the study required approximately six hours for each participant to complete the protocol. Table 2 provides a summary of the maximum luminance and minimum blur conditions organized by sequence as well as the type of instructions and availability of the speedometer.

Table 2. Maximum luminance and minimum blur conditions organized by sequence as well as the type of instructions and availability of the speedometer.

	Pre	Post
Speed limit instructions and speedometer	Training check	Training control
Comfortable speed instructions and no speedometer	Baseline	Control

Data Analysis

Driving performance. Simulator data were sampled at a rate of ten Hertz. The first 30 seconds of each five-minute trial were dropped to allow the participants to reach their desired speeds. While multiple simulator variables are available, the primary measure of this investigation is overall speed, which provides a measure of the speed chosen by the drivers under the different visual manipulations. Also, the percentage of the trial spent in the lane was used to check if the participants followed the instructions to drive at a speed where they could stay in their lane.

Experimental design. This study used a 3 (Luminance: 1, 0, and -1 log cd/m^2) × 3 (Blur: 0, 2, 5 Diopters) within subjects design.

RESULTS

To aid in the examination of the effects of luminance and blur on the dependent variables, each was first analyzed for practice or fatigue effects using two t-tests, one involving the participant performance when the speedometer was available and one when it was not. The conditions used for these comparisons were maximum luminance with no blur. The first compared their performance at the end of the training, (i.e. the training check), with their performance during the final session, (i.e. the training control).

The second compared participant performance during their first experience without the speedometer immediately after the training check and prior to dark adaptation, (i.e. the baseline), to their performance during one of the final three experimental conditions with maximum luminance. The one used depended on when the no-blur condition appeared during maximum luminance, the final luminance condition, meaning participants drove the maximum luminance, no blur condition for a second time during one of the last three experimental driving sessions, (i.e. the control). Also, the training check and training control were compared and the baseline and control were compared.

To examine the experimental data, repeated measures ANOVAs investigated the effects of luminance and blur. An alpha level of .05 was used for all significance tests, and the Greenhouse-Geisser degrees-of-freedom correction was used for all repeated measures ANOVAs. Pairwise comparisons used the Bonferroni correction for multiple comparisons.

Percentage of the trial spent within the lane (%)

The percentage of the trial spent in the lane was measured as the ratio between the time the vehicle is entirely within the lane and the total time driving. The comparison between the training check and the training control did not reveal a difference in the two time periods, with participants spending an average of 92.7% of the trial within the lane, $t(9) = 1.44$, $p = .183$. The second comparison between the baseline and the control also failed to reveal a difference with participants spending an average of 94.9% of the trial within the lane, $t(9) = 2.00$, $p = .077$. These results suggest no evidence of practice or fatigue effects.

The percentage of each trial spent within the driver's lane as a function of luminance and blur can be seen in Figure 2. An ANOVA did not reveal a significant Luminance × Blur interaction, $F(3.36, 30.21) = .04$, $p = .994$; a significant main effect of luminance, $F(1.76, 15.82) = 1.87$, $p = .188$; or a significant main effect of blur, $F(1.44, 12.91) = 2.19$, $p = .159$. Averaged across all conditions, participants remained in the lane 92.5% of the time. While no differences were identified, or expected, this variable served as a manipulation check to ensure participants did not sacrifice steering ability for speed as well as to check the effectiveness of the driving instructions. Additional simulator variables including center position, standard deviation of center position, mean lateral speed, and standard deviation of lateral speed, were also analyzed. The analyses for these variables are reported in Appendix A.

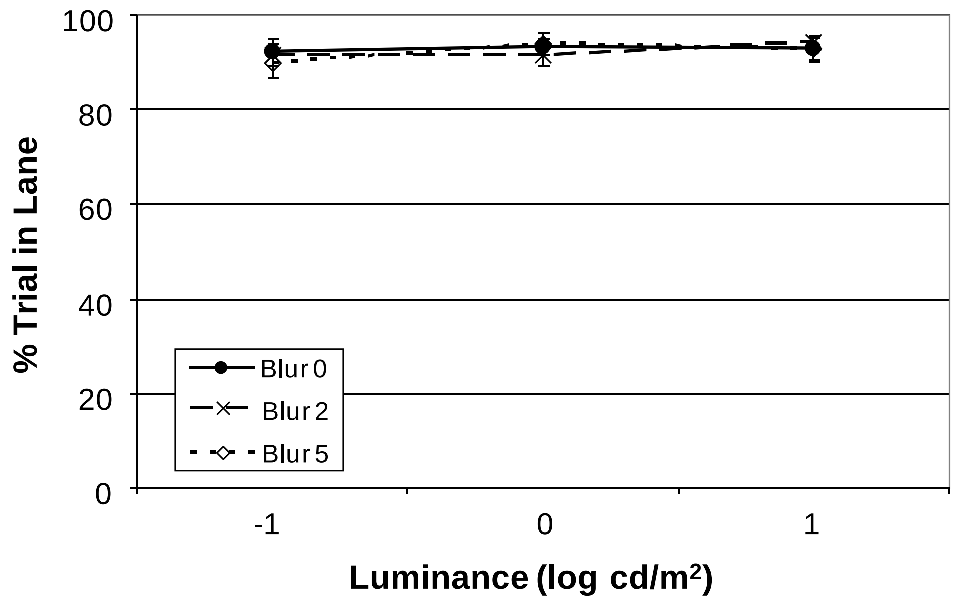


Figure 2. Percentage of trial spent entirely in the lane as a function of luminance and blur.

Overall speed (mph)

The overall speed is the average speed driven during the trial. The first comparison between the training check and the training control failed to reveal a difference in the average overall speed of 53.2 mph, $t(9) = 1.68$, $p = .128$. The second comparison, between the baseline and the control, also failed to reveal a difference where participants' average overall speed was 47.3 mph, $t(9) = 2.11$, $p = .064$. Thus, there was no evidence of practice or fatigue effects.

The mean speed for each trial as a function of luminance and blur is presented in Figure 3. While decreased speeds were anticipated, an ANOVA revealed a significant main effect for blur, $F(1.47, 13.2) = 9.61$, $p = .005$. Neither the Luminance × Blur interaction, $F(2.67, 24.00) = 1.44$, $p = .256$, nor the main effect for luminance, $F(1.62, 14.54) = 2.94$, $p = .093$, was significant. Follow-up tests investigating the main effect of blur when averaged across the three luminance conditions found slower speeds for the 5-diopter condition (M = 37.71 mph) than for the 2-diopter condition (M = 42.81 mph) and the 0-diopter condition (M = 42.62 mph). No significant difference in speed was identified between the 0-diopter condition (M = 42.62 mph) and the 2-diopter condition (M = 42.81 mph).

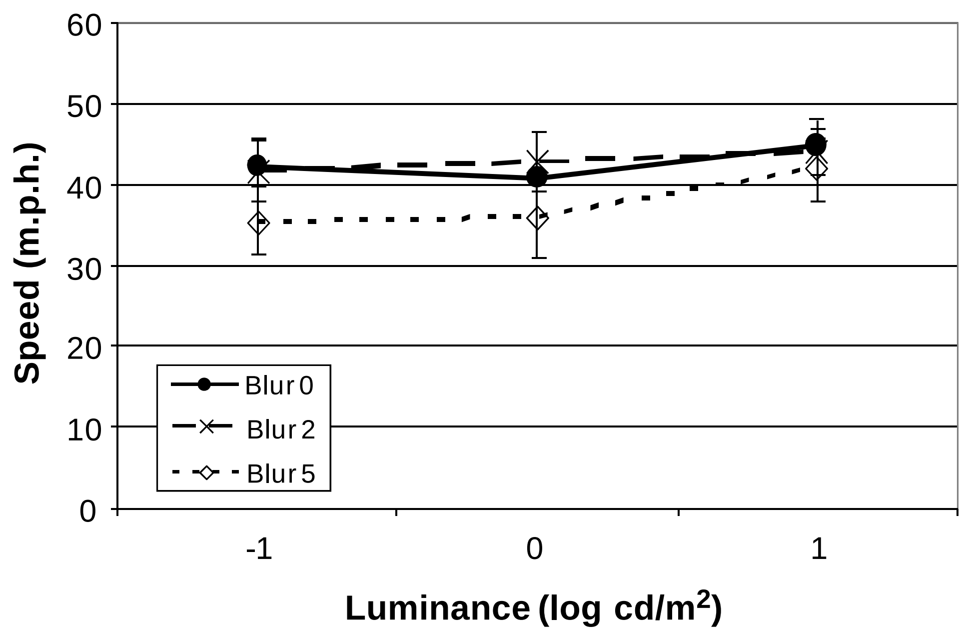


Figure 3. Overall speed as a function of luminance and blur.

Since a significant difference was expected, further analyses examining only the optimal viewing conditions (maximum luminance, no blur) were conducted. An ANOVA compared (1) speeds from the trials at the beginning of the study (training-check and baseline) to those at the end of the study (training-control and control), as well as the (2) trials with instructions to drive the speed limit using the speedometer (training-check and training-control) to the trials with instructions to drive a comfortable speed without using the speedometer (baseline and control; see Table 2). The mean speed as a function of the different instructions and speedometer availability groups as well as the sequence in which they occurred during the study is presented in Figure 4. No significant interaction was found between these groups, $F(1,9)=3.22$, $p=.106$ and there was no main effect of time between the pre and post conditions, $F(1,9)=4.89$, $p=.093$. However, a main effect of instructions and speedometer was observed, $F(1,9)=19.05$, $p=.002$. The conditions with the instructions to drive the speed limit using the speedometer had speeds on average of 53.2 mph compared to speeds of 47.3 mph in the conditions with the instructions to drive a comfortable speed without using the speedometer. In addition to overall speed the standard deviation of the mean speed was also investigated.

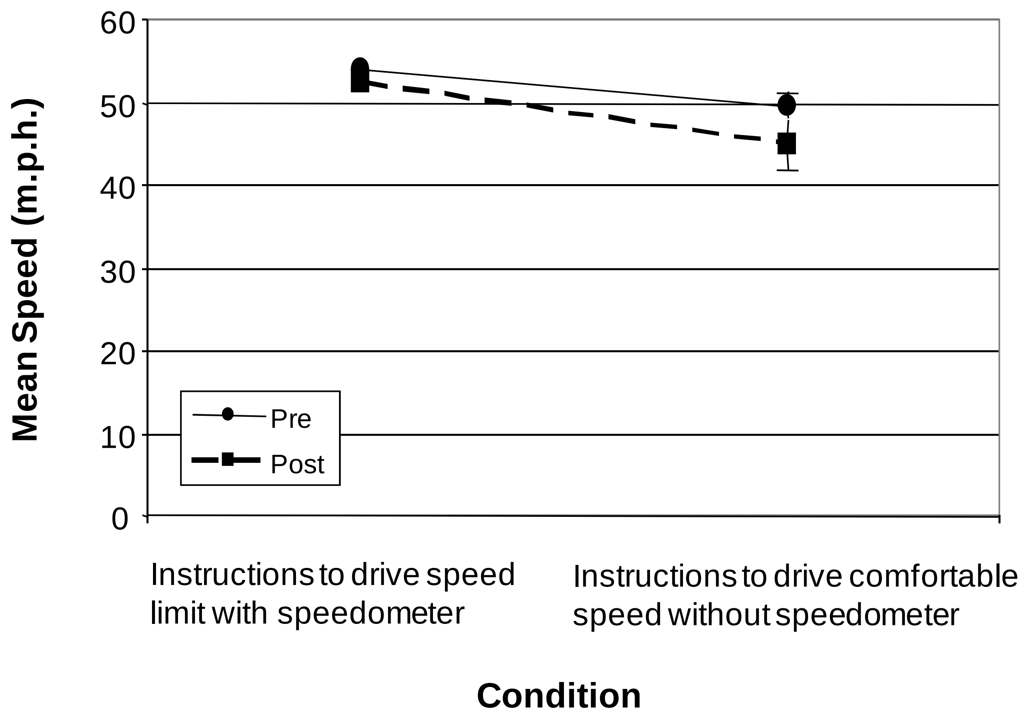


Figure 4. Overall speed as a function of pre and post tests as well as instructions and speedometer availability.

Standard deviation of mean speed (mph)

To further examine driver speed, the standard deviation of mean speed was calculated. The first comparison between the training check and the training control failed to reveal a difference in the standard deviation for speeds of 3.11 mph, $t(9) = 1.18$, $p = .267$. The second comparison, between the baseline and the control, also failed to reveal a difference where participants' standard deviation in speed was 3.67 mph, $t(9) = .08$, $p = .937$. Thus, there was no evidence of practice or fatigue effects.

The standard deviation of speed as a function of luminance and blur can be seen in Figure 5. An ANOVA did not reveal a significant Luminance × Blur interaction,

$F(3.36, 30.21) = .04$, $p = .994$; a significant main effect of luminance, $F(1.76, 15.82) = 1.87$, $p = .188$; or a significant main effect of blur, $F(1.44, 12.91) = 2.19$, $p = .159$. Averaged across all conditions, the participants' standard deviation in speed was 4.07 mph.

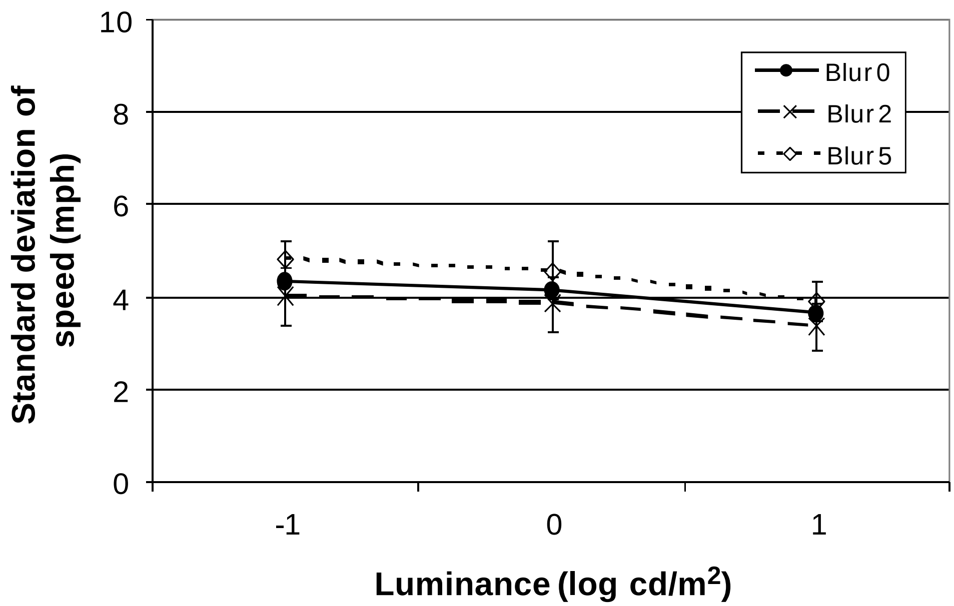


Figure 5. Standard deviation in speed as a function of luminance and blur.

Additional simulator variables such as center position, standard deviation of center position, and lateral speed are reported in Appendix A.

High contrast visual acuity (logMAR)

High contrast visual acuity was measured using Bailey-Lovie high contrast far visual acuity charts and quantified using the logarithm of the minimum angle of resolution, logMAR. The first comparison between the training check and the training control failed to reveal a difference for the average high contrast visual acuity of .229 logMAR (Snellen 20/34), $t(9) = .48$, $p = .643$. The second comparison, between the baseline and the control, also failed to reveal a difference where participants'average high contrast visual acuity was .181 logMAR (Snellen 20/30), $t(9) = 1.59$, $p = .147$. Thus, there was no evidence of practice or fatigue effects.

The participants' high contrast visual acuity as a function of luminance and blur is presented in Figure 6. As expected, an ANOVA did not reveal a significant Luminance × Blur interaction, $F(2.82,20.54) = 2.43$, $p = .107$. However, consistent with the previous literature, when averaging across blur conditions an ANOVA did reveal a main effect of luminance, $F(1.59,14.33) = 53.46$, $p = .001$ and when averaging across luminance conditions, an ANOVA revealed a significant main effect for blur, $F(1.82,16.40) = 94.69$, $p = .001$.

Follow-up tests revealed differences between all three luminance levels. The 1 log cd/m^2 condition of logMAR .634 (Snellen 20/86) was different from both the 0 log cd/m^2 condition of logMAR .759 (Snellen 20/115) and the -1 log cd/m^2 luminance condition of logMAR .986 (Snellen 20/194). The 0 log cd/m^2 luminance condition of logMAR .759 (Snellen 20/115) was also different from the -1 log cd/m^2 luminance condition of logMAR .986 (Snellen 20/194).

Follow-up tests revealed differences between all three blur levels. The 0-diopter condition of logMAR .412 (Snellen 20/52) was different from both the 2-diopter condition of logMAR .741 (Snellen 20/110) and the 5-diopter condition of logMAR

1.225 (Snellen 20/336). The 2-diopter condition of logMAR .741 (Snellen 20/110) was also different from the 5-diopter condition of logMAR 1.225 (Snellen 20/336).

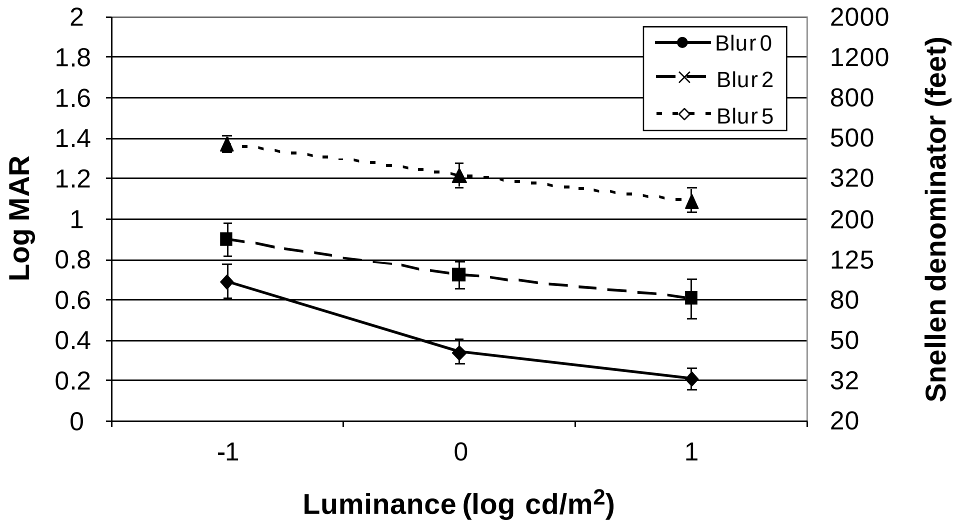


Figure 6. High contrast visual acuity as a function of luminance and blur.

Additional data for low contrast visual acuity and contrast sensitivity were collected. Results and figures are presented in Appendix B.

Subjective Workload

Although no hypotheses were developed subjective workload was collected and reported. Calculations are the mean responses to the RSME. The first comparison between the training check and the training control failed to reveal a difference in the average subjective workload reports of 47.2 on the scale of mental effort, $t(9) = .48$, $p = .643$. The second comparison, between the baseline and the control, also failed to reveal a difference where participants' average workload report was 37.4 on the scale of mental effort, $t(9) = .71$, $p = .493$. Thus, there was no evidence of practice or fatigue effects.

Participant's subjective workload as a function of luminance and blur is presented in Figure 7. An ANOVA did not reveal a significant Luminance × Blur interaction, $F(2.32,20.85) = .43$, $p = .684$. However, when averaging across blur conditions the ANOVA revealed a main effect of luminance, $F(1.20,10.83) = 6.51$, $p = .023$, and when averaging across luminance conditions, the ANOVA revealed a significant main effect for blur, $F(1.06, 9.81) = 7.66$, $p = .019$.

Follow-up tests revealed differences for luminance between the 1 log cd/m^2 condition (49.8 mental effort) and the -1 log cd/m^2 condition (64.3 mental effort). And follow-up tests for blur revealed differences for blur between the 0-diopter condition (49.4 mental effort) and both the 2-diopter condition (57.1 mental effort) and the 5-diopter condition (72.8 mental effort).

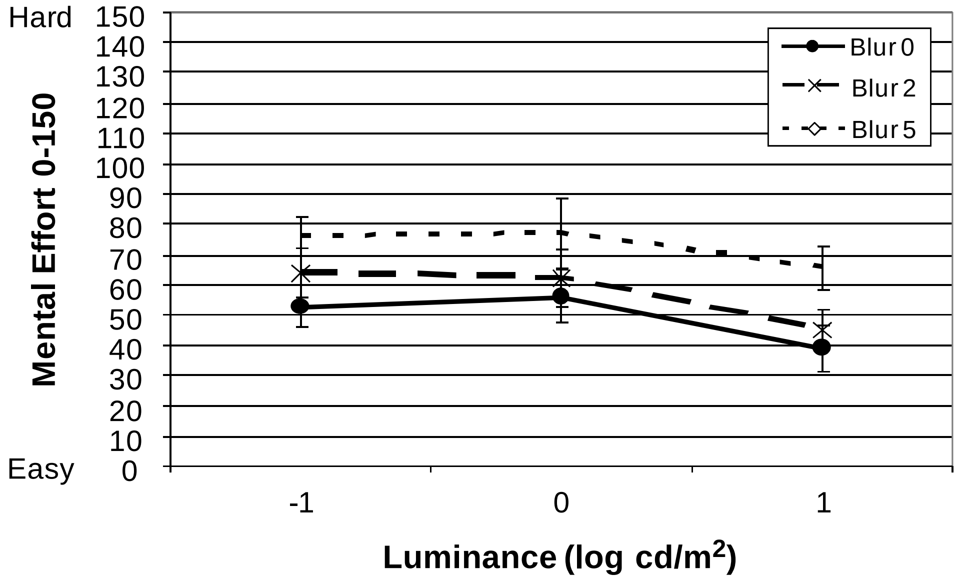


Figure 7. Workload as a function of luminance and blur where 0 is minimum the least amount of effort and 150 is the maximum amount of effort.

Since an effect was found between the speeds from the trials with instructions to drive the speed limit using the speedometer to the trials with instructions to drive a comfortable speed without using the speedometer, an additional ANOVA was conducted to see if these same conditions would exist for driver workload. No significant interaction was found between these groups, $F(1,9)=.01$, $p=.972$ and there was no main effect of time between the pre and post conditions, $F(1,9)=.56$, $p=.473$. However, a main effect of instructions and speedometer was observed, $F(1,9)=10.62$, $p=.010$. The conditions with the instructions to drive the speed limit using the speedometer had subjective workload reports of 47.2 on average compared to reports of 37.4 in the conditions with the instructions to drive a comfortable speed without using the speedometer.

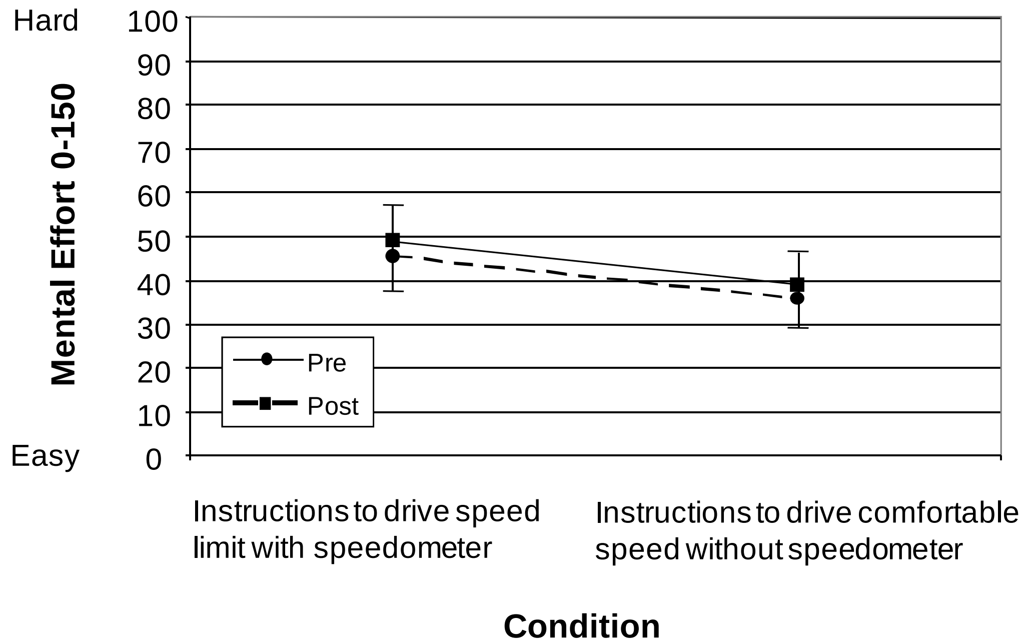


Figure 8. Workload as a function of pre and post tests as well as instructions and speedometer availability where 0 is the minimum amount of effort and 150 is the maximum amount of effort.

DISCUSSION

Previous research has shown that drivers are capable of navigating effectively at lowered luminance and increased blur levels even though their ability to recognize objects or see detail is impaired (Owens, Wood, & Owens, 2007; Brooks, 2005; Brooks et al., 2005; Owens, 2003; Owens & Tyrrell, 1999). However, several of these studies revealed that advancing age decreases performance on both acuity and driving tasks (Owens, Wood, & Owens, 2007; Brooks, 2005; Owens, 2003; Owens & Tyrrell, 1999). These studies addressed blur and luminance separately, attempting to hold speed constant to measure the effects of challenging visual conditions on steering performance. Despite the advantage of measuring this capability directly, these scenarios where the driver has little or no control over vehicle speed are not typically encountered outside the laboratory. Instead of drivers steering at set speeds, it may be more practical to allow them to choose their own. In this study participants drove in a simulator and then read vision charts while wearing various combinations of neutral density filters to reduce luminance and positive diopter lenses to induce blur. These luminance values were selected because they represent the range of luminance levels encountered during civil twilight (Olson & Farber, 1996), and the range of blur selected includes common refractive errors that typically go unnoticed or untreated in the general population in addition to an extreme case (+5D; e.g. S.J. Grygier, personal communication, August 10, 2006). To measure driver speed preference, participants drove curvy two-lane rural roads with a 55 mph speed limit, intended to be challenging even under optimal viewing conditions.

The drivers' high contrast visual acuity was measured at the end of each trial. While the manipulations were selected to represent naturally occurring luminance (-1 log cd/m^2 to 1 log cd/m^2) and blur levels, they were powerful enough to cause a significant reduction with each luminance decrease or blur increase. Under the optimal conditions the drivers' acuity was approximately 20/30, decreasing to almost 20/200 averaged across all blur conditions under minimum luminance. When averaging across all luminance levels, the moderate blur condition (+2D) averaged 20/110 and the more extreme condition (+5D) was approximately 20/340. The challenging visual conditions affected visual acuity as expected and as seen in other studies (Brooks, 2005; Brooks et al., 2005; Johnson & Casson, 1995; Johnson, Casson, & Zadnick, 1992; Owens & Tyrrell, 1999). This same pattern was found for low contrast acuity as well as contrast sensitivity. While naturally occurring manipulations were purposefully selected, these findings confirm that the visual manipulations selected for the study were powerful, systematically degrading participant focal vision.

While the manipulations degraded visual acuity, the drivers had no difficulty with their steering performance. Across all experimental conditions, drivers remained within the lane on average 93% of the trials. To further examine steering performance, additional variables were investigated, including center position and lateral speed. The decrease in luminance and increase in blur did not lead to changes in any of these steering-related variables. The only steering variable sensitive to any of the manipulations was the standard deviation of center position, where performance under the condition of most extreme blur differed from the no blur condition. These results are consistent with previous research, showing steering performance is robust (Owens, Wood, & Owens, 2007; Brooks, 2005; Brooks et al., 2005; Klein & Brooks, 2006; Owens, 2003; Owens & Tyrrell, 1999).

While previous studies held driver speed constant, the primary focus of this investigation was to determine if aging drivers naturally slow down under reduced luminance or increased blur. To determine driver preferred speed, the vehicle speedometer was turned off after the training sessions. Overall, drivers did not slow down during the experimental conditions as predicted (M = 41 mph), the only exception being the 5-diopter condition, which was specifically selected as an extreme case (M = 38 mph). Neither the decreases in luminance nor the moderate increases in blur caused drivers to slow down. This pattern is consistent with previous literature, which found that drivers are able to steer while driving at a constant speed under similar conditions (Owens, Wood, & Owens, 2007; Brooks, 2005; Brooks et al., 2005; Owens, 2003; Owens & Tyrrell, 1999).

Prior to driving the experimental trials, all drivers passed a training check in which they were required to stay in the lane a minimum of 85% of the trial at a minimum average speed of 50 mph. Immediately following this check, the participants drove a baseline condition. There were two important differences between these two driving trials: 1) the availability of the speedometer and 2) the instructions. For the training check the speedometer was available, and the participants were instructed to drive the speed limit of 55 mph. For the baseline condition, the speedometer was not available, and participants were reminded that the speed limit was 55 mph and that they were to drive the speed at which they could comfortably stay in the lane. At the conclusion of the experimental sessions, the participants completed two parallel conditions. Parallel to the baseline, the final maximum luminance, no blur trial (or control) was identical to the baseline condition. The final session of the experiment, the training control was parallel to the training check.

Comparisons between the training check and training control provided no evidence of learning or fatigue effects. None of the simulator variables (percentage of the trial spent within the lane, speed, standard deviation of mean speed, center position, standard deviation of center position, and lateral speed) differed between the training check and the training control. Similarly, comparisons between the baseline and the maximum luminance, no blur (or control) trial provided no evidence of learning or fatigue effects.

One unexpected finding was a reduction in speed between the training check and training control (M = 53 mph) and the baseline and control (M = 47 mph). Even under optimal viewing conditions, the drivers chose to decrease their speeds by 8 mph when they were given the opportunity. While the drivers were expected to slow down with decreased luminance and increased blur, it was unexpected to find that drivers reduced their speed under these optimal viewing conditions, providing evidence that older adults choose a speed below their capabilities. This finding may require a distinction between capability and preferred driving speeds when discussing older drivers.

A similar distinction was made by Sackett, Fogli, and Zedeck (1988; Sackett 2007) when they examined the performance of supermarket cashiers in an effort to assess the best employees and to establish a test battery for the position. Using cashiers from a national sample of supermarkets consisting of both traditional type input cash registers and modern barcode scanners capable of monitoring performance, Sackett et al. (1988) began collecting speed and accuracy data. For the manual input registers, a work sample approach was used since there was no way to gather data automatically over a long period of time as was possible with the scanners. This approach entailed having cashiers ring up a cart containing a controlled number of items while a supervisor timed and scored their performance. Since the measures obtained from the electronic scanners might not be comparable to those of the manually entered prices, the researchers administered the work sample to all the employees, resulting in two measures of performance where the long-term computerized performance measures were available. Only a modest correlation between these two highly reliable measures was found, meaning that no comparable information about the relative performance of the cashiers was produced. These measures, termed typical (long term) and maximum (short-term work samples) have since initiated a new line of research (Sackett, 2007). A maximum performance situation can be characterized as one that is relatively short in duration and one in which performers know they are being evaluated and accept some explicit or implicit instruction to maximize their efforts (Klehe, Anderson, & Viswesvaran, 2007).

According to Klehe et al. (2007) in their introduction to a special issue on typical and maximum performance, very few empirical papers were published following the Sackett et al. (1988) publication. This led to a call for papers on this topic, for which a number of studies adopting different perspectives and research paradigms were published. One such study used a sample of basketball players from the NBA to investigate how maximal and typical performance influences the value organizations place on their employees (Barnes & Morgeson, 2007).

Barnes and Morgeson (2007) used the NBA players' average points for the season as a measure of typical performance and their game high as the maximum performance, both of which were then correlated with the players' contracts, i.e. the compensation. The results showed that compensation predicts only typical performance, not maximum performance. One problem with this study is that the researchers used the players' game high as the maximum performance measure, when Sackett et al. (1988) specifically distinguish between high and maximum performances. A more valid measure would be scores during the playoffs as these conditions would demand maximum performance. For driving, one form of compensation seems to be safety, which may influence maximum performance; however, in the research setting drivers are compensated with money. Since the compensation was the same rate for all the drivers in the current study, it is unlikely that it influenced individuals unless they have different perceptions of the pay rate; however, it is unknown how different amounts of pay might influence typical performance.

A study by ForsterLee (2007) found that context influenced motivational determinants of maximum and typical performance on a verbal knowledge task. In the driving simulator the context remained constant across scenarios and participants. Even though manipulations were made to the visual scene, the scenery and road curvature were uniform. However, when driving outside of the simulator, the road context is constantly changing, a situation which, applying the findings of ForsterLee (2007), might cause increases and decreases in performance ranging from typical to maximum.

The length of time that maximum performance can be sustained (Sackett et al., 1988; Sackett, 2007) was not investigated until Mangos, Steele-Johnson, LaHuis, and White (2007) developed and tested a multiple task measurement framework for assessing maximum and typical performance over time. This framework addressed the questions of how long maximum performance can be sustained over time under appropriate conditions and how close people will perform to their maximum without the appropriate conditions. The results of this test found that the framework was successful at addressing the sustainability of maximum performance over time and the tendency to perform near one's maximum. In addition, they determined that maximum performance assessment requires typical performance as a reference and that their difference emerges as a new meaningful performance dimension reflecting the degree to which one is performing (or tends to perform) close to his or her potential over time. An application of this framework to the task of driving may reveal similar insights into driver performance and potential over time.

Mesemer-Magnus and Viswesvaran (2007) investigated if pre-training goals induce trainees to maximize their learning efforts in training. They found that pre-training goals focused on maximizing learning efforts yielded higher performance on post-training cognitive skill and affective learning assessment. In the study reported here, participants were trained to drive the speed limit, i.e. the maximum goal. According to Mesemer-Magnus and Viswesvaran (2007), this training performance may have influenced the drivers to tend toward their maximum when they could choose their own speeds, i.e. the typical condition. If the drivers had trained under the latter, they may have chosen even slower speeds under that condition as they would not have been influenced by the maximum training.

Despite the research into this theory, this study represents the first application of typical and maximum performance measures to driving. Driving safely can be considered a job requiring a certain level of competency, which is determined by state licensing. Since it is a public activity, drivers are under evaluation by passengers, other drivers, law enforcement officers, and traffic cameras. Performance may vary between typical and maximum levels based on this evaluation. For example, when driving at the Department of Motor Vehicles during an examination, performance is probably closer to one’s maximum than typical level of driving. Drivers may also increase or decrease their performance between these two levels as task demands vary. Conditions such as low light levels and increased blur may require maximum performance to maintain safe homeostasis when driving, a condition only observable via measures of driver workload since no change in performance can be observed.

The distinction between typical and maximum performance is relevant to the current study because drivers were given two types of instructions during the protocol, leading to different performance outcomes. The instructions to drive at the speed limit were essentially a maximum performance condition, while the instructions to drive a comfortable speed represented a typical performance condition. This study supports this line of research, which has established that even though humans may be capable of performing at a maximum level, they do not necessarily do so. Moreover, they tend to perform at a typical level over the long term, reserving the potential to increase their performance when needed (Sackett et al., 1988; Sackett, 2007).

When drivers adopted their typical performance level before the visual manipulations, they held in reserve potential resources to exploit as the driving task became more challenging. By moving from their typical performance level towards their maximum one, they were then able to maintain their original speed choice, avoiding the need to slow down further.

This situation does not contradict the subjective workload reports obtained during the experimental trials when drivers observed increases in their workload as visual conditions became more challenging. While there were no changes in driver speed as a result of the experimental manipulations, driver subjective workload increased with reduced luminance and increased blur. As luminance decreased, driver workload increased from a score of 50 on the mental effort scale under the maximum luminance condition to a score of 64 under the dimmest condition. Workload increased as blur increased as well. Under the clear condition, workload was reported as a 49 on the mental effort scale, increasing to a 57 under the 2-diopter condition and then to a 73 under the 5-diopter condition. These increases in subjective workload are evidence that drivers in this study were sensitive to the challenging visual conditions.

Consistent with the reduction in speed between the training check and training control to the baseline and control, a reduction in workload was also observed. Workload reports decreased from 47 under the conditions where the participants were instructed to drive the speed limit, similar to maximum performance, to 37 under the conditions where drivers were allowed to choose their speed, similar to typical performance. Maintaining the higher speed requiring maximum performance resulted in higher workload reports. This pattern is similar to the actual speeds observed between these two conditions, where drivers drove faster under the conditions associated with higher workload scores. Driving at a comfortable speed required less effort than driving at the target speed of 55 mph.

This distinction between typical and maximum performance relates the results of this study to predictions of the selective degradation hypothesis. Research investigating this hypothesis found that driver steering capabilities remained robust under low luminance, while their visual acuity was severely degraded (Owens & Tyrrell, 1998). If this theory was applied to the hypotheses of the current study, drivers would be expected to stay in their lane and maintain high speeds under the challenging visual conditions. This prediction assumes drivers are performing at their maximum capabilities. However, the current study found that drivers slow down when given the choice, behavior serving as an example of typical performance. Even though drivers are capable of performing at a maximum level does not mean they are comfortable doing so. This typical performance measure may be an accurate assessment of driver performance.

Klein et al. (2006) found that older drivers tend to drive slower relative to their younger counterparts when afforded the opportunity to choose their own speed. Additionally, they continued to slow down as luminance levels decreased. This slower speed choice may be a result of older drivers choosing a speed closer to their typical performance level while the younger drivers chose to drive near their maximum. It is unknown, however, why the older drivers in the current study opted for a blanket reduction in speed whereas Klein et al. (2006) observed an incremental reduction. Due to both differences in instructions and the presence or absence of the speedometer, it is unknown if drivers would have slowed down as the visual conditions became more challenging if there were not a reduction in speed under the optimal viewing conditions (e.g. the baseline and control conditions).

Since older drivers do not reveal their sensitivity to decreased luminance and increased blur in their speed choice but only in their subjective workload reports, their typical speed choice seems to be low enough overall to handle the challenges. If this speed choice is slower than that of the rest of the population, then the seniors may be increasing the risk on roadways by increasing the variability in the traffic stream, known as speed dispersion (Solomon, 1964; Bohlin, 1967; Munden, 1967; Nilsson, 1981). Since other age groups were not tested, it is unknown how the older adults speed choice relates to that of the rest of the driving population.

One limitation of this study is that no comparison group was tested, preventing relative performance measures. By including younger drivers, the effect of age could be reported between the two groups. It would be beneficial to know how the older drivers compared with the younger drivers with their speed choices and their subjective workload reports. This information would also help determine if speed dispersion is occurring.

Another limitation lies within the experimental design as there was no way to tease out the effects of the instructions from the effects of the speedometer availability since they were both varied in the four maximum luminance conditions. Since the exact cause of why drivers slowed down from the training check and training control to the baseline and control conditions cannot be determined as these conditions are confounded, additional conditions that hold the instructions constant, varying the speedometer availability and vice versa might determine the cause for the different speeds and workload reports observed in these conditions.

Exploring other factors that influence driver speed would be the next step in this line of research in the future. This study employed scenarios without other vehicles or roadside scenery and used only older drivers. Enriching the scenarios to see if drivers adjust their speeds would give insight into the driver's capabilities. Interacting with traffic and roadside distractions may influence the speed choices of drivers, which also may vary with age. Drivers may not slow down if someone is tailgating them or they are in a faster stream of traffic.

This investigation into driver speed choice needs to be conducted outside of the simulator as well using instrumented vehicles. If driver activity is being monitored and cameras are employed to document traffic conditions a more ecologically valid measure of driver speed choice could be established. By monitoring over the long term, a measure of driver typical and maximum speeds can be established. This information would be useful for licensing requirements and driver training.

APPENDICES

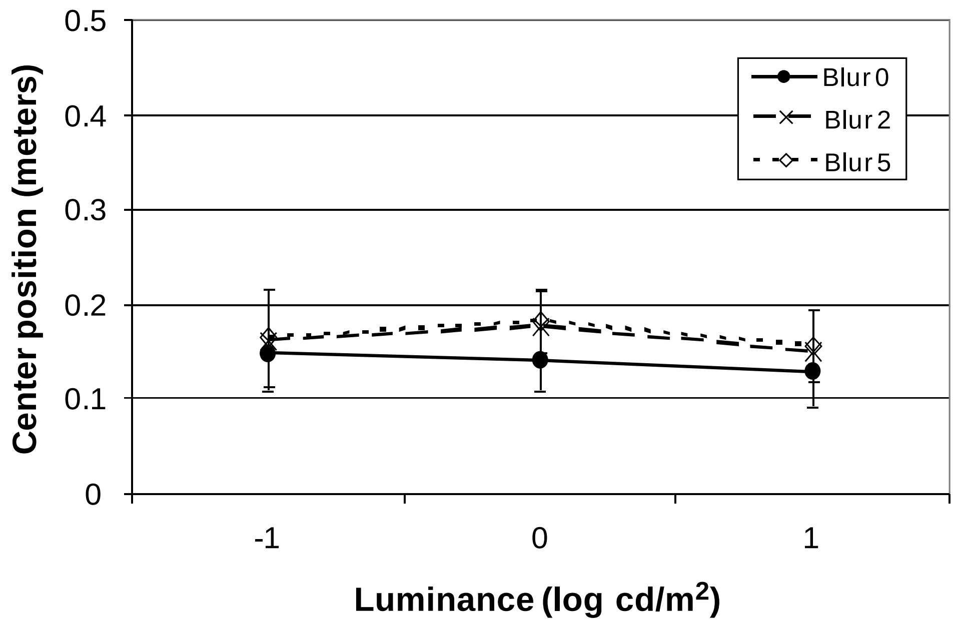
Appendix A

Analyses examining additional simulator variables including center position, standard deviation of center position, and lateral position.

Center position (meters)

Center position is calculated as the average distance from the center of the lane. The first comparison between the training check and the training control failed to reveal a difference in the center position of 0.05 meters to the right of the center of the lane, $t(9)=.83$, $p=.430$. The second comparison, between the baseline and the control, also failed to reveal a difference where participants' center position of 0.13 meters, $t(9)=.19$, $p=.851$. Thus, there was no evidence of practice or fatigue effects.

An ANOVA did not reveal a significant Luminance × Blur interaction, $F(2.08,18.69)=.11$, $p=.901$, a main effect of luminance, $F(1.43,12.9)=.57$, $p=.524$, or a main effect for blur, $F(1.41, 12.66)=1.73$, $p=.217$. When averaged across all luminance and blur conditions, the position of the drivers relative to the center of their lane was .16 meters to the right.

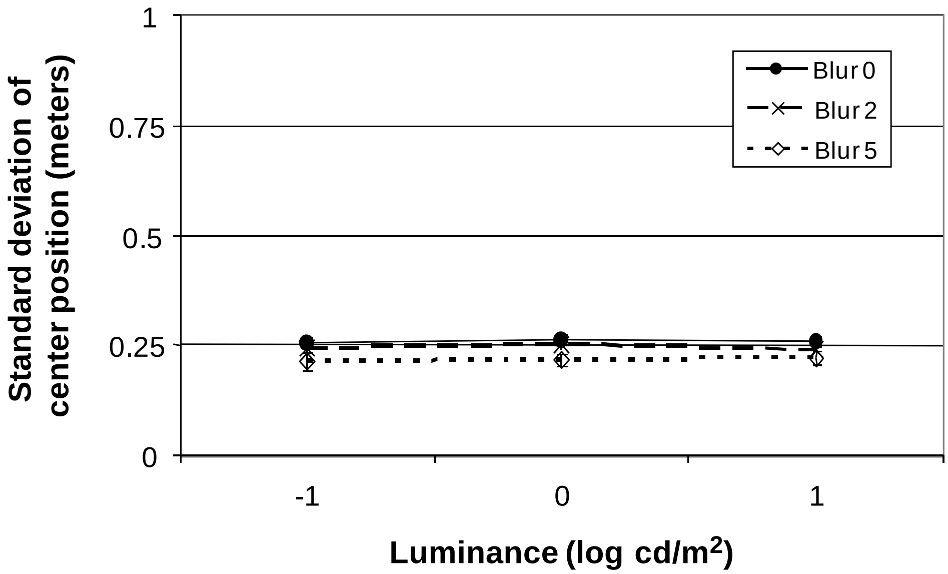


Center position as a function of luminance and blur.

Standard deviation of center position (meters)

Standard deviation of center position is the average deviation from the center of the lane. The first comparison between the training check and the training control failed to reveal a difference in the standard deviation of center position of 0.29 meters, $t(9)=.47$, $p=.652$. The second comparison, between the baseline and the control, also failed to reveal a difference in the standard deviation of center position of 0.25meters, $t(9)=.57$, $p=.585$. Thus, there was no evidence of practice or fatigue effects.

An ANOVA failed to reveal a significant Luminance × Blur interaction, $F(1.72,15.5)=.17$, $p=.815$, or a main effect of luminance, $F(1.73,15.58)=.24$, $p=.759$. However, when averaging across luminance conditions, an ANOVA revealed a significant main effect for blur, $F(1.54, 13.89)=7.46$, $p=.009$. Follow-up tests revealed differences between only the 0- diopter condition (.258 m) and the 5-diopter condition (.216 m).

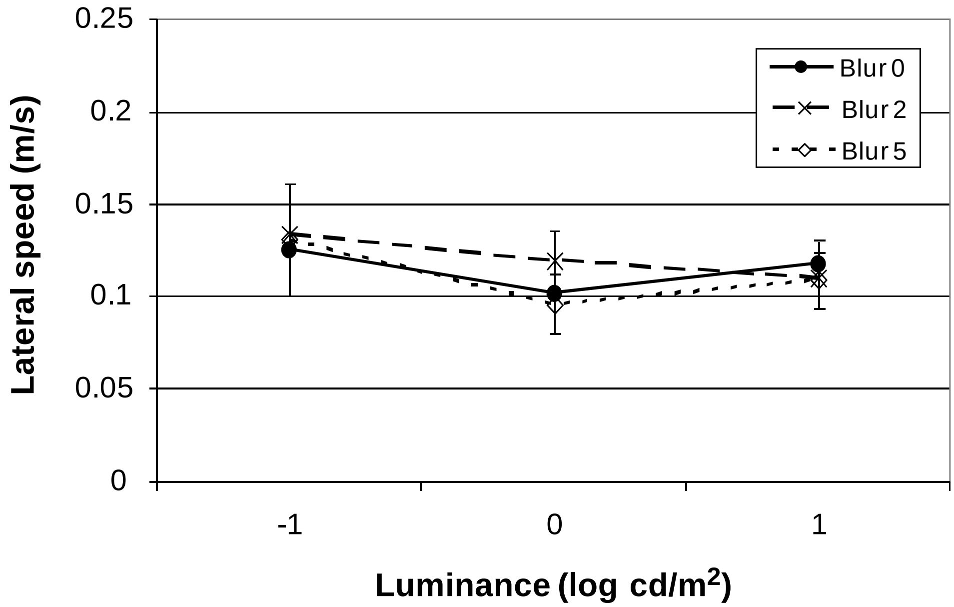


Standard deviation of center position as a function of luminance and blur.

Lateral speed (meters/second)

Lateral speed is measured as the average velocity the vehicle travels laterally within the lane. The first comparison between the training check and the training control failed to reveal a difference in the lateral speed of 0.167 meters per second, $t(9)=.03$, $p=.978$. The second comparison, between the baseline and the control, also failed to reveal a difference in the lateral speed of 0.123 meters per second, $t(9)=.99$, $p=.35$. Thus, there was no evidence of practice or fatigue effects.

An ANOVA did not reveal a significant Luminance × Blur interaction, $F(2.15,19.31)=1.18$, $p=.332$, a main effect of luminance, $F(1.22,10.96)=2.50$, $p=.140$, or a main effect for blur, $F(1.34, 12.06)=.45$, $p=.573$. When averaged across all luminance and blur conditions, the lateral speed was .116 meters/second.



Lateral speed as a function of luminance and blur.

Appendix B

Analyses examining additional visual assessment measures including low contrast visual acuity and contrast sensitivity.

Low contrast visual acuity (logMAR)

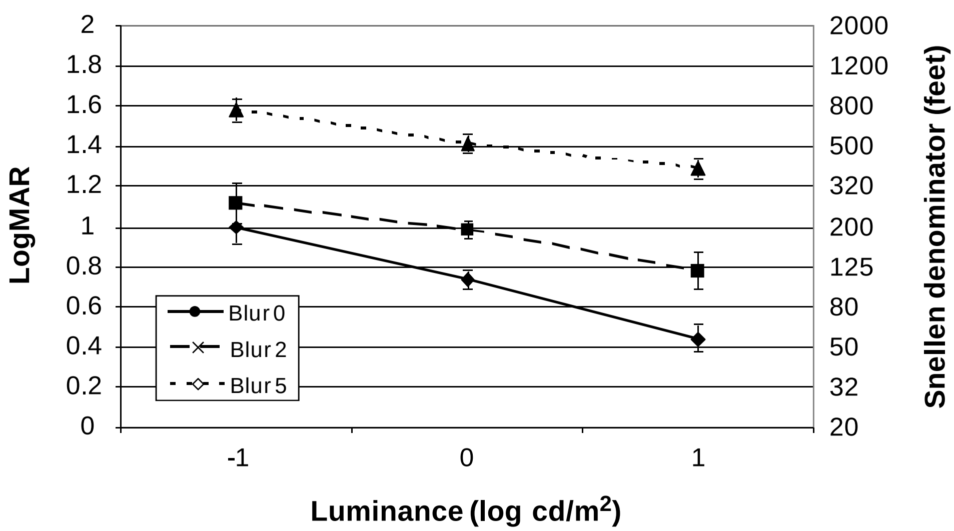
Low contrast visual acuity was measured using Bailey-Lovie low contrast far visual acuity charts and quantified using the logarithm of the minimum angle of resolution, logMAR. The first comparison between the training check and the training control failed to reveal a difference in the low contrast visual acuity of .446 logMAR (Snellen 20/56), $t(9) = .92$, $p = .087$. The second comparison, between the baseline and the control, also failed to reveal a difference where participants' low contrast visual acuity was .445 logMAR (Snellen 20/56, $t(9) = .13$, $p = .903$. Thus, there was no evidence of practice or fatigue effects.

An ANOVA did not reveal a significant Luminance × Blur interaction, $F(1.46,13.15) = 1.41$, $p = .271$. However, when averaging across blur conditions an ANOVA did reveal a main effect of luminance, $F(1.74,15.69) = 38.19$, $p = .001$ and when averaging across luminance conditions, an ANOVA revealed a significant main effect for blur, $F(1.44,12.94) = 90.67$, $p = .001$.

Follow-up tests revealed differences between all three luminance levels. The 1 log cd/m^2 condition of logMAR .836 (Snellen 20/137) is different from the 0 log cd/m^2 condition of logMAR 1.045 (Snellen 20/222). The 1 log cd/m^2 condition of logMAR.836 (Snellen 20/137) is different from the -1 log cd/m^2 luminance condition of logMAR 1.232

(Snellen 20/341). And the 0 log cd/m^2 luminance condition of logMAR 1.405 (Snellen 20/508) is different from the -1 log cd/m^2 luminance condition of logMAR 1.232 (Snellen 20/341).

Follow-up tests revealed differences between all three blur levels. The 0-diopter condition of logMAR .724 (Snellen 20/106) is different from the 2-diopter condition of logMAR .960 (Snellen 20/182). The 0-diopter condition of logMAR .724 (Snellen 20/106) is different from the 5-diopter condition of logMAR 1.429 (Snellen 20/537). And the 2-diopter condition of logMAR .960 (Snellen 20/182) is different from the 5-diopter condition of logMAR 1.429 (Snellen 20/537).



Low contrast visual acuity as a function of luminance and blur.

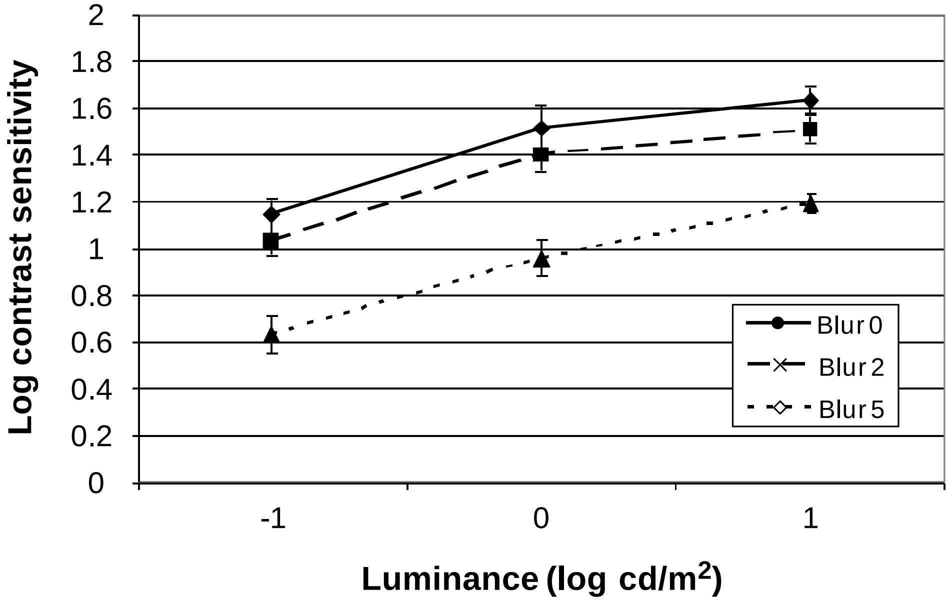
Contrast sensitivity

Contrast sensitivity was measured using a Pelli Robson Contrast Sensitivity chart. The first comparison between the training check and the training control failed to reveal a difference in the log contrast sensitivity of 1.63, due to zero variance between conditions. The second comparison, between the baseline and the control, also failed to reveal a difference where participants' log contrast sensitivity was 1.64, again a result of zero variance between conditions. Thus, there was no evidence of practice or fatigue effects.

An ANOVA did not reveal a significant Luminance × Blur interaction, $F(1.75,15.71) = .96$, $p = .394$. However, when averaging across blur conditions an ANOVA did reveal a main effect of luminance, $F(1.40,12.60) = 118.96$, $p = .001$ and when averaging across luminance conditions, an ANOVA revealed a significant main effect for blur, $F(1.16,10.48) = 31.9$, $p = .001$.

Follow-up tests revealed differences between all three luminance levels. The 1 log cd/m^2 condition (1.447 log contrast sensitivity) is different from the 0 log cd/m^2 condition (1.292 log contrast sensitivity). The 1 log cd/m^2 condition (1.447 log contrast sensitivity) is different from the -1 log cd/m^2 luminance condition (.940 log contrast sensitivity). And the 0 log cd/m^2 luminance condition (1.292 log contrast sensitivity) is different from the -1 log cd/m^2 luminance condition (.940 log contrast sensitivity).

Follow-up tests revealed differences between all three blur levels. The 0-diopter condition (1.433 log contrast sensitivity) is different from the 2-diopter condition (1.315 log contrast sensitivity). The 0-diopter condition (1.433 log contrast sensitivity) is different from the 5-diopter condition (.930 log contrast sensitivity). And the 2-diopter condition (1.315 log contrast sensitivity) is different from the 5-diopter condition (.930 log contrast sensitivity).



Contrast sensitivity as a function of luminance and blur.

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