

**Contrast Sensitivity for Drifting Sine Wave Gratings in
Near Visual Periphery Predicts Older Drivers' Accident Risk**

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Abstract

Drivers over the age of 70 have a significantly higher rate of intersection collisions than younger drivers. Many of their accidents involve a visual detection error, resulting in a right-of-way violation and a collision with an oncoming vehicle.

Three studies relating older drivers' peripheral motion detection to accident risk demonstrate that peripheral motion contrast threshold (PMCT) for low spatial frequency drifting sine wave gratings significantly declines with age, and that PMCT predicts about 40% of driving performance variance ($p > .001$). Approximately twenty older drivers participated in each study.

In all three studies, older drivers' PMCT was assessed using forced choice psychophysical procedures, with 0.4 cycle/degree sine wave gratings drifting at 13.75 or 27.5 degrees/second. The stimulus spanned 5 or 10 degrees of visual angle and was presented at 10–20 degrees of retinal eccentricity. Useful Field of View (UFOV®) was also assessed in the second and third studies.

The first and second studies used a bespoke driving perception questionnaire to measure accident risk, and the second study validated that questionnaire against an abridged Manchester Driver Behaviour Questionnaire. The third study's measure of accident risk was driving simulator performance (i.e., driving examiners' assessments and crash counts). PMCT and UFOV® predicted accident risk equally well.

Future work will include development of a practicable two-minute version of the PMCT for use by DMV staff and clinical practitioners.

Résumé

Les conducteurs âgés de 70 ans ou plus ont un taux de collisions aux intersections nettement plus élevé que les conducteurs plus jeunes. Plusieurs de ces accidents s'expliquent par une défaillance relative au repérage d'informations visuelles, ce qui, par conséquent, résulte en une violation du droit de passage du ou des véhicules en approche.

Trois études traitant de perception visuelle des mouvements en relation avec les risques d'accidents révèlent que le seuil de contraste dynamique en périphérie visuelle (SCDPV) pour des ondes sinusoïdales de basses fréquences spatiales augmente significativement avec l'âge. Soulignons que les résultats au SCDPV expliquent environ 40% de la variance des indices de performance au volant ($p < .001$). Approximativement vingt conducteurs âgés de 65 ans ou plus ont participé à chaque étude.

Dans chacune des trois études, le SCDPV des conducteurs plus âgés a été évalué en utilisant des procédures psychophysiques de choix forcé. Le stimulus consistait en une ondelette sinusoïdale de 0.4 cycle/degré avec un déplacement centripète de 13.75 ou 27.5 degrés/seconde. Le stimulus avait une largeur de 5 ou 10 degrés d'angle visuel et a été présenté à 10 à 20 degrés d'excentricité rétinienne. Un test évaluant l'attention et la vitesse de traitement (Useful Field of View; UFOV®) a également été administré dans la deuxième et la troisième étude.

Un questionnaire évaluant le risque d'accident à partir d'items portant sur la perception de la conduite automobile a été développé et utilisé dans la première étude, puis validé dans la seconde par l'intermédiaire du Questionnaire Manchester portant sur les comportements du conducteur (Manchester Driver Behaviour Questionnaire). La troisième étude mesure le risque d'accidents en conduite simulée (c.-à-d., évaluation des

réactions au volant par un observateur et nombre total d'accidents). Le SCDPV et le UFOV® ont un pouvoir de prédiction équivalent de la conduite en contexte de simulation.

Les travaux futurs incluront le développement d'une version écourtée du SCDPV dans le but d'en promouvoir l'usage par les professionnels et par les autorités en matière de sécurité routière.

Preface

Acknowledgements

I wish first of all to thank my wife Pam Hodges for her endless patience, love, and trust through this process, and my daughter Sarah for her love and patience as well. My supervisor, Dr. Don Donderi, has always been a very receptive audience for my ideas, a source of good ideas of his own, and an invaluable brainstorming partner who well understands how to foster and facilitate scientific creativity. Without Dr. Donderi's involvement, this thesis would not exist. Thank you, Don.

I wish also to thank my mother, Marguerite MacKay, for her strong encouragement to get an education, and my mother-in-law, Jacqueline Claire Hodges for all her support and patience through my graduate studies career.

Finally, thank God.

Contributions of Authors

I designed all three studies, and I analyzed the data and drafted the articles for all three studies. I developed a new forced choice psychophysical methodology for rigorously assessing peripheral contrast sensitivity in naive, untrained participants, and I developed a questionnaire for assessing detection failure accident risk in older drivers. I wrote the software and built the cases for the x-y display monitors (i.e., bare-bones oscilloscopes) used to present drifting sine wave gratings and measure peripheral contrast thresholds for the first study. Mr. David Kernighan built the hardware for generating the sine wave gratings, and I thoroughly enjoyed our challenging hardware/software collaboration to pull the sine wave presentation apparatus together. Thank you, Dave.

Dr. Don Donderi, my coauthor on the first study (which was conducted at McGill University), in addition to his enormous overall contribution as my supervisor and collaborator from the start of the older driver research program, helped me to work out the psychophysical methodology that enabled the accurate measurement of peripheral contrast sensitivity of untrained older participants within fewer than ten training trials. Dr. Donderi was also the first to realize, upon revisiting and reworking my analysis of study 1 data, that contrast thresholds for drifting gratings explained the variance in the driving safety measure just as well and more simply than the ratio of stationary to drifting thresholds that had informed my research rationale from the start. His realization was truly a breakthrough insight. Dr. Donderi's incisive and insightful edits and revisions to the writeup of the first study were also essential contributions to that work. I owe Dr. Donderi a debt of gratitude too large to express here for his endless patience, encouragement, and facilitation of creativity.

Two of my coauthors on the second and third studies are professors in the Department of Psychology at the University of Ottawa, and the second and third studies were carried out in their laboratory facilities. Dr. Sylvain Gagnon, whose field is cognitive psychology and older drivers, and Dr. Collin, whose field is visual perception and psychophysics, collaborated with me in designing the second and third studies. Dr. Gagnon provided the participants for the second and third studies from his pool of participants, and provided the driving simulator and scenarios for testing older drivers in the third study. Dr. Charles Collin provided the visual perception laboratory facilities to conduct visual psychophysics tests of the older drivers who participated in the second and third studies. Dr. Gagnon's graduate student Alexandre Bélanger administered my

questionnaire and the abridged Manchester Driver Behaviour Questionnaire to the participants in the second study and tabulated their responses. Ricardo Tabone, a computer programmer on staff in Dr. Collin's laboratory, programmed the forced choice procedure test equipment in collaboration with me, and conducted visual psychophysics testing of the older drivers who participated in the second and third studies. Dr. Collin also developed an important modification to the procedure for the third study which changed the forced choice from two temporal alternatives to two spatial alternatives, halving the time required for the procedure. Arne Stinchcombe, a graduate student of Dr. Gagnon, administered the driving simulator test to the older drivers participating in the third study, and organized the data generated from those trials. Mr. Stinchcombe also wrote the gist of two paragraphs of text describing the simulator methodology in the third study. Dr. Sylvain and Dr. Collin also critiqued my drafts of the second and third studies and suggested numerous modifications, greatly improving those articles.

I owe a large debt of gratitude to Dr. Sylvain and Dr. Collin for providing the resources and knowledge to enable this important program of research to be carried out, and to Ricardo Tabone, Alexandre Bélanger, and Arne Stinchcombe for all their hard work on this project. Thank you all for helping to make it a success.

I. Introduction

In 2009 in the United States, 4,401 people over the age of 65 died in traffic accidents. Many researchers believe that we may be about to enter a perfect storm of older driver accidents (see for example Hu, Jones, Reuscher, Schmoyer, & Truett, 2000). After sixty-five years of age, drivers have progressively more accidents per distance driven. Year after year an increasing proportion of older people are active drivers, and they drive more per year than earlier cohorts. In addition, the baby boomer cohort born between 1945 and 1964 are beginning to swell the ranks of older drivers enormously in a demographic “squaring of the pyramid”, which will more than double the U.S. population over 65 years of age, from 40.2 million in 2010 to 81.2 million by 2040 (U.S. Census Bureau, 2008). All of these factors drive an increasingly urgent need to determine which perceptual, cognitive and physical functions and skills are most critical for safe driving, and then to use that knowledge to develop and deploy driving fitness assessment tools capable of identifying those older drivers whose age-related functional deficits in those abilities render them substantially more likely than their age peers to have accidents. As Staplin and Dinh-Zarr (2006) stated so aptly, “Researchers have sought for decades to identify a set of core constructs representing (diminished) driver capabilities that define the best predictors of motor vehicle crash involvement or, preferably, crash *causation*” (p. 129, italics theirs).

Most of the information needed to drive safely is visual. However, despite many funding dollars and many years of research, no visual function has been found and no sensory test of vision developed that relates strongly to accident risk. The best candidate

to date is Useful Field of View (UFOV®). The UFOV® subtests are strong predictors of accident risk, and are acknowledged by the developers to tax sensory, perceptual, attentional, and cognitive processes (Ball & Owsley, 1991; Ball, Owsley, Sloane, Roenker, & Bruni, 1993; Owsley, Ball, Sloane, Roenker, & Bruni, 1991). Ball, Owsley and coworkers have presented this broad scope as an advantage of UFOV®, stating that the complexities of the driving task mean that no sensory test of vision will be capable of predicting accident risk. For example, Ball et al. (1993) stated the following:

Sensory tests, such as visual acuity and peripheral field sensitivity ... do not by themselves reflect the visual complexity of the driving task, and therefore would not be expected to reveal a strong relationship between vision and driving... For these reasons an approach limited to visual sensory factors is by itself inadequate in identifying factors that place older adults at risk for driving problems (p. 3111).

However, when UFOV® is included in a well-chosen test battery with other more specific assessment tools of higher-level visual functions, the overlap of UFOV® with those higher-level assessments may result in it being dropped from the battery (e.g., Wood, Anstey, Kerr, Lacherez, & Lord, 2008). That is, UFOV® may contribute no additional power when other vision tests are used in parallel with it.

An additional consideration regarding sensory visual factors may be that a low-level functional deficit may impede or degrade the availability of visual information to higher-level attentional and cognitive processes. A sensory test of vision may therefore be a powerful and appropriate addition to a practical assessment battery for older drivers' critical function deficits.

The program of research described here is a study in applied visual perception, and resulted in the development of just such a sensory measure of vision, which predicts a meaningful portion of older drivers' accident risk. The characteristics of older drivers' accidents were reviewed to identify the age-related functional deficit that may be the underlying cause of many of those accidents. Then, a psychophysics methodology from the domain of visual perception research was employed in a novel way within an older driver cohort to significantly associate individual differences in a particular visual function with individual differences in accident risk. In applied terms, the psychophysical vision test served to identify which older drivers had a relatively greater accident risk.

The applied research presented here makes four novel and important contributions to knowledge. First, a bespoke self-report questionnaire for detection failure accident risk was developed as a dependent measure of accident risk. Second, a novel forced choice psychophysics methodology was developed from pure vision research and used to quickly and accurately measure criterion-free visual motion contrast thresholds in the near visual periphery of naive, untrained participants. Third, a strong tendency for some people's visual motion contrast sensitivity in the near visual periphery to decline with age was identified. Fourth and most important, a strong link between peripheral motion contrast threshold (PMCT) and accident risk was found, demonstrating that PMCT is a useful predictor of older drivers' accident risk.

The research program consisted of three studies. The first study related older drivers' PMCT to their detection failure accident risk as measured by the bespoke questionnaire. The second study replicated the first, and validated the questionnaire against a well-accepted and widely used accident risk questionnaire. The third study

demonstrated that PMCT predicted driving simulator performance (assessed according to driving examiner criteria) and simulator accident risk. The overall result of the research is a sensory test of vision that substantially predicts which older drivers have a relatively higher risk of detection failure accidents.

The next logical and practical extension of this research, now in the planning stage, will be to develop a simple two-minute PMCT test (modified from the forced choice procedure used in the three studies) that will be usable in DMV settings or doctors' offices, and that hopefully will reduce older driver fatalities and serious injuries.

II. Literature Review

Older Driver Accidents

Fatality and Accident Rates

Older drivers have more accidents per mile beginning at about the age of 70, and the trend accelerates markedly by the age of 80 (Carsten, 1981; Cerrelli, 1973; Chipman, MacGregor, Smiley & Lee-Gosselin, 1993; Eberhard, 2008; Li, Braver, & Chen, 2003; NHTSA, 2001; Rallabandi, 2009). Figure 1 (Highway Loss Data Institute, 2010) shows the well-known U-shaped curve, both for fatal accidents per distance traveled and for all accidents per distance traveled.

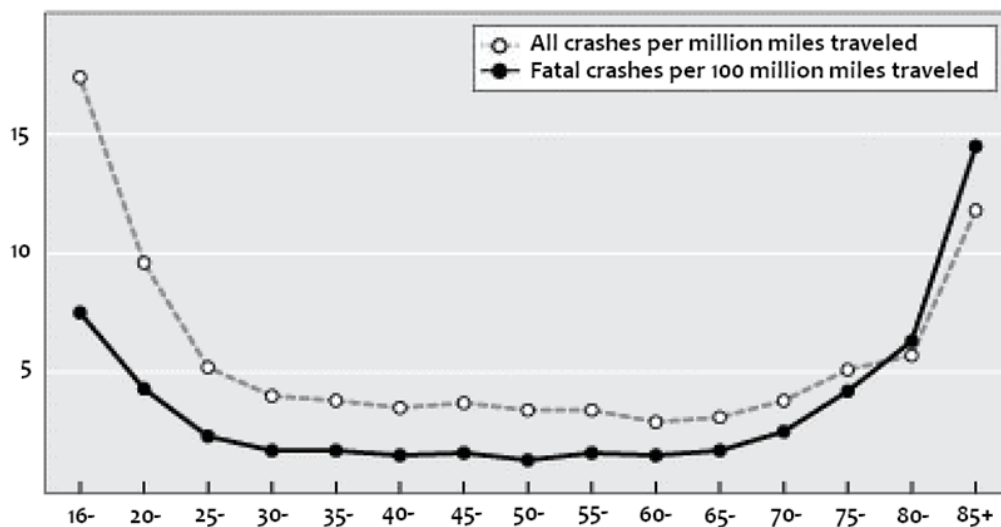


Figure 1. Fatal and insurance-only crashes per mile by age, 2001-2002 (Highway Loss Data Institute, 2010).

However, accidents per licensed driver do not increase until about the age of 85, due to the downward trend in driving miles with age (Braver & Trempel, 2004; Chipman et al, 1993). Numerous cohort effects, aging effects, technological advances and demographic trends are impacting on older drivers' safety. The older population is

increasing in absolute terms and in proportion of the population as the first members of the Baby Boom generation reach 65 years of age in 2010. The U.S. population aged 65 and older is expected to more than double in the next thirty years, from 40.2 million in 2010 to 81.2 million by 2040 (U.S. Census Bureau, 2008). The proportion of the older population who are active drivers is increasing (Cheung & McCartt, 2011), and the annual mileage of each older driver is increasing (Burkhardt, Berger, Creedon, & McGavock, 1998).

The demographic shift caused by the aging of Baby Boomers has been termed “the squaring of the pyramid” (see Figure 2). Coughlin (2009) offers an interesting review of the many impacts of Baby Boomers on personal transportation and their future expectations regarding it.

Based on those projections, some researchers have predicted enormous increases in traffic fatalities involving drivers 65 and older. Hu et al. (2000) predicted that older driver fatalities and total fatalities involving older drivers would increase by factors of 2.86 and 3.17 respectively, from 1995 to 2025. Lyman, Ferguson, Braver, and Williams (2002) predicted that fatal crash involvements of older drivers would increase from 1999 levels by a factor of 1.86 in 2020 and a factor of 2.55 in 2030. Wiggers (1999, as cited in Hu et al., 2000) predicted that older driver fatalities would double by 2020 relative to the 1993-1997 annual average, and would triple by 2030. Finally, Burkhardt et al. (1998) made the most extreme estimates, predicting that older driver fatalities would increase from 1995 levels by a factor of 4.87 in 2020 and 5.94 in 2030.

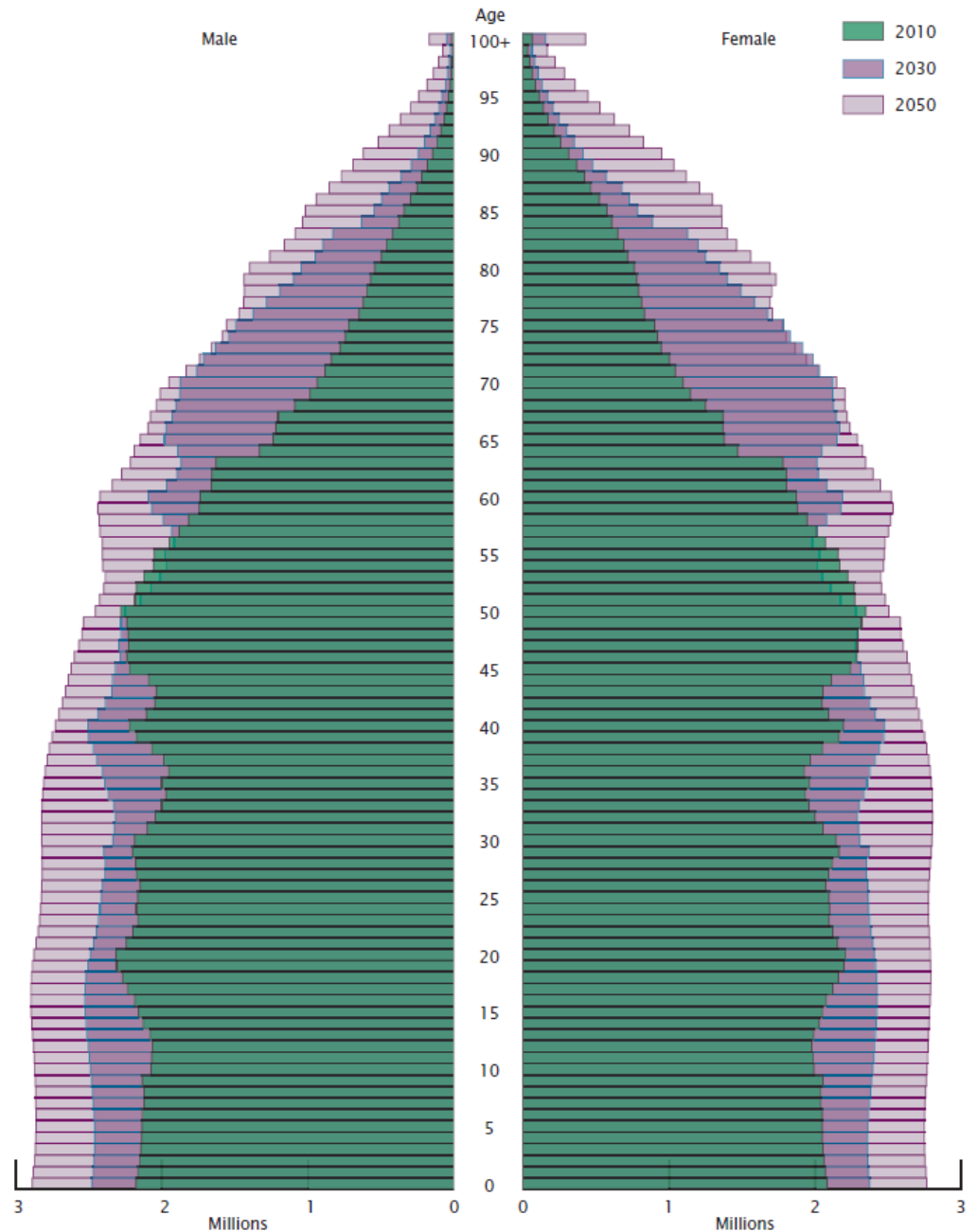


Figure 2. Squaring the pyramid: Projected U.S. population by age and sex (thousands) (U.S. Census Bureau, 2008).

These forecasts have generated much concern on the part of researchers and government policymakers. Funding agencies have set their priorities in response to those concerns. For example, the Centers for Disease Control and Prevention: National Center

for Injury Prevention and Control (2009) has targeted the identification and measurement of factors affecting older driver safety as a research priority according to the CDC Injury Research Agenda, 2009-2018. The National Institute on Aging (2007) has committed to fund research to identify the factors (including visual impairment) that reduce older driver safety, and “to support the development of tools for assessing visual, cognitive, and other abilities associated with safe driving...to support the special needs of older drivers” (p. 16). The Transportation Research Board has held two major conferences on aging drivers in 1987 and in 1999 (TRB, 1988, 2004). The National Transportation Safety Board (2010) held a public forum entitled Safety, Mobility, and Aging Drivers on November 9-10, 2010, where numerous leading older driver researchers made presentations, presided over by Deborah Hersman, NTSB Chair.

However, contrary to predictions of driving fatality increases, traffic fatalities fluctuated between about 40,000 and 42,000 from 1991 to 2007, and then dropped from 41,259 in 2007 to 37,423 in 2008 and 33,808 in 2009. NHTSA (2010) reported that the rate of fatalities per 100 million vehicle miles of travel (VMT) was 1.36 in 2007, 1.25 in 2008 and 1.16 in 2009. Regarding the overall drop in fatal accidents per driver, Sivak (2009) determined through regression analysis that distance driven, proportion of rural driving, and fuel price (as a surrogate for leisure driving) accounted for 81% of the variance in monthly accident fatalities from January 2007 to December 2008.

Cheung and McCartt (2011) examined the trend in fatalities per licensed driver from 1997 to 2008, broken out into four age cohorts. As shown in Figure 3, while fatal accidents per driver dropped by 23% from 1997 to 2008 for drivers 35 to 54 years of age, the 70-74 year old rate dropped by 30%, the 75-79 year old rate by 35%, and the 80+ rate

by 47%. They concluded that the steeper downward trend in older driver fatal crash rates relative to overall fatal crash rates is due in part to their declining crash rate relative to middle-aged drivers, and in part to their lessening frailty and more robust health. Although Cheung and McCartt professed to not see any crashworthiness-related differential benefit for older drivers, stating that “... it is unclear in what ways the increased safety of vehicles may have benefited older drivers more” (p. 6), the proliferation of side curtain airbags certainly offers a preferential benefit to older drivers, who tend to be involved in multiple vehicle side impact crashes at intersections, as discussed below.

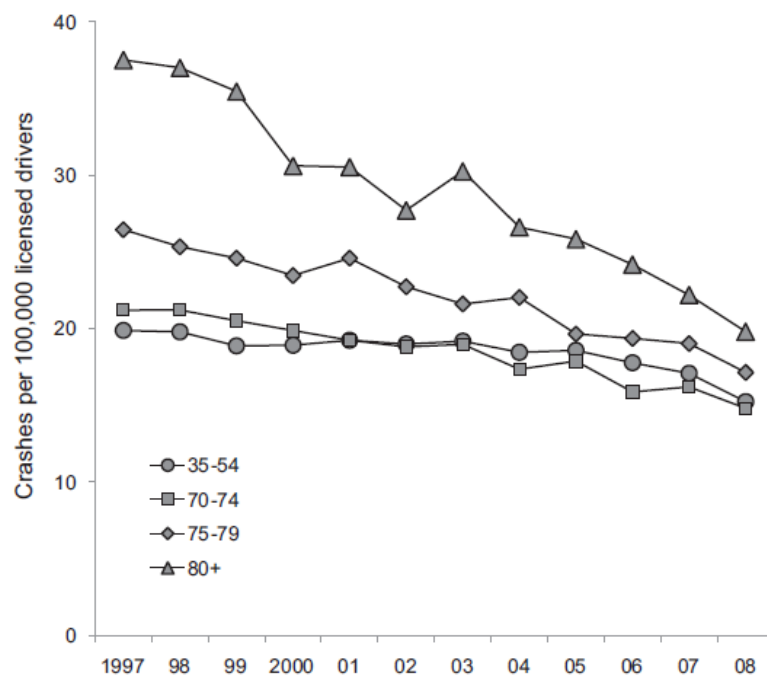


Figure 3. U.S. fatal passenger vehicle driver crash involvements per 100,000 licensed drivers by driver by group, 1997-2008 (Cheung & McCartt, 2011, p. 668).

Consistent with Cheung and McCartt’s analysis, fatality counts for vehicle occupants (including drivers, passengers, and motorcyclists) aged 65 or more have been trending downward since 1998, according to Fatality Analysis Reporting System (FARS)

data (NHTSA, 2011), while overall vehicle occupant fatalities only began trending downward in 2006. However, from 2007 to 2009, when fatalities to occupants 65 and older declined by 11%, fatalities to occupants under 65 declined by 20%.

Regarding crash rates for any severity, Cheung and McCartt reported that all police-reported property-only crashes also declined more for older drivers than for the 35-54 year old comparison group. However, insurance claim data show no such relative decrease. The Highway Loss Data Institute (HLDI) (2009) reported that from 1997 to 2006, insurance collision claims per 1000 insured vehicle years declined by 9% for middle-aged drivers, but only 5-7% for older drivers.

Possible explanations for the difference between the two studies may be that older drivers involved in property-damage-only crashes may have become more reluctant than younger drivers to report their accidents to the police (while still filing an insurance claim), perhaps for fear of having their driving skills called into question and their license revoked, particularly given the increasing public awareness of older driver issues. Cheung and McCartt suggest that the difference between their PDO data and the IIHS data may be because IIHS restricted their data to vehicles four years old or less, while they did not. However, over time that restriction would include more vehicles with side impact protection, which should have resulted in a *more* extreme decline for older drivers.

The reduction in fatality rate (fatalities per 1,000 crashes) for older drivers from an overrepresentation factor of 3.5 in 1997 to an overrepresentation factor of 2.9 in 2005 may be reflective of the relative effectiveness of crashworthiness advances in multiple vehicle lower-speed side impact crashes, and in particular, the increasing availability of side airbags, which differentially benefit older drivers (Sivak & Schoettle, 2010) due to

their overinvolvement in side impact crashes.

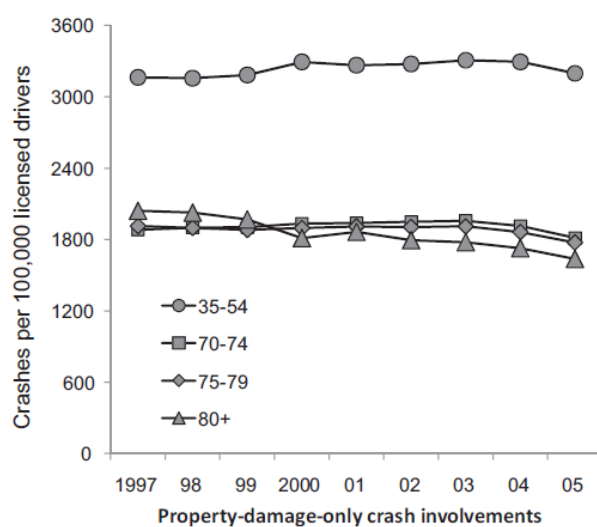
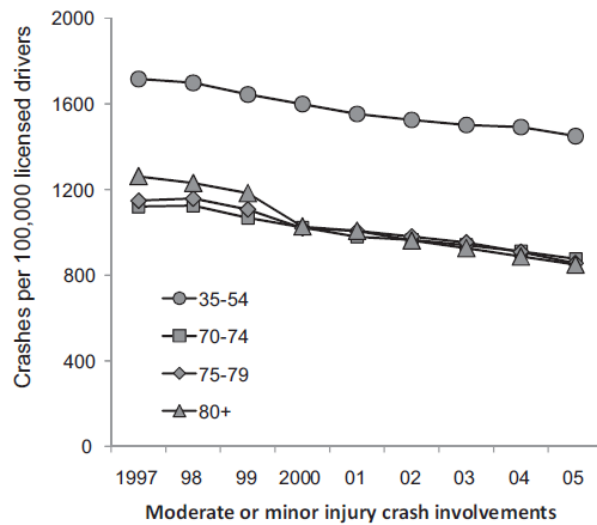
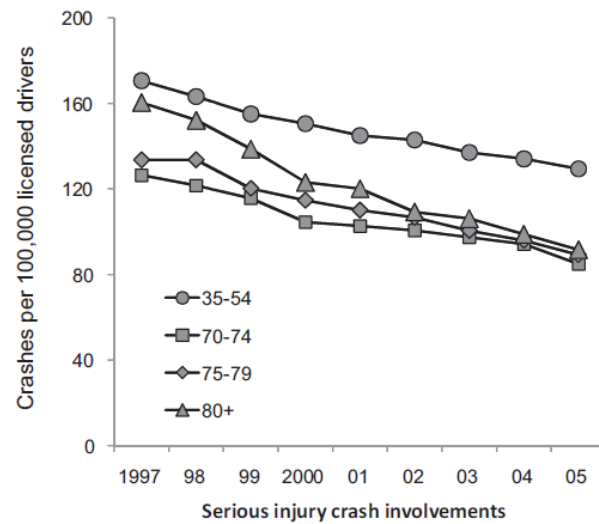


Figure 4. Passenger vehicle driver crash involvements per 100,000 licensed drivers for three crash severities in 13 selected states combined by driver age group, 1997-2005 (Cheung & McCartt, 211, p. 670).

Three graphs from Cheung and McCartt (see Figure 4) of fatal, serious injury, minor injury crash trends 1997-2005 show that the older the cohort, the steeper the downward trend, but also, the less severe the accident, the flatter the downward trend. The most parsimonious explanation for the evident age by severity interaction is that crashworthiness improvements and perhaps improvements in fitness, from 1997 to 2005, differentially benefited older drivers.

An additional explanation is that the increase in fuel costs impacts on discretionary travel more than work-related travel, which reduces older driver risk exposure relative to the reference middle-aged group, as Sivak (2009) noted. In a related vein, changing economic conditions may even have caused some licensed older drivers to become inactive, inflating Cheung and McCartt's exposure estimate (licensed drivers) but not the HLDI (2009) exposure estimate (ensured vehicles). With increasing age, a larger proportion of licensed drivers become inactive. Cheung and McCartt used number of drivers (many licensed but not active) to estimate risk exposure, while HLDI (2009) used insured vehicle-years (which would not include most inactive but licensed drivers). In addition, HLDI only included ensured vehicles four years old or less, while many of Cheung and McCartt's drivers may have been driving older, less economical vehicles, perhaps making them more sensitive to rising fuel prices and more likely to reduce their travel in response.

I conclude that the overall drop in fatalities is a result of a small drop in overall travel miles (Federal Highway Administration, 2010) and a large improvement in vehicle crashworthiness. The steeper reduction in fatalities for older drivers through 2006 is most likely realized from differential crashworthiness benefits (e.g., side curtain airbags) that are of more benefit in lower-speed urban environments and in multiple vehicle intersection crashes, and from a fuel cost-mediated travel reduction by older drivers relative to the middle-aged cohort. It is not likely due to a downward trend in older drivers' relative propensity to have accidents, as is shown by HLDI (2009).

Biases

Numerous researchers have suggested several biases that may tend to inflate older driver fatality and crash rates, reducing those rates' utility for analyzing the issue of older driver safety.

Frailty bias. First, older drivers are physically frailer, and therefore less likely to survive an accident than is a younger driver. Evans (1988) proposed that the higher fatality rate (per licensed driver) of older drivers is due to an older driver being much more likely to die than a younger driver in a crash of a given energy, and gave the example that an 80 year old male would be four times more likely to die than a 20 year old male in a crash of equivalent energy. When Evans corrected crash fatality data to eliminate the frailty effect, the older driver fatality over-representation (fatalities per licensed driver) disappeared. However, his analysis rested on the critical assumption that older driver accidents and middle-aged driver accidents have the same energy, which is not the case. As discussed below, older drivers' accidents occur more often in urban driving than middle-aged drivers' accidents, so assuming that each cohort's crashes have

equal energy overestimates the contribution of frailty. Note also that when Evans applied a frailty correction to fatality rate per distance travelled, the older driver fatality rate was reduced but not eliminated.

While frailty accounts for some of older drivers' increased fatality risk, older drivers' likelihood of having any accident increases with age. Dellinger, Langlois, and Li (2002) applied a "decomposition" analysis to determine the relative influences of frailty, accident risk per distance driven, and exposure in older drivers' overall fatality risk. Dellinger et al. examined Fatality Analysis Reporting System (FARS) fatal crash data, National Automotive Sampling System (NASS) / General Estimates System (GES) data, and Nationwide Personal Transportation Survey (NPTS) data from 1990 and 1995.

(The Fatality Analysis Reporting System (FARS) is maintained by the National Highway Traffic Safety Administration (NHTSA), and contains records of all public road motor vehicle crashes that led to the death of a motorist or pedestrian within 30 days of the crash. The National Automotive Sampling System (NASS) / General Estimates System (GES), also maintained by NHTSA, is a representative annual sample of about 50,000 U.S. police-reported crashes of all severities, and contains data on vehicle types, crash severity, and other variables recorded in standard police accident reports. For further information on FARS and NASS GES, see NHTSA (a, b). The National Household Travel Survey (NHTS), named the Nationwide Personal Transportation Survey (NPTS) until 2001, is maintained by the Federal Highway Administration (FHWA), and is a large telephone survey of the nature and characteristics of the personal travel activity of representative U.S. households. The survey is conducted every 5-7 years. For further information about the NHTS, see FHWA (NHTS).)

Dellinger et al. (2002) benchmarked crash and exposure data of 65-74, 75-84, and 85+ year old drivers against crash and exposure data of 55-64 year-old drivers. *Fatal crash involvement rates* (fatalities per 10,000 drivers) were decomposed into *crash fatality rates* (fatalities per 1,000 crashes, i.e., frailty), *crash incidence density* (crashes per million miles), and *exposure prevalence* (average annual miles driven). From 1990 to 1995 all age groups drove more miles annually, and the number of older drivers increased substantially, as reported elsewhere. Within all age groups, fatal crash involvement rates were almost identical between 1990 and 1995, as lower crashes per mile were offset by more miles traveled. In 1990, compared to drivers aged 55-64, drivers aged 75-84 had 50% more fatal crashes per 10,000 drivers, and drivers 85 or older had 178% more fatal crashes per 10,000 drivers. In 1995 the respective increases for those two age groups were 60% and 186%. (Drivers aged 65-74 did not have substantially more fatal crashes per 10,000 drivers than those aged 55-64.) Only some of this increase was accounted for by frailty, as increasing age was strongly associated with an increasing *crash incident density* (accident rate per million miles). In 1990, the 65-74, 75-84, and 85+ drivers had 55%, 115%, and 402% more accidents per distance driven respectively than the 55-64 drivers, and in 1995 those rates were 5%, 109%, and 276% higher respectively than the 55-64 drivers. Dellinger et al. determined that:

In sum, the three components of the fatal crash involvement rate behaved quite differently during the study period: The crash fatality rates increased with age but were stable over time ..., the incidence densities increased with age and decreased over time ..., and the exposure prevalences decreased with age and increased over

time, ultimately leading to a stable fatal crash involvement rate between 1990 and 1995. (p. 239)

For drivers aged 65-74, crash fatality rates in 1990 and 1995 were very similar to drivers aged 55-64, indicating that frailty contributed very little to fatal crash involvement rates for drivers aged 65-74. Comparing drivers aged 85+ to drivers aged 55-64, *fatal crash involvement rate* increased by about a factor of three, as a function of *crash fatality rate* which approximately doubled, *crash incidence density* which increased by a factor of five in 1990 and a factor of almost four in 1995, and *exposure prevalence* which decreased by a factor of about three.

Dellinger et al. also applied a logarithmic transformation analysis to the data to assess the relative contributions of the three components of the fatal crash involvement rate (i.e., fatal crashes per 10,000 drivers), and concluded from the results that frailty (fatal crashes per 1,000 crashes) had a lesser influence than crash incident density (crashes per million miles) or exposure prevalence (annual mileage per driver). They stated that “In other words, the risk of crashing and the amount of driving explained more of the difference in fatal crash involvement than the risk of dying when there was a crash.” (p. 239). In a quantitative example of the logarithmic transformation technique applied to 1995 fatal crash rates for benchmark drivers aged 55-64 and drivers aged 85 years or more, they stated that the 186 percent difference in fatal crash involvement rate between the two cohorts was explained by a 24% frailty contribution, a 42% crash incidence density contribution, and a 33% exposure prevalence contribution.

Li et al. (2003) also examined the contribution of frailty to older drivers’ over-representation in fatal accidents per distance travelled. For drivers 85 and over, they

estimated that 60% of the elevated fatality rate was related to frailty, and paradoxically up to 80-85% for drivers 60-74. (Although their data showed that younger old drivers were less frail than the older old, the younger old crash propensity was hardly higher than middle-aged drivers).

Note however that Li et al. used police-reported crashes (from GES) to estimate crash propensity, and that older drivers may be less likely to report their property-damage-only accidents to the police for fear of losing their licenses, which would increase the frailty metric by shrinking the denominator, and decrease the crash propensity metric by shrinking the numerator, leading to an overestimation of the frailty contribution to the fatality rate of older drivers.

The difference between the fatal rate curve and the accident rate curve in Figure 1 is a result of the change in fragility with age. That difference appears to be most consistent with the Dillenger et al. estimate of frailty contribution.

Low-mileage bias. Langford, Methorst and Hakamies-Blomqvist (2006) analyzed self-reported travel distance and accident survey data gathered from 47,502 Dutch drivers between 1990 and 2003. When they grouped driver data across five age groups (20 and under, 21-30, 31-64, 65-74, 75 and over) and low (3,00 km or less), medium (3,001-14,000 km) and high (over 14,000 km) annual distance driven, only the low-mileage drivers showed an age-related u-shaped accident rate curve (due entirely to the oldest driver cohort). Drivers who traveled more than 3,000 km a year showed decreasing accident rates as they got older, including the oldest cohort of drivers, and within each age cohort, drivers with higher annual km traveled had substantially fewer accidents per million km. Within each cohort, the accident rate of the low annual km drivers was

approximately a factor of six higher than the high annual km drivers, with the exception of the oldest cohort whose low km drivers 75 or older had an accident rate 18 times higher than the high km drivers. Langford et al. made the strong claim that the apparent high crash risk of older drivers is driven entirely by the approximately 10% of those older drivers who traveled less than 3,000 km a year. However, the low-mileage drivers aged 75 and over numbered only 98, and had eight accidents annually on average. Langford et al. therefore acknowledged that the crash rate of those drivers were not statistically different from the younger cohorts of low-mileage drivers (i.e., the u-shaped curve was not significant).

The Langford et al. study may be critiqued on several points. First, Staplin, Gish and Joyce (2008) observed that Langford et al. relied entirely on self-reported collision and risk exposure (i.e., annual mileage) data for their analysis. Those data are notoriously inaccurate. For example, Staplin et al. (2008) compared self-reported annual mileage of participants in their Maryland Pilot Older Driver Study (Staplin, Gish, & Wagner, 2003) to those drivers' self-reported mileage in a State of Maryland Emission Exemption Database (EED) for drivers over 70 years of age who stated that they drove fewer than 5,000 miles annually in order for their vehicle to be exempted from emissions testing. Approximately 30% of the older drivers who were classified in the EED as driving less than 5,000 miles per year (self-reported), reported driving *more* than 5,000 miles annually in the MaryPODS survey. Staplin et al. also showed that weekly and annual mileage estimates gathered in the MaryPODS survey were extremely inconsistent, with more than 10% of their participants being in error by 100% or more, and over 40% of participants being in error by 50%. Finally, they compared self-reported annual mileage to odometer-

based annual mileage from the 2001 National Household Travel Survey (NHTS), and determined that low-mileage drivers substantially underestimated their annual mileage, and furthermore that low-mileage drivers 20 and under and low-mileage drivers 75 and older under-estimated their annual mileage by approximately 100%, whereas middle-aged low-mileage drivers underestimated by approximately 50%. They concluded that this underestimation could entirely explain the increase in accident risk of low-mileage drivers 75 and over reported by Langford et al. (2006).

In another example of inaccurate self-reporting of annual mileage, Betz and Lowenstein (2010) examined data from the Second Injury Control Survey (ICARUS-2) conducted by the Centers for Disease Control and Prevention in 2001 to 2003, and reported that self-reported annual mileage estimates were unusable: "For example, 13% of older drivers reported driving 100,000 miles or more in the past year, so mileage estimates were not included in the main analyses" (p. 1932).

Finally, Huebner, Porter, and Marshall (2006) conducted a test of the CarChip, a commercially available recording device that connects to a vehicle's on-board diagnostic system to record various exposure metrics (i.e., trip variables such as time, duration, average velocity, and distance travelled) and found that it correlated very well with GPS data (which they considered to be "the gold standard"). They also showed that the correlation between CarChip data and retrospective self-reported distance travelled was .59 (I derived the correlation by calculating their data from the screen coordinates of their Figure 1 scatter plot of CarChip data against self-reported data), and "determined that retrospective self-reports of weekly driving distances are inaccurate" (p. 76).

Self-reports of accidents are also known to be inaccurate. McGwin, Owsley and Ball (1998) selected a sample of 278 drivers 55 or more years of age (average age 71), with either zero, or one or more police-attended crashes within the previous five years (crashing drivers were purposely over-represented in their sample). Of the 175 drivers involved in a police-attended crash (crashers) and 103 drivers not involved in a police-attended crash (non-crashers), 111 crashers self-reported a crash while 64 crashers self-reported no crash. That is, 37% of crashers reported that they had not crashed. Strangely, 14 of the 103 non-crashers also reported a police-attended crash. Finally, of those who did self-report police-attended crashes, many reported fewer crashes than police records indicated.

Taken together, these results strongly indicate that results based on self-reported accidents and mileage (i.e., Langford et al., 2006) should not be given undue weight, particularly as they acknowledged that those results were not statistically significant. Langford, Koppel, McCarthy and Srinivasan (2008) reanalyzed their Dutch data from Langford et al. (2006) by applying an underestimation correction factor derived from the Staplin et al. (2008) NHTS data analysis, and also by applying a second correction factor that they derived from 2001 NHTS data using the methodology of Staplin et al. They reported that the low-mileage older drivers still had a substantially higher accident rate than low-mileage younger drivers, but that the difference was reduced. Given the questionable assumption that details of low-mileage older U.S. drivers' under-reporting can be generalized to a Dutch driving population, that the second analysis still rested on an average of eight accidents per year incurred by low-mileage drivers 75 years and older, and that the difference between oldest low-mileage accident rate and other low-

mileage accident rates was originally not statistically significant and became smaller upon reanalysis, the existence of low mileage bias is in doubt. A further reason to question the accuracy of the self-reported mileage estimates reported by Langford et al. is that the cohort of drivers 75 and over had the *smallest* proportion of low-mileage drivers compared to younger age groups, which is certainly not characteristic of North American driver demographics.

The final point against the low mileage bias is more theoretical than empirical. Janke (1991) suggested that; “In fact, it seems not unreasonable to hypothesize that drivers with a low level of competence tend to have low mileages. Circularity is introduced because the causality here might go in either direction” (p. 185). While Langford and Koppel (2006) and Langford et al. (2008) offers the low mileage bias as an explanation for higher accident rates with age, if Janke’s suggestion is correct, the low mileage bias becomes a simple observation of drivers self-limiting their risk, perhaps due to some recognition of their diminishing functional capabilities.

Urban driving. Although traffic experts consider limited access highways to be safer because they offer far fewer opportunities for traffic conflict than urban streets do (Bédard, Weaver, Dārzinš, & Porter, 2008) and Ontario drivers living in rural areas have a significantly lower accident rate by distance traveled or by traveling time than Ontario drivers living in urban areas (Chipman et al., 1993), older drivers tend to avoid highways and other high-speed roads, increasing their accident rate relative to younger drivers (Dissanayake & Perera, 2009; Di Stephano, 2003; Janke, 1991). (Note however, that the lower energy of urban crashes will somewhat mitigate the frailty bias inherent in fatal accident rates, and furthermore, that older drivers have a lower driving speed than

younger drivers (Schlag, 1993; Szlyk, Seiple, & Viana, 1995), further reducing their fatality risk in an accident, relative to Evans' (1988) estimates.)

Chipman et al. (1993) proposed that driving time rather than driving distance as a risk exposure metric would eliminate some of the bias against drivers who travel more in urban, intersection-dense high-risk environments, and against older drivers who prefer to drive in that environment.

Induced Exposure

Janke (1991) recommended that the indirect risk estimation technique of "induced exposure" be used to eliminate the bias inherent in mileage-based measures. This technique, pioneered by Thorpe (1964), is based on the assumption that in a sample of two-vehicle accidents in which one driver was found to be completely at fault, the not-at-fault drivers comprise a random sample whose age distribution is a measure of relative risk exposure across groups. The accident responsibility ratio of a group is the ratio of at-fault accidents (the numerator) to not-at-fault accidents (the denominator). A ratio greater than one indicates that the group causes more than its expected share of two-vehicle accidents (i.e., the group is overrepresented in relation to drivers overall). The induced exposure technique allows much more specific hypotheses to be investigated without requiring that exposure (for example, mileage on urban roads in darkness) be anticipated and measured *a priori* for specific environmental characteristics.

Verhaegen, Toebat, and Delbeke (1988) analyzed a sample of 660 two-vehicle accidents and found a responsibility ratio of 2.23 for drivers aged 60 to 69 years, and a ratio of 2.5 for drivers over 70 years of age.

Cooper (1989) derived accident responsibility ratios from a database of 14,063 accident-involved drivers in British Columbia in 1986. He reported ratios of 1.56 for age 71 to 75, 2.13 for age 76 to 80, 2.64 for age 81 to 85, and 5.67 for age 86 to 90. Cooper (1990) stated that the ratio of responsible to not-responsible accidents by age showed "an exponential-looking increase in accident responsibility from age sixty-five up" (p. 95). The proportion of right of way (ROW) violations to total traffic convictions by age also follows a similar rising curve (Cooper, 1990).

Stamatiadis and Deacon (1995) calculated accident responsibility ratios from a database of 144,410 two-vehicle accidents, and reported ratios of 1.55 for age 70 to 74, 2.24 for age 75 to 79, and 3.66 for drivers over 80 years of age. They also applied logistic regression (at-fault versus not at fault – conceptually analogous to induced exposure) to Michigan accident data spanning 1978 to 1988 determine that older drivers were particularly over-represented in at-fault intersection accidents, that middle-aged drivers were safer than younger drivers who were safer than older drivers, and that more recent cohorts of older drivers were safer than more distant cohorts (i.e., older driver cohorts became safer between 1978 and 1988, relative to young and middle-aged drivers).

Stutts, Martell, and Staplin (2008) applied the induced exposure technique to FARS (an exhaustive dataset of traffic fatalities) and NASS/GES (sample of injury and property-damage-only traffic accident data) from 2002-2006 to determine overinvolvement ratios (at-fault to not-at-fault) of ten-year age cohorts (60-69, 70-79, 80+) for two-vehicle accidents where only one driver was found at fault. They then examined the particular risk factors associated with a cohort's overrepresentation. They found that older drivers under the age of 70 had crash rates similar to middle-aged

drivers, although they were somewhat over-represented in intersection crashes and left turn crashes. Drivers over 60 were more likely to be in the struck vehicle than the striking vehicle, and given a crash, they were more likely to be cited for failure to yield. Drivers over 70 were particularly likely to be over-represented in crashes at passively controlled intersections (i.e., stop or yield signs), driveways and alleys.

Clarke, Ward, Bartle, and Truman (2010) used induced exposure methodology to examine over 2,000 U.K. police-reported crashes involving drivers aged 60 or more, occurring from 1994 to 2007 inclusive. All crash records contained detailed data, including an indication if the older driver was fully, partly or not at fault for the accident, and a police narrative. As expected, approximately 50% of drivers below 70 years of age were determined to be fully or partly responsible (summing fully responsible drivers with half of partly responsible drivers). Accident responsibility increased monotonically with age above 70, with 81% of drivers aged 85 or above being responsible for their accidents. Logistic regression showed that increasing age significantly predicted likelihood of being the at-fault driver ($p < 0.0001$).

Clarke et al. found that older drivers had the highest right of way violation (ROWV) crashes. Sixty-four percent of all ROWV crashes involving at-fault older drivers were cross-flow right turns onto a roadway or right turns across traffic off a roadway (corresponding to left turns in North America and Europe), and 54% of those were caused by the error type "visual search problems". They concluded that older drivers (after age 70) are increasingly at risk to cause ROW violation crashes at intersections because they have difficulty "detecting and responding to other vehicles at intersections." (p. 1023).

Cerrelli (1973) validated the induced exposure technique against insurance rates, and Kirk and Stamatiadis (2001) validated the technique against trip diaries.

Chandraratna and Stamatiadis (2009) used Kentucky accident data to statistically validate quasi-induced exposure as an accurate estimator of risk exposure. They also demonstrated in that study that police accident investigators were not biased against older drivers when determining fault (as Eustace and Wei (2010) cautioned) by showing that the age distribution of not-at-fault second vehicle drivers was the same as the age distribution of the not-at-fault drivers in multiple vehicle crashes excluding the drivers of the first two vehicles.

Increasing Variability with Age

Although policy-makers use epidemiological estimates of the overall magnitude of the older driver issue to determine the level of funding and research effort to be brought to bear, that approach risks treating the population of older drivers as a homogeneous group. However, that group is more heterogeneous with regard to functional abilities of perception and cognition than any younger age group (Landy, 1992; Levin, Dukic, Henriksson, Mårdh & Sagberg, 2009; McLaughlan & Murtha, 2010; Nelson & Dannefer, 1992; Owsley, Sekuler, & Siemsen, 1983; Rabbitt, 1993; Tsang, 1997, 2003). Therefore, overrepresentation of older drivers in the accident statistics is a manifestation of increased accident risk for a subset of that population. The challenge is to develop means to identify members of that subset. Some older driver researchers contend that most members of the high-risk subgroup of older drivers are functionally incapacitated to some degree by diseases of old age and that healthy aging confers little or no accident risk increase. For example, Dr. Dobbs (2010), a leading expert on

Alzheimer's Disease and older drivers, stated in her testimony before a National Transportation Safety Board public enquiry into older driver safety on November 9, 2010 that, "In terms of identification, we know that the changes associated with normal aging are unlikely to affect a person's ability to drive..."(p. 24, day 1 transcript). In contrast to her statement, most researchers agree that healthy older drivers are more likely than middle-aged drivers to be affected by one or more age-related decrements in perceptual, cognitive or physical capacities critical for safe driving. It follows that identifying those critical functions, and developing tests to quantify critical capacities in older drivers, is the key to identifying the older drivers who are members of the high-risk subset. This literature review will focus specifically on visual capacity and older drivers.

Accident Characteristics

The accident characteristics of older drivers indicate the critical capacity decrements associated with increased accident risk. Older drivers are strongly overrepresented in intersection accidents involving other vehicles (Bao & Boyle, 2009; Clarke, Ward, Truman, & Bartle, 2009; Daigneault, Joly, & Frigon, 2002; Dissanayake & Perera, 2009; Edwards, Creaser, Caird, Lamsdale, & Chisholm, 2003; Hellinga, 1999; Langford & Koppel 2006; Levin et al. 2009; Ragland & Zabyszny, 2003; Schlag, 1993; Skyving, Berg, & Laflamme, 2009; Stamatiadis & Deacon, 1995; Subramanian & Lombardo, 2007). Given accident involvement, older drivers are more likely to have committed a right of way (ROW) violation and to be found at fault for the accident (Bédard, Porter et al., 2008; Braitman, Kirley, Ferguson, & Chaudhary, 2007; Clarke et al., 2009; Clarke et al., 2010; Dissanayake & Perera, 2009; Di Stefano & Macdonald, 2003; Langford & Koppel, 2006; Levin et al., 2009; Massie, Campbell, & Williams,

1995; Mayhew, Simpson, & Ferguson, 2006; NHTSA 2010 - Traffic Safety Facts 2009; Rabbitt & Parker, 2002; Rallabandi & Dissanayake, 2009; Retting, Weinstein, & Solomon, 2003; Schlag, 1993; Strauss, 2005; Stamatiadis & Deacon, 1995; Subzwari et al., 2009; Williams & Shabanova, 2003).

Intersections and Right of Way Violations (ROWV)

Schlag (1993) found that 1989 statistics on fatal and injurious accidents in Germany showed increased accident responsibility with age, and noted that three-quarters of the accidents caused by older drivers occur at intersections or junctions, "...due to failing to observe right of way or other mistakes when changing direction." (p. 48).

Daigneault et al. (2002) analyzed the driving records of 426,408 Quebec drivers aged 60 years and over (i.e., the entire population of elderly Quebec drivers) from a 6-year period (1992–1997). Giving a snapshot of the older driver demographic at the end of that period, 44% were aged 65-69, 30.8% were 70-74, 16.8% were 75-79, and the remaining 8.4% were 80 years or more. Within that period, 27.5% of men had an accident, and 16.7% of women had an accident. Ninety percent of these accidents were multiple vehicle accidents, and 29% occurred at an intersection, 14% when turning left. While 22% of the general driving population's accidents were right-angle crashes at intersections, 29% of older drivers' accidents were of that type. Furthermore, the relative frequency of right-angle intersection crashes and left-turn intersection crashes steadily increased for each age group.

Dissanayake and Perera (2009) examined all police-reported crashes in Kansas between 2002 and 2006. During that time, 45,741 older drivers (65+) were involved in 43,290 police-reported crashes, with 14,594 rural crashes and 31,146 urban crashes.

Although 80% of older drivers were not injured, 276 older drivers died. Older drivers were overrepresented in intersection accidents, left turn accidents, and angle collisions.

Langford and Koppel (2006) examined Australian traffic fatality data from 1996 to 1999, when 6,388 fatal road crashes resulted in 7,103 deaths. Middle-aged drivers were compared with young-old and old drivers. Compared to middle-aged drivers (40-55 years), who had 21% of their accidents at intersections, young-old drivers (65-74 years) had 35% of their accidents at intersections, and old drivers (75 years or more) had 50% of their accidents at intersections, and 60%, 65%, and 74% respectively of middle-aged, young-old, and old drivers' accidents involved multiple vehicles. Langford and Koppel estimated that frailty accounted for up to one half of older drivers' over-involvement in fatal crashes. Given involvement in an intersection accident, older drivers (75+) were more than two times more likely than middle-aged drivers to have turned across the path of a vehicle coming from the opposing direction, more than two times more likely to have crashed into a vehicle in an adjacent lane as they travelled in the same direction, and five times more likely to have turned into a vehicle travelling in an adjacent lane. Furthermore, "older drivers were five times more likely to be in the vehicle making the right turn (corresponding to a left turn in North America) rather than the driver going straight ahead – thereby accounting for 28 per cent of all older driver crashes, compared to 5 per cent of middle-aged drivers' crashes." (p. 317).

Oxley, Fildes, Corben, and Langford (2006) conducted a "black spot" study involving crashes at 62 sites in Australasia from 1994 to 1998. More than 400 accident-involved drivers were over 65 years of age, and most were involved in intersection accidents. Older drivers were over-represented by a factor of two or three depending on

location. The top contributing factor in older driver accidents (76% of accidents) was inappropriate gap selection, either when making a right turn across traffic (left turn in North America) at a green light with no control of the turning phase, or when crossing traffic with ROW at intersections controlled by stop or yield signs. Oxley et al. (2006) concluded that "...older drivers are likely to experience more difficulty in *detecting* and reacting to the motion of approaching vehicles accurately" (p. 343, italics mine).

Levin et al. (2009) carried out an extensive analysis of all fatal or injury accidents in Norway from 1983 to 2006, and found that older drivers were overrepresented in intersection crashes, particularly when turning left across oncoming traffic, or when turning left onto a roadway across the path of vehicles approaching from the right. While ROW violations at yield signs accounted for about 10% of the youngest drivers' crashes, that accident type accounted for 30% of the oldest (80+) drivers' crashes. Older drivers also had difficulty detecting pedestrians away from intersections.

Raglund and Zabyshny (2003) examined the crash database from the NASS GES. (Recall that the NASS GES is a representative sample of about 50,000 U.S. police-reported crashes, and contains data on vehicle types, crash severity, and other variables recorded in standard police accident reports.) Raglund and Zabyshny determined that 11% of drivers involved in crossing path crashes were older, but that only 6% of drivers in all other crash types were older (which may in part be a reflection of their under-representation in single vehicle accidents or rear-end accidents).

Stamatiadis and Deacon (1995) determined through their induced exposure analysis and logistic regression of the large Michigan dataset (discussed above) that

intersection complexity underlies the overrepresentation of older drivers in intersection crashes.

Subramanian and Lombardo (2007) reported that 31% of fatal crashes at traffic signals or stop signs between 1997 and 2004 in the U.S. involved at least one older driver (aged 65 or more), compared to only 13% of fatal crashes at non-intersection areas. Also, for fatal two-vehicle intersection crashes they compared failure-to-obey (did not stop) and failure-to-yield (to oncoming traffic *after* stopping) violations separately for traffic signals and stop signs across age cohorts. While younger drivers showed a slightly increased tendency to not obey the traffic control device than to stop and then violate another vehicle's ROW, older drivers were nearly two times more likely to fail to yield than to fail to obey the traffic control device. That is, at traffic signals, drivers 16 to 20 years of age accounted for 14% of failure-to-obey violations and 12% of failure-to-yield violations, while older drivers accounted for 18% of failure-to-obey violations and 34% of failure-to-yield violations. Similarly, at stop signs, drivers 16 to 20 years of age accounted for 18% of failure-to-obey violations and 14% of failure-to-yield violations, while older drivers accounted for 23% of failure-to-obey violations and 40% of failure-to-yield violations. Those results are consistent with risk-taking by younger drivers, and perceptual errors (e.g., detection failures or gap acceptance errors) by older drivers.

Bao and Boyle (2009) recorded visual scanning behavior of young, middle-aged and older drivers as they negotiated intersections along a road test route and found that older drivers scanned significantly less to the left and right before, during, and after negotiating intersections than younger and middle-aged drivers (with two small exceptions, which were that younger and older drivers both looked less to the right than

middle-aged drivers when in the intersection, and when exiting the intersection). I suggest that older drivers' reduced scanning behavior indicated that their attention was not being attracted by vehicles in their vicinity.

Age and Gap Acceptance Errors

Braitman et al. (2007) interviewed two groups of older drivers (78 drivers between 70 and 79 years of age and 76 drivers 80 years or older) and a comparison group of 73 drivers between 35 and 54 years of age. All drivers had been found at-fault in a serious-injury accident not more than 10 weeks previously. Failure to yield ROW increased significantly with age (26%, 37%, and 58% of accidents respectively). Drivers 70-79 predominantly misjudged the approach speed and time to contact of approaching vehicles, while drivers 80 or over overwhelmingly failed to detect the approaching vehicle at all.

Hancock and Manser (1997) conducted two simulator experiments to assess younger and older drivers' accuracy in estimating an approaching vehicle's time-to-contact (TTC) while waiting to make a left turn across traffic. Vehicles approached at 35, 40, or 45 mph in the first experiment, and at 6, 9, 15, or 44 mph in the second experiment, and were occluded by a shrub and disappeared 128 feet away or 66 feet away respectively in the two experiments. The participant's task was to press a button when they thought that contact would have occurred. All participants underestimated TTC (providing a safety margin when turning across traffic), with older drivers underestimating substantially more than younger drivers. As approach speed increased in experiment 1, younger but not older drivers became more accurate. That is, older drivers maintained a margin for error with increasing approach speeds, while the younger drivers did not.

However, participants in experiment 2, which used a larger range of velocities and a much shorter gap, showed a different pattern at the highest speed. While older drivers underestimated TTC more than younger drivers for 6, 9, and 15 mph approach speeds, they overestimated TTC by 50%, which was slightly higher than younger drivers' TTC overestimation at the highest approach speed of 44 mph. (A driver who makes a left turn based on an overestimation of TTC has a high risk of collision.)

Yan, Radwan, and Guo (2007) carried out a left-turn gap acceptance simulator study of young, middle-aged and old drivers' performance at a stop-controlled intersection. Approaching traffic travelled at 25 or 55 mph. Older drivers accepted significantly longer gaps than all other drivers for 25 mph traffic, but not significantly different gaps for 55 mph traffic, indicating that while they increased their margin of safety, their gap acceptance was not responsive to the speed of approaching vehicles. Therefore, although older drivers showed more conservative gap acceptance, higher speed gaps remain relatively riskier for older drivers. They are at a particularly increased risk of collision if an approaching vehicle is travelling at a higher than expected speed.

On the other hand, Skaar, Rizzo, and Stierman (2003) found that older drivers' gap acceptance judgments in actual road traffic were more conservative than younger drivers in general, but that older drivers adjusted their gap acceptance values according to the speed of approaching vehicles as completely as did younger drivers. Skaar et al. also reported that older drivers were aware of their reduced ability to operate vehicle controls, and compensated appropriately.

Side Impact Crashes

Consistent with older drivers' tendency to have multivehicle collisions at intersections, older drivers are particularly at risk of incurring side impact crashes. Viano, Culver, Evans, and Frick (1990) analyzed 1975-1986 FARS data, and 1982-1986 National Accident Sampling System (NASS) and National Crash Severity Study (NCSS) multivehicle crash cases, and determined that older people were severely overinvolved in fatal multivehicle side impacts, with 64% of "near-side seated occupants" (i.e., drivers in left-side impacts, front-seat passengers in right-side impacts) were over 50 years of age, and 36% were over 70. Eighty-eight percent of multivehicle crashes occurred at intersections, and 48% were caused by driver error and 16% by a traffic violation. (Note that the older driver / passenger overrepresentation in these fatal multivehicle side

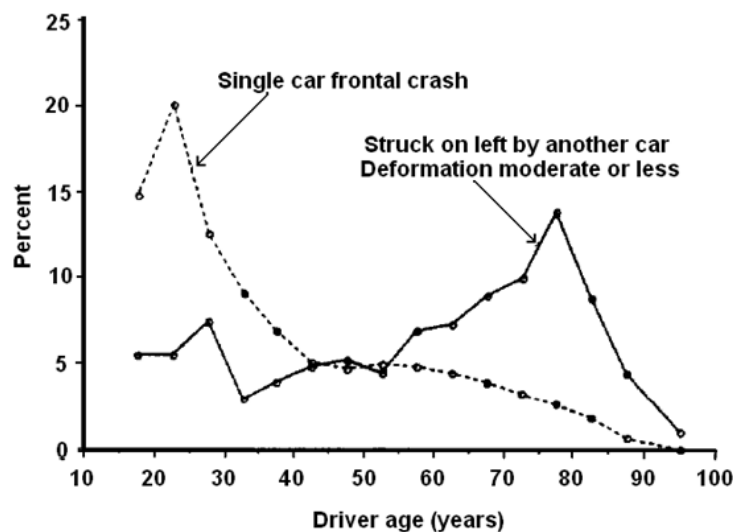


Figure 1. Percent involvement of occupants in single vehicle frontal and nearside crashes with moderate or less damage as a function of the age of the fatally injured victim (from 1973-1986 FARS). (Viano et al., 1990, p. 184)

impacts is a function both of increased propensity to have this type of accidents, and of increased frailty.) Figure 5 shows the age distribution for these side impact crashes, and for comparison, for frontal crashes as well. Percents sum to 100 across all ages for each crash type. Viano et al. concluded that “Changes in visual perception, judgment, and attention of the older driver may be factors in their missing a traffic signal or turning in front of traffic under the right-of-way.” (p. 177).

Austin and Faigin (2003) analyzed 1997-2001 NASS-GES records of police-reported crashes, and “confirm[ed] the continued overinvolvement of older occupants, particularly drivers, in side impact collisions at intersections and while making turns.” (p. 445).

Accident Responsibility

Williams and Shabanova (2003) analyzed 1996-2000 FARS data (42,028 two-passenger-vehicle collisions resulting in 50,345 fatalities). For each age cohort (5-year bins under 30, 10-year bins from 30 to 69, 5-year bins from 70 to 84, and a single 85+ bin) they calculated the percent of deaths for which drivers were found responsible (including their own). Drivers aged 40-59 were found responsible by police for 36% of deaths in two-vehicle collisions that they were involved in. Beginning from age 70 to 74, older drivers were responsible for 56%, 67%, 77%, and 83% of their crash fatalities with each successive 5-year age cohort.

Hakamies-Blomqvist (1993) examined accident reports from multi-disciplinary crash investigation teams deployed to fatal crash sites in Finland from 1984 to 1989, and identified the primary causal and contributing factors. Considering only multiple-vehicle crashes, older drivers were found at fault for 87 per cent of their crashes, compared to 50

per cent for the younger group. In addition, older drivers were more likely to have collided at intersections with a crossing vehicle because they either did not notice it or saw it too late to avoid. Observation error was the direct cause of 58% all fatal crashes for which older drivers were responsible, compared to 31% for younger drivers.

Most recently, Eustace and Wei (2010) examined FARS data from 2001 to 2003, and the driver errors associated with those fatal crashes. They noted that while drivers 16-19 years of age and drivers 75 and older accounted for 6.4% of travel in 2001 (from NHTS 2001 data), they accounted for 83.1% of the fatal crashes caused by driver error. They computed three metrics to assess the responsibility grouped by age and gender for fatal crashes. The numerator for each metric was driver error accidents of an age and gender group, and the denominator (i.e., risk exposure) was either drivers in the group, not-at-fault accidents incurred by the group (i.e., induced exposure), or annual mileage by the group respectively. Figure 6 shows at-fault accidents by driver age per billion miles of travel

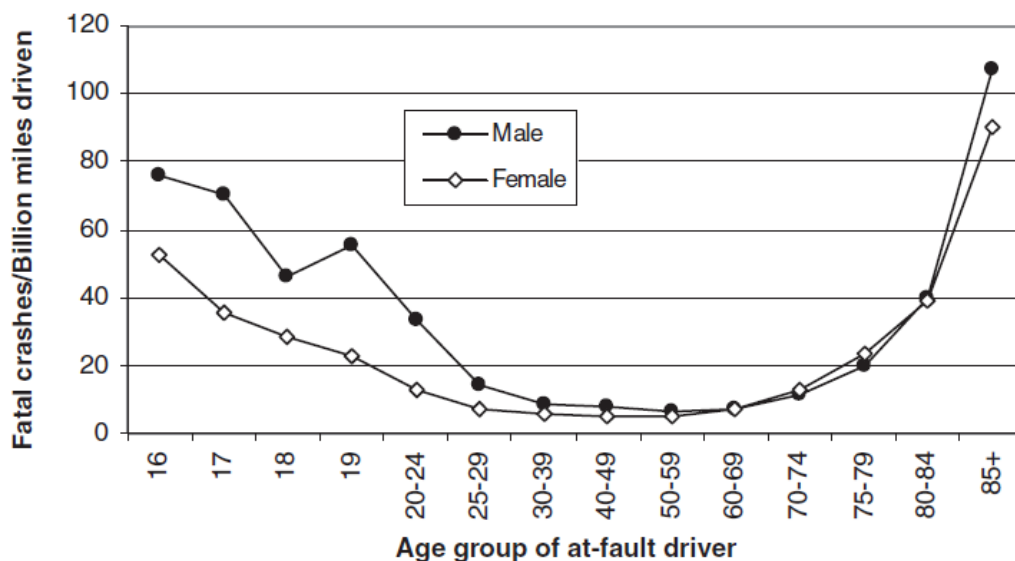


Figure 6. Single and two-passenger vehicle fatal crashes per billion miles of travel for which drivers were likely responsible, 2001-2003 (Eustace & Wei, 2010, p. 38)

More specific analysis of driver error types showed that failure to yield right of way was the only error that increased with age, beginning at about 5% of driver error-related fatal crashes until it increased for drivers in their fifties, rising to 40% for drivers 85 years and older, as shown in Figure 7.

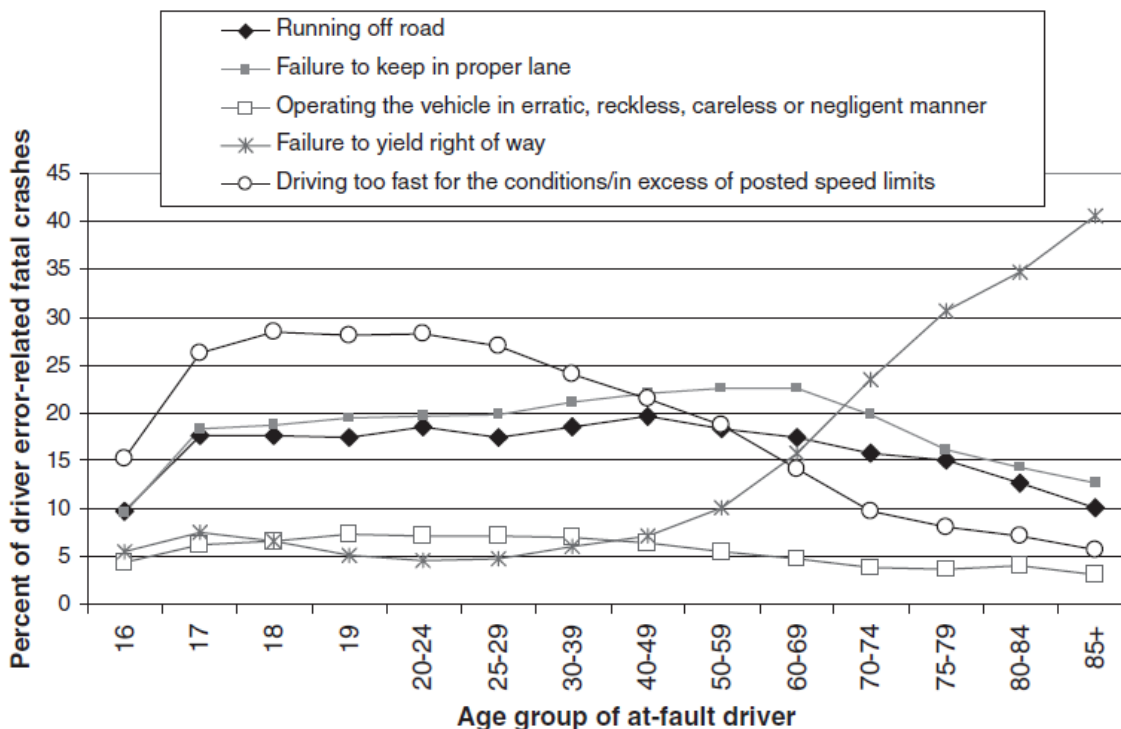


Figure 7. The top five driver errors responsible for passenger vehicle fatal crashes, 2001-2003 (Eustace & Wei, 2010, p. 33).

That figure is very consistent with the finding of Summala and Mikkola (1994) that among the five largest categories of primary non-alcohol causal factors for 1,357 fatal multi-vehicle accidents, only “failures of attention” (including detection) increase with age, as shown in Figure 8. Eustace and Wei also found that about 20% of young and

middle-aged drivers' fatal crashes occurred at intersections, but that figure rose to 30% for 60-69 year old drivers and to 50% for drivers 80 and older.

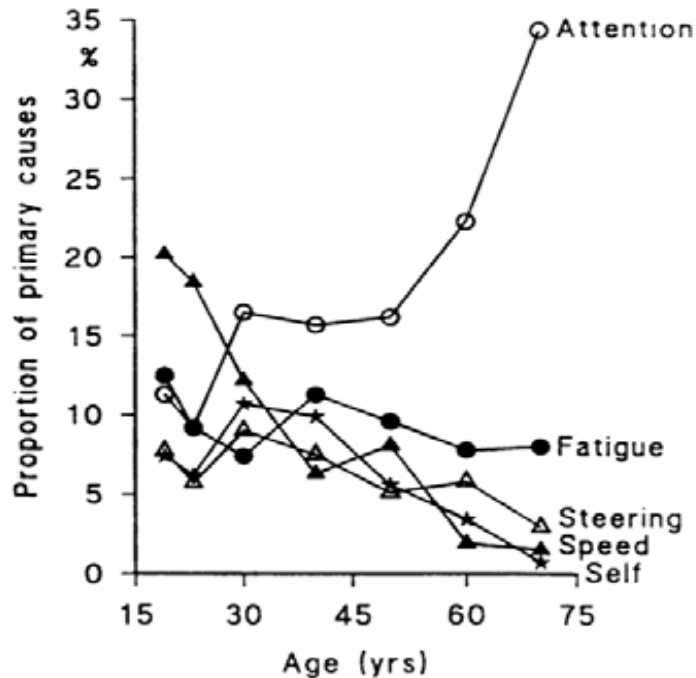


Figure 2. Attention failure accidents, by age (Summala & Mikkola, 1994, p. 321).

In summary, older drivers have more accidents per distance driven than middle-aged drivers in all jurisdictions, and older drivers are more likely to be found at fault when involved in an accident. The characteristic accidents of older drivers involve right-of-way violations at intersections, and the majority of those accidents involve failure to detect an approaching vehicle, although some may result from a gap estimation error (due to an age-related deficit in estimating an approaching vehicle's speed and time to contact).

Vision Measures and Driving

Most of the information necessary to drive safely is acquired through the visual system, which is not to say that many cognitive and physical functions are not also critical to safe driving. Nevertheless, impairment of a critical function of visual

perception may well affect critical functions later in the information processing continuum (from sensory to perceptual to cognitive). Furthermore, diseases associated with aging (e.g., Alzheimer's disease, Parkinson's disease, and stroke) which are widely thought to affect cognitive and physical function respectively, may also directly affect critical visual functions. I will touch on that issue in the general discussion section. However, the focus of this review is on visual function in healthy aging drivers.

Although transportation experts and regulators agree that vision is important for driving safely, current regulations do not reflect that understanding. Strauss (2005) observed that "... current U.S. Vision Standards for Driver's Licenses stem from antiquated 1937 visual standards, a 1925 report approved by the American Medical Association, and widespread implementations and modifications of the Snellen Eye Chart of the 1860s" (p. 57). NHTSA's current (2010) *Physician's Guide to Assessing and Counseling Older Drivers* offers a functional test battery, the Assessment of Driving Related Skills (ADReS), for the practical office use of physicians charged with assessing older patients' fitness to drive. However, the only visual assessments in ADReS are of visual acuity and visual fields, although the *Guide* does acknowledge that visual functions important for driving that are not assessed by the battery include contrast sensitivity, angular movement sensitivity, dynamic visual acuity, depth perception, and colour vision.

Visual acuity. Visual acuity (VA) declines strongly and monotonically with age from the age of 18 (Owsley et al., 1983; Salthouse, 1996). However, although widely used by most licensing authorities around the world to assess older drivers, VA is a poor predictor of older driver performance (Wood & Owen, 2005) or accident risk (Cross, McGwin, Rubin, Ball, West, Roenker, & Owsley, 2009; Keffe, Jin, Weih, McCarty &

Taylor, 2002), although Rabbitt and Parker (2002) did find that VA was significantly associated with older driver performance, but not with their accident involvement. Visual acuity most likely has some relation to the distance at which signage can be read, which arguably has more to do with wayfinding than with safety.

Although the authors of the *Physicians Guide – Assessing and Counseling Older Drivers*, 2nd Ed. (NHTSA, 2010) stated that Levy (1995) “... concluded that tests of visual acuity were associated with a lower fatal crash risk for older drivers.” (p. 69), in fact Levy simply compared older driver licensure rates between states that did or did not have renewal tests (e.g., vision, knowledge and road tests) and found that fewer older drivers maintained their licenses in states with renewal tests (i.e., vision and road tests in particular). Although Levy hypothesized that the decrease in older drivers due to the presence of renewal tests resulted in turn in fewer older driver fatalities, he did not investigate the hypothesis that tests of visual acuity are able to identify higher risk older drivers. Furthermore, he did not investigate whether older drivers failed the renewal tests or did not participate in the renewal process. Therefore, it may be that some older drivers are simply unwilling to renew their licenses if faced with renewal tests that may be anticipated as onerous and difficult to pass. The impact on licensure rates would be the same.

Dynamic visual acuity. The first important study to use a visual perception test battery to assess driver accident risk factors (including aging) was conducted by Burg in 1964, the last year of baby boomer births. Numerous analyses and reports from that research, which involved the participation of over 17,000 California drivers, who incurred a total of 5,200 accidents in their 3 year accident histories, were published by

Burg (1967, 1968, 1971), Henderson and Burg (1974), and Hills and Burg (1977). Burg's main finding was that dynamic visual acuity (DVA) – a measure of the ability to resolve a visual acuity target (i.e., a checkerboard pattern) in motion at 90 or 120 degrees per second – was the strongest visual predictor of accident risk, particularly among older drivers. However, visual function tests, including DVA, were very weak predictors of accident involvement, and only achieved significance due to the massive size of Burg's sample.

Henderson and Burg (1974) constructed a device for automated measurement of the visual functions, including DVA, that had been laboriously tested in the earlier work. Of interest is that in pilot testing of the measures, DVA was found to have such low test-retest reliability that it was dropped from the device's test battery.

Hills and Burg (1977) carried out a reanalysis of the 1967 study data including accident rates and performance on six vision tests from over 14,000 drivers, broken out into four age groupings: under 25, 25-39, 40-54, and 55+. They concluded that vision tests significantly predicted accident involvement only in the 55+ age group, and furthermore that “although significant, the very low correlation coefficients indicate that the accident prediction value of these tests is very low” (p. 13). They reported specifically that with a sample of 2,933 drivers 55+ years of age, the Pearson Product-Moment correlation between DMV accident rate and DVA (90 degrees/sec) was .054 ($p < .05$).

Nevertheless, Burg's results were the first to show the involvement of motion processing in the accident risk of aging drivers.

Contrast sensitivity charts. Driving researchers commonly assess contrast sensitivity (CS) for stationary stimuli in central vision with Pelli-Robson low contrast

letter charts (Pelli, Robson, & Wilkins, 1988) or Vistech three-alternative printed gratings (Ginsburg, 1984). These charts have been validated against oscilloscope-based forced-choice contrast sensitivity performance (Leat & Woo, 1997). Some studies have found a moderate to strong association between CS and driving performance (Janke & Hersch, 1997), self-reported driving performance (Schieber, Kline, Kline, & Fozard, 1992) or accident risk (Hennessy, 1995; Brown, Greaney, Mitchel, & Lee, 1993, as cited in Hennessy & Janke, 2009), while others have not (Cross et al., 2009). Note that these CS assessments present stationary stimuli to central vision.

Useful Field of View. To date, the Useful Field of View (UFOV®) subtests offer the most powerful visual assessment of older driver accident risk. The same procedure is applied in all three subtests. In the speed of processing subtest, participants are required to indicate whether they perceive the silhouette of a car or truck in the center of the monitor. Display time of the stimulus is manipulated across trials. The divided attention subtest requires the participant to simultaneously locate a car presented eccentrically while identifying the central stimulus (a car or a truck). In the selective attention subtest, the peripheral and central stimuli are surrounded with visual distracters (triangles), with the same response as in the divided attention subtest. Performance (milliseconds) corresponds to the threshold at which a participant is able to detect the target information.

These tests are known to be valid and reliable instruments for identifying older drivers with a history of prior accidents (Ball et al, 1993; Clay, Wadley, Edwards, Roth, Roenker, & Ball, 2005; Goode, Ball, Sloane, Roenker, Roth, Myers, & Owsley, 1998; Owsley et al., 1991; Sims, Owsley, Allman, Ball, & Smoot, 1998), predicting subsequent motor vehicle collisions (Ball, Roenker, Wadley, et al., 2006; Clay et al., 2005; Cross et

al., 2009; Rubin et al., 2007; Sims, McGwin, Allman, Ball, & Owsley, 2000), and predicting performance in a driving simulator (Roenker, Cissel, Ball, Wadley, & Edwards, 2003). UFOV® has also been found to correlate with driving performance on closed (Wood, 2002; Wood & Troubeck, 1995) and open road circuits (De Raedt & Ponjaert-Kristoffersen, 2000; Roenker et al., 2003), and to correlate with self-report assessments of driving ability (van Rijn et al., 2002).

Hoffman (2005) observed that "The levels of sensitivity and specificity in accident prediction reported by the creators of the UFOV have so far not been replicated in studies in which participants were not oversampled for accident frequency (Brown, Greaney, & Mitchel, 1993, cited in Harris, 1999; Hennessey, 1995, cited in Staplin, Lococo, Stewart, & Decina, 1999)." (p. 611). (Like Hoffman, I have been unable to secure copies of Brown et al. (1993) or Hennessey (1995) as they are privately held.) However, Clay et al. (2005) reported in the discussion following their meta-analysis of UFOV research that a convenience sample of 2,114 older drivers renewing their drivers' licenses at three Maryland DMVs were evaluated by a brief test battery that included UFOV Subtest 2. Participants with poor UFOV2 performance were more than two times as likely to have an at-fault crash (adjusted for exposure) in the 2.5 years following the assessment. Although Clay et al. cited an abstract apparently published in *The Gerontologist* in 2001, I was unable to retrieve the abstract although other abstracts and articles were available from that journal, so I surmise that information on that study was likely not available to Hoffman in 2005.

An additional issue regarding UFOV as a screening tool is that it taxes sensory, attentional and cognitive capacities, which the developers have presented as an

advantage, given the complexities of the driving task (Ball & Owsley, 1991; Ball et al., 1993; Owsley et al., 1991). However, because it overlaps many other assessment tools' scope, when included in a well-chosen test battery it may not be included in the optimum regression model given the predictive contribution of more specific overlapping tests (see for example Wood, Anstey et al, 2008).

Sekuler, Bennett, and Mamelak (2000) compared the performance of 176 observers from 15 to 84 years of age on modified UFOV tasks: focused attention (peripheral localization); focused attention (central identification of a letter from a four-letter set); and divided attention (peripheral localization concurrently with central identification). The two focused attention tasks were presented in separate blocks. (The UFOV condition missing from their study was *selective attention*, or peripheral localization with distracters, and their condition not found in most other UFOV studies was peripheral localization without central identification). They found a large interaction between age and attention condition (focused vs. divided) on the peripheral localization task, indicating that "the detrimental effect of dividing attention generally increased with age" (p. 113). Surprisingly, they also found that errors in peripheral localization (both focused and divided) began to increase from the 15-25 year old group to the 55-65 year old group, and increased more steeply above that age. Finally, because peripheral localization decreased with increasing eccentricity at the same rate for all ages, they concluded, in contrast to Ball, Beard, Roenker, Miller, and Griggs (1988), and Ball et al. (1993), that the UFOV is not *constricted* in older observers, but rather, "*The UFOV size is the same, but within the UFOV older observers process information less efficiently* [and]

... The difference in efficiency between young and old observers increases under divided-attention conditions" (p. 118, italics in the original).

Vision measures in combination. As part of the Salisbury Eye Evaluation (SEE) Project, Cross et al. (2009) measured visual acuity (EDTRS chart, log minimum angle resolvable or logMAR), Pelli-Robson contrast sensitivity and UFOV performance of over 3,000 older drivers (an aggregation of four samples). None of the samples was representative of healthy older drivers in general (that is, one had been selected to have half the sample accident-involved within the previous five years, another was evenly split between drivers with and without cataracts, a third sample was evenly split between drivers with or without impaired UFOV, and the fourth and largest sample of 2520 drivers had various types and degrees of visual impairment). After measurement, drivers' subsequent police-reported accident data were collected for the next several years. A total of 363 accidents occurred. Cross et al. found no association between visual acuity and crashes, no association between Pelli-Robson contrast sensitivity and crashes, and a strong association between UFOV scores and crashes.

Schlag (1993) conducted off-road laboratory tests of 80 older drivers and reported strong age effects relative to 30 middle-aged drivers, but found little age-related overall difference in driving performance on an on-road test of those drivers, although some increase in errors at intersections was noted (e.g., red-light running, presumable from a failure to detect the traffic light). Schlag suggested three possible reasons for the low association: even the 5-10% of older drivers that may be high-risk would be unsafe only in extreme situations and would not often manifest risk behaviour in a driving test; psychophysical tests may be more sensitive to age than the road test in his study; or the

functional capacities measured in the laboratory may not be as relevant as expect to the driving task and that older drivers may compensate for these functional declines.

Hoffman, DeDowd, Atchley and Dubinsky (2005) tested the performance of 155 normal adult drivers between 63 and 87 years of age on UFOV and on DriverScan (a change detection task using the flicker paradigm in which an original and a modified scene are alternately presented for 200-400 msec, separated by a 60-100 msec uniform equiluminant mask, until the change is detected). Contrast sensitivity (VisTech 6500 Contrast Sensitivity Chart, requiring 3-alternative orientation choices to sine-wave patches varying in spatial frequency from 1.5 cpd to 18 cpd, and at one of eight contrast levels), and binocular Snellen acuity were also measured. Three-year prior accident history and driving simulator performance provided two dependent measures of accident risk. Considered separately, DriverScan scores and UFOV scores account for 36% and 34% respectively of the variance in simulator performance, although neither DriverScan nor UFOV significantly predicted prior accident involvement. Because neither VisTech contrast sensitivity nor Snellen visual acuity significantly predicted simulator performance, Hoffman et al. suggested that higher level attentional processes were more likely than basic sensory visual processes to account for driving impairment in older drivers. However, their results may simply demonstrate that VisTech contrast sensitivity and Snellen acuity are not appropriate measures of a basic sensory visual process that drives bottom-up visual attention.

Hoffman et al. also noted that as screening tools, UFOV and DriverScan were “mediocre at best”, given that DriverScan had a 35% false positive rate at the best sensitivity rate of 71%, and that UFOV had a 48% false positive rate at the best

sensitivity rate of 85%. They concluded that although visual attention deficits were often suggested as the primary deficit of unsafe older drivers, little emphasis had been placed on developing tools for assessing individual differences in that function.

Contrast Sensitivity and Aging

After about 60 years of age, contrast sensitivity for stationary gratings in central vision falls off at middle and high spatial frequencies and remains unchanged for spatial frequencies at or below 1 cycle per degree (cpd) (Derefeldt, Lennerstrand, & Lundh, 1979; Owsley et al, 1983), although Scheffrin, Tregear, Harvey and Werner (1999) used a temporal two-alternative forced choice methodology to demonstrate age-related scotopic contrast sensitivity declines for stationary gratings at or below 1.2 cpd presented at 6° of nasal eccentricity. Owsley and Sloan (1987) measured contrast sensitivity for gratings from .5 to 22.8 cpd using the method of increasing contrast (which is not criterion-free) and reported that contrast sensitivity dropped significantly after 60 years of age for 6 cpd gratings and above. In addition, they found that low and intermediate (i.e., 6 cpd) contrast sensitivity related most strongly to the ability to detect and recognize faces, road signs, and commonplace objects. Similarly, Owsley et al. (1983) measured contrast sensitivity using a von Békésy tracking task in which grating contrast increased until participant detected the grating and pushed a response button, whereupon the grating contrast decreased until participant no longer detected the grating and released the button, continuing for eight contrast reversals. Although not criterion-free, the method is very fast. Owsley et al. found that stationary contrast sensitivity for 2 cpd and above fell with age, beginning for 4 cpd and above at 40 to 50 years of age, and for 2 cpd at about 70 years of age. Owsley et al. also examined contrast sensitivity for a 1 cpd grating drifted at

1.1 or 4.3 degrees per second, and found that participants in their 20s were able to detect a faster grating at 1/4 to 1/5 the contrast of a stationary grating, while “motion enhancement” fell to a factor of less than two for participants over the age of 70. They showed that although a substantial part of the age-related contrast sensitivity reduction for stationary gratings was due to reduced retinal illumination and increased scatter, the motion enhancement deficit was not.

In a seminal study, Sekuler and Hutman (1980) used a von Békésy tracking task to measure the contrast sensitivity functions (CSF) of young ($M = 18.5$, $sd = .7$, $n = 25$) and old ($M = 73.2$, $sd = 3.8$, $n = 10$) participants for sine wave gratings presented to central vision and counter-phase flickered at .33 Hz or 6 Hz. For both temporal frequencies, the older participants showed the largest deficit relative to the young participants at the lowest spatial frequency of .5 cpd, with the relative deficit decreasing to zero by 16 cpd (see Figure 9, from Sekuler & Hutman, 1980, p. 694).

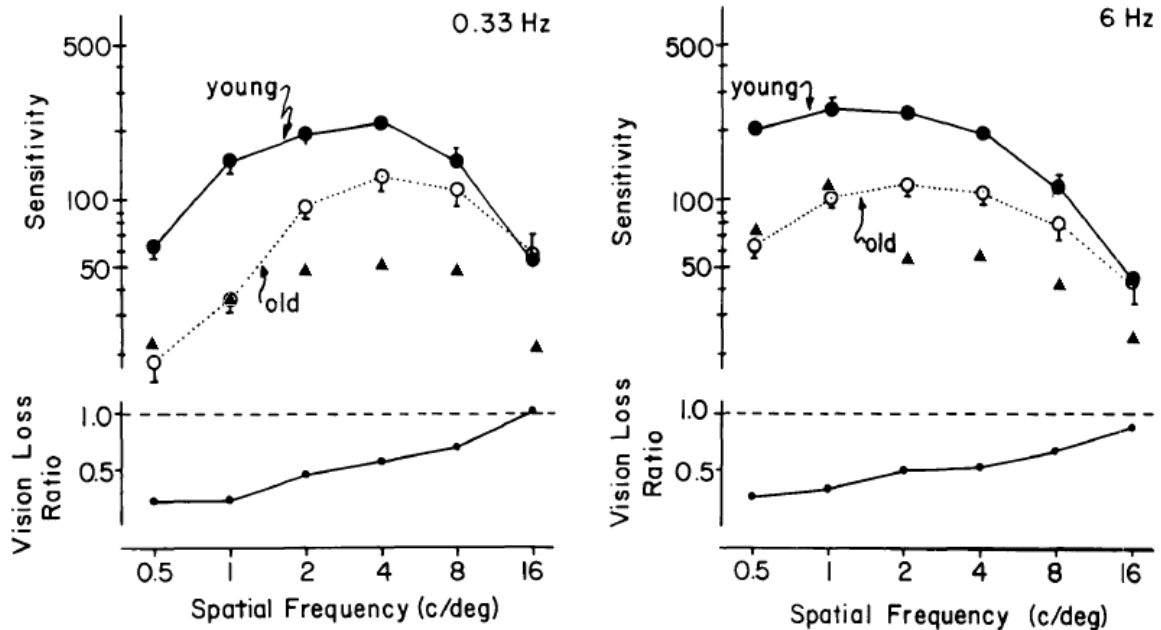


Figure 9. CSF (± 1 standard error) of young and old participants for 0.3 and 6.0 hz flicker. The ratio of older to younger sensitivity is plotted at the bottom of the graph. Triangles show macular degeneration participant. (Sekuler & Hutman, 1980, p. 694).

In their words, they found “... an age difference primarily at the low spatial frequencies, with the older age group the less sensitive.” (p. 695). They also showed that the finding was not due to optical pathology, including normal optical factors of aging such as senile meiosis (reducing retinal illumination) or cataract, and proposed that the reduced sensitivity is due to a neural loss in the subsystem used to detect low spatial frequency, temporally transient targets. Furthermore, in an immediately following article in the same journal, Hutman and Sekuler (1980) demonstrated that the results were not due to an age-related criterion shift.

Sekular, Hutman and Owsley (1980) reported the same results, as well as results from an additional study comparing the contrast sensitivity of younger (20.2 ± 3.1 years, $n = 25$) and older (75.0 ± 4.8 years, $n = 8$) participants for a 1 cpd grating drifted at 0.5 or 10.0 hz. As shown in Figure 10 (Sekuler, Hutman, & Owsley, 1980, p. 1256), the older participants were much less sensitive than the younger participants to the drifting grating, particularly at the higher drift rate ($p < .001$), and the age by drift rate interaction was significant as well ($p < .002$).

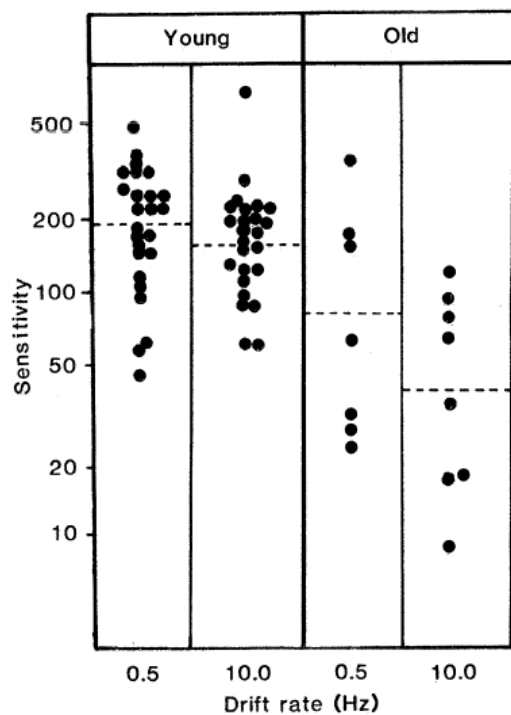


Figure 3. Contrast sensitivity of young and old participants for 1 cycle per degree gratings drifting at either .05 hz or 10.0 hz. Dashed lines indicate mean thresholds (Sekuler, Hutman, & Owsley, 1980, p. 1256).

Schefrin et al. (1999) used a T2AFC procedure to measure the scotopic contrast sensitivity functions of 50 participants ranging from 20 to 88 years of age, with 13 older than 65 years of age. The test stimulus was a stationary Gabor (a sine wave grating between 0.2 and 3.0 cpd in a Gaussian spatial window) presented in a 1-second Gaussian

temporal window, presented at 6 degrees of nasal eccentricity. Statistically significant age-related losses were reported for gratings at or below 1.2 cpd, with age accounting for 41% of the variance in contrast sensitivity for 0.2 and 0.4 cpd stimuli, dropping to 31% and 28% for 0.8 and 1.2 cpd stimuli respectively. They concluded that the age-related scotopic contrast sensitivity loss was most likely due to neural factors rather than optical factors, and that their results were due to age-related changes in magnocellular pathways.

Stationary Contrast Sensitivity (CRT Presentation) and Driving

Schieber et al. (1992) related contrast sensitivity, measured for central stationary gratings presented on a CRT to a survey questionnaire of driving experience and perception entitled *Your Vision Survey*. The questionnaire (Sekuler, Kline, & Kosnik, 1988) consisted of demographic questions, questions about the levels of difficulty associated with everyday visual tasks, questions about participants' driving experience, followed by 8 items designed to assess any difficulty participants experienced carrying out various visually based driving tasks. A sample of 397 survey participants from the Baltimore Longitudinal study on Aging (BLSA) were drivers between 22 and 92 years of age, with 184 between 60 and 79, and with 59 at least 80 years of age. After eliminating the (mostly older driver) data of former drivers, daytime-only drivers, and drivers reporting serious eye diseases, survey data from 333 drivers were analyzed. Principal components factor analysis was applied to the survey data and five factors were identified, with only one loading on age. After age, 9 of the 18 survey items loaded on the *Age-related Visual Driving Problems* factor, with the five most strongly related items being (in order): difficulty judging vehicle speed; self-rated overall visual quality; being surprised by vehicles when merging; unexpected appearance of vehicles in the peripheral

visual field; and other vehicles moving too quickly. Note that most of these items relate to motion processing and visual attention.

Contrast sensitivity of 225 of the survey participants (86 drivers 60-79, and 8 drivers 80+) was measured using a spatial two-alternative forced choice (S2AFC) staircase procedure. Stationary vertical sine wave gratings were presented on a monochrome CRT at .5, 1, 2, 4, 8, and 16 cycles per degree (cpd) in either the top or bottom half of a 6 degree by 6 degree area. Data across the 6 spatial frequencies were summarized by peak contrast sensitivity, and high and low cutoff spatial frequencies (the spatial frequencies at which contrast sensitivity fell to less than half of the peak contrast sensitivity). All three aggregate measures were significantly correlated with age (peak contrast sensitivity ($r_{233} = -0.24$, $p < .01$), low cutoff frequency ($r_{233} = -0.26$, $p < .001$), high cutoff frequency $r_{233} = -0.31$, $p < .05$). Peak contrast sensitivity and low cutoff frequency remained unchanged to the age of 60, then fell precipitously, while high cutoff frequency declined gradually from the age of 40.

Results of a canonical correlation analysis determined that the three summary CSF measures related very strongly to the questionnaire items associated with the *Age-related visual driving problems* factor.

Schieber et al. noted that their result relating "the magnitude and frequency of *self-reported visual problems* ... to more objective measures of visual function and status - namely, the *contrast sensitivity function* ... offers *strong support for both the reliability and validity of survey techniques* toward the characterization of the effectiveness of visual function in non-laboratory environments [my italics]." (p. 6).

They also noted that their older participants' reported difficulty estimating speed and correctly perceiving rapid traffic flows, and that older drivers recognized and compensated to some degree for their age-related visual declines. They concluded that the two survey items related to peripheral vision difficulties (i.e., unexpected appearance of vehicles in periphery, and tendency to be surprised by other vehicles when merging) indicated that "older drivers may be at least partially aware of the [age-related] emergence of a sort of functional tunnel vision" (p. 6), and that age-related functional deficits impair some older drivers' ability to detect vehicles in their visual periphery.

Other Motion Sensitivity Measures

Motion and driving. Gabaude and Ficout (2005) contrasted 20 accident-prone older drivers (age 61-80) with 20 control drivers. Participants completed three visual and four cognitive lab tests, and an on-road driving assessment in traffic. Movement perception (Ergovision) and "Zazzo time" (time to complete the Zazzo crossing-out task - a neuropsychological test for cognitive impairment) significantly predicted accident risk when age and group were controlled for in a regression analysis.

Motion perception (Ergovision) was the only vision test to significantly predict driving performance in the on-road test. Visual acuity and "low-contrast vision" (apparently a contrast sensitivity type test) did not.

De Raedt and Ponjaert-Kristoffersen (2000) tested 84 older drivers using a commercial visual assessment device (Ergovision, ESSILOR., now of Bristol, UK) which assessed movement perception by presenting moving arrow structures, with participants indicating their direction of motion. They found that movement perception significantly predicted on-road test score ($r = .73$) but not accident record ($r = -.26$, ns), while

UFOV[®] significantly predicted both on- road test score ($r = -.66$) and accident record ($r = .32$).

Using a test battery containing 20 visual, cognitive, and physical measures to predict on-road test performance of a randomly selected sample of 270 drivers over 70 years of age, Wood et al. (2008) determined through stepwise regression that the most parsimonious model contained four variables, with motion detection as the only vision measure. (UFOV2 was eliminated.) The model was highly significant (Cox-Snell $R^2 = .26, p < .01$). The motion detection measure was the minimum coherent dot displacement that could be detected in a random dot array spanning 2.9 degrees of visual angle (VA).

Conlon and Herkes (2008) noted from the literature that magnocellular pathways show an age-related deficit, and proposed two motion processing tests as predictors of a driving self-report questionnaire. The tests were: a) *global motion sensitivity*, a comparative speed judgment between two adjacent moving random dot patches spanning in total 14 degrees VA high and 25 degrees VA wide, and b) a *rapid visual sequencing task* using a stimulus spanning 0.3 degrees VA. Thirty-three older and thirty-five younger participants filled out a driving self-report questionnaire, and a factor analysis was carried out. “Three factors were produced ... The first and only robust factor combined items that evaluated reported difficulties when *perceiving other vehicles or road signs*” (p. 467, italics theirs). *Global motion sensitivity* was significantly related to *perception of other vehicles and road signs* ($r = -.41, p < .001$). Note that the *global motion sensitivity* stimulus fell mostly in the near visual periphery. *Rapid visual sequencing* was not significantly related to any questionnaire measure.

Raghuram and Lakshminarayanan (2006) tested a small sample of 15 older drivers on several measures, including a comparative speed judgment between two adjacent high-contrast 2 cycle/degree sine wave gratings, drifting at 2 or 8 degrees VA/second, depending on condition. Each grating spanned 1.5 degrees VA square, and they were separated by a 1.5 degrees VA square with a central fixation point. The outcome measure was a driving questionnaire. Driving difficulty was significantly predicted by speed discrimination at 2 degrees VA/second ($r = -.717, p = .003$), and by VISTECH CS ($r = .525, p < .05$).

Peripheral motion and aging. In a seminal investigation of age effects on motion detection thresholds in central and peripheral vision, Atchley and Anderson (1998) measured random dot coherence thresholds of 20 younger participants (10 men averaging 22.4 years of age and 10 women averaging 23.3 years of age) and 20 older participants (10 men averaging 68.7 years of age and 10 women averaging 70.7 years of age). Minimum random dot coherence thresholds for detecting laminar flow (uniform translation or horizontal motion) in random dot kinematograms subtending 10 degrees of visual angle were presented at 0, 10, 20, and 40 degrees of eccentricity and at dot velocities of 4.8 or 22.0 degrees/second (corresponding to walking and driving speed respectively). The method of adjustment was used.

Figure 11 shows graphically the significant three-way interaction of Age, Retinal Eccentricity and Target Speed. The Age by Retinal Eccentricity interaction was only significant in the high stimulus speed condition (corresponding to optical flow during driving), and within that condition younger coherence thresholds were significantly lower

(better) than older coherence thresholds at 0, 10, and 20 degrees of eccentricity.

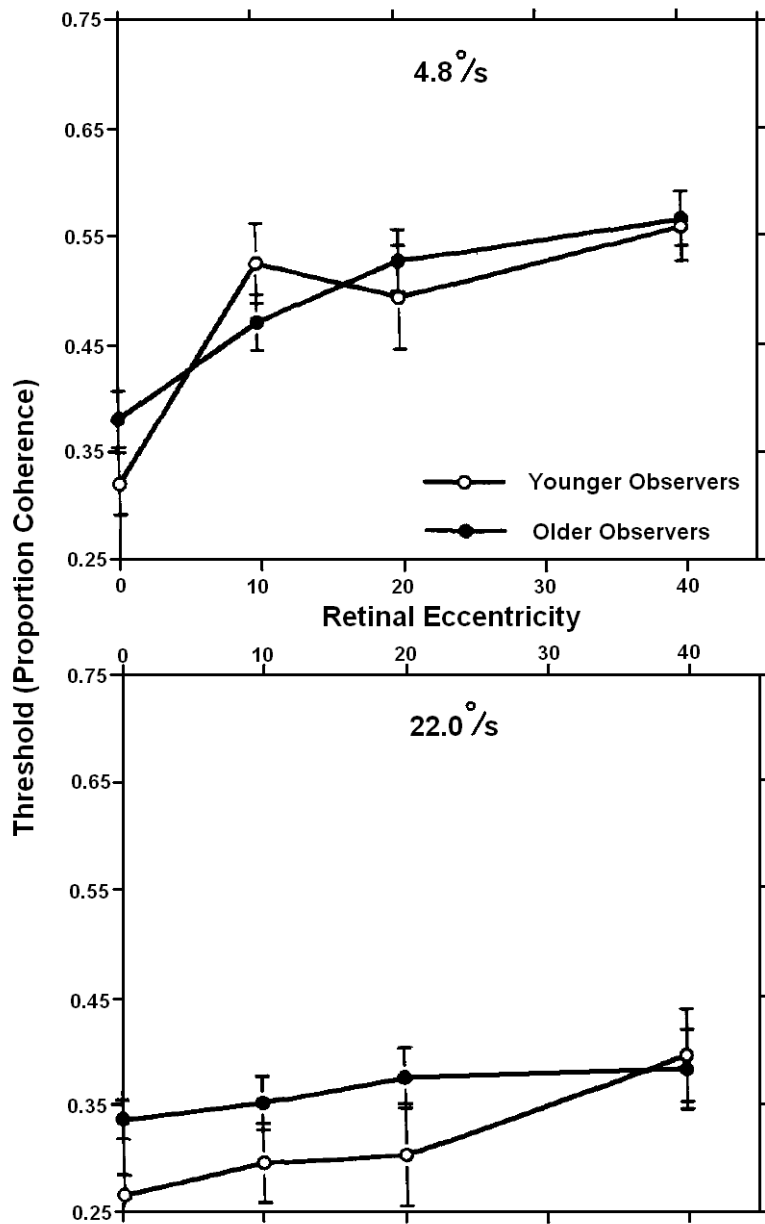


Figure 11. A graph of the interaction of age, retinal eccentricity, and target speed for perception of lamellar flow. (Atchley & Anderson, 1998, p. 301).

Although they only tested in central vision, Wood and Bullimore (1995) also showed that random dot displacement detection thresholds became significantly poorer

with age, as did both high and low contrast visual acuity and contrast sensitivity (i.e., r of .5 to .6).

Taken together, these driving and/or motion studies demonstrate the important contribution that visual motion processing makes to safe driving, and that aging affects that important visual function in some drivers.

Test Batteries

Staplin and coworkers have arguably developed and tested the most extensive visual function test batteries to date. Staplin, Lococo, McKnight, McKnight, and Odenheimer (1998) carried out an extensive review of the literature regarding age-related decrements to sensory/perceptual, cognitive, and physical/psychomotor decrements, and regarding the impact of dementia on driving skills. In addition they reviewed the extant literature regarding older drivers' overrepresentation in intersection crashes and their behaviours leading to those crashes. Finally, they carried out a task analysis of intersection negotiation by older drivers. The review and task analysis of Staplin, Lococo et al. (1998) informed the development and validation by Staplin, Gish, Decina, Lococo and McKnight (1998) of a battery (*MultiCAD*) of functional tests for identifying older drivers with intersection negotiation problems. The *MultiCAD* battery included static and dynamic visual acuity, static and dynamic contrast sensitivity, sensitivity to relative motion of other vehicles in a driving video, divided attention in a braking scenario, detection of peripheral pedestrians and vehicles during a primary task in central vision, and head and neck flexibility. Eighty-two older drivers (mean age of 77) were referred for testing to the California Department of Motor Vehicles (DMV), with 26 labeled as cognitively impaired by the referrer, and 56 labeled as cognitively unimpaired. After

completing the test battery, all participants performed a familiar route test drive and an unfamiliar route accompanied by a DMV driving examiner who recorded intersection negotiation (and all other) driving errors, which were weighted according to the seriousness (i.e., danger) of the error. (Scanning errors were extremely common.) Correlational analyses were then applied to determine how strongly each MultiCAD functional test predicted driving performance (i.e., weighted DMV-recorded error score). In individual correlational tests for sensory visual functions (e.g., static and dynamic acuity for 20/40, 20/80, and 20/200 targets; static and dynamic contrast sensitivity for 20/40 and 20/80 high and low contrast targets), the response time (correct trials only) was a much better predictor of driving performance than was response accuracy. Significant Pearson Product-Moment correlations ranged from .25 to .42. For higher-level perceptual tests such as divided attention braking and peripheral threats with a concurrent central task, however, response accuracy rather than response time significantly predicted driving performance. Staplin et al. concluded that traffic controls substantially mitigated older drivers' tendency to commit driving errors while negotiating intersections. They concluded that functional status measurement was not sufficiently predictive to be useful in a practical setting. They concluded that the *MultiCAD* test battery took an excessive amount of time to administer (40 minutes) to be practical as a screening tool, which must be accomplished in some jurisdictions within 5 to 10 minutes. They concluded that their results did not indicate that a shorter test battery could be constructed from their tests and still have sufficient sensitivity and specificity to be usable in practice.

With one exception, the *Model Driver Screening and Evaluation Program* (Staplin, Lococo, Gish, & Decina, 2003) – which included the Maryland Pilot Older

Driver Study (MaryPODS) as the empirical component of the program – will not be discussed further in this review, as vision measures were not included in its *GRIMPS* test battery (although Staplin, Lococo et al. (2003) recommended that visual acuity, visual contrast sensitivity, and field of view, as well as more cognitive tests of visual function, such as directed visual search and visual (divided) attention processing speed, be included in any functional capacity screening battery for older drivers). The exception relates to the responses of senior Driver License Administrators (one from each state, totaling 47, and from each province or territory, totaling 12) to a survey question asking for a judgment as to the practical upper time limit for a functional test battery. Responses were evenly divided among the four offered alternatives of under 15 minutes, 15 to 30 minutes, 30 to 45 minutes, and 45 minutes to 1 hour (or no limit). In short, to be accepted across all jurisdictions, a test battery must require no more than 15 minutes to complete, aside from all other requirements regarding sensitivity and specificity.

Janke and Eberhard (1998) developed and conducted a pilot test of a test battery for assessing the competency of older drivers with chronic medical conditions or age-related functional decrements. Their intention was to determine which of the tests might be used in a graded licensing program. They proposed that such a program could consist of three assessment tiers, the first to be conducted quickly by trained staff at Department of Motor Vehicles (DMV) offices, the second consisting of longer and more elaborate tests of drivers who had failed the first tier or who had been referred by physicians, police officers, family members or concerned others, and the third consisting of a road test.

Two groups were tested. The referral group contained 75 older drivers who had been referred by the DMV for reexamination due to a medical condition, repeatedly

failing a licensing test, committing a flagrant driving error or showing some other indicator of possible driving impairment. The volunteer group contained 31 paid volunteers of approximately similar age (average referral age was 75.7 years while the average volunteer age was 68.4).

The test battery consisted of many proposed Tier 1 and Tier 2 tests, including cognitive, visual and physical measures. Visual tests included a modified standard-letter Snellen chart, Cue Recognition (a measure of perceptual speed in a simulator in response to simple cues to brake, turn, or choice RT to either), the Pelli-Robson test of low-contrast acuity (a letter chart with decreasing contrast from left to right and from top to bottom, often referred to in the literature as a test of contrast sensitivity), as well as several measures from *MultiCAD*, including automated tests of static and dynamic acuity (see Staplin, Gish, et al., 1998), static and dynamic contrast sensitivity, angular motion sensitivity (detecting relative motion of own versus other vehicles in a suburban driving video), and a measure of complex attention while watching a driving video (braking response to unexpected critical events in the visual periphery while responding appropriately to monitored events directly ahead), as described above.

Participants took part in two road tests that the California DMV developed specifically for the study from their prototype road test for both novice drivers and experienced but functionally impaired drivers. Road test additions included destination-finding tasks intended to tax cognitive function and spatial memory used for navigation. Two extensively trained DMV examiners, blind to drivers' performance on the non-driving test battery, conducted the road tests and recorded critical errors and hazardous errors (a subset of critical errors which included dangerous maneuvers or required

examiner intervention). Road test scores were adjusted by weighting hazardous errors by a factor of five and other critical errors by a factor of three to take error severity into account.

Prospective tier 1 tests were used to identify whether a participant was a referral or a volunteer. The best logistic regression model for predicting group membership (i.e., identifying referrals) included Pelli-Robson errors, number of observed problems (that is, subclinical behaviours potentially indicating impaired function), and Auto-Trails time (Auto-Trails is a modified, automated version of Trails A of the Trail Making Test, with the participant required to touch each of a set of numbers in increasing order, intended to detect dementia). The number of observed problems was by far the strongest predictor of group membership in the model; Pelli-Robson errors was the next strongest; and Auto-Trails added the least, perhaps because count of observed problems had already captured much of the variance in cognitive function. Despite the age difference between the two groups, age was not included in the model.

Multiple linear regressions were run to identify which prospective tier 2 tests best predicted road test scores. Although only a small number of referrals (29) and volunteers (9) completed all of the prospective tier 1 and tier 2 tests, the final regression model for referrals included the vision variables of dynamic contrast sensitivity errors and static acuity time in addition to two cognitive variables forced to enter the model, and the final model for all participants also added static acuity errors to that model.

Driving Measures

Questionnaires

Questionnaires have been widely accepted as valid dependent measures of driving performance and accident risk.

Manchester Driver Behaviour Questionnaire (DBQ). The first DBQ studies (Parker, Reason, Manstead, & Stradling, 1995; Reason, Manstead, Stradling, Baxter, & Campbell, 1990) surveyed driving samples across the whole driving age range, and using principal components analysis, identified three factors underlying self-reported driving behaviour : violations (deliberate deviations from rules and accepted safe practices), errors (intentional action with unintended consequences, including failures of attention), and slips and lapses (unintentional actions and failures of memory respectively, which are usually inconsequential). Reason et al. applied a principal components analysis to 520 drivers' responses to a 50-item DBQ, and identified a violation factor, which accounted for 22.6% of the total response variance, a dangerous error factor, which accounted for 6.5% of overall variance, and a low-risk error factor, which accounted for 3.9% of the overall variance. Reason et al. did not collect any accident data to empirically relate these factors to accident risk.

Parker et al. (1995) replicated the earlier study with 1,656 drivers spanning 17 to 69 years of age, using an abbreviated 24-item DBQ (questionnaire items which loaded most highly on one of the three factors), and self-reported accidents in the previous five years. A principal components analysis confirmed the presence of the three factors identified by Reason et al. (1990), and determined that together, they accounted for 37.4% of the overall score variance. Only violations were significantly associated with a

history of accidents, and violations declined significantly with age. No age effect was found for the other two factors (nor was it expected, given the truncated older age range and the relatively small proportion of drivers aged 60-69 included in the sample).

Parker, McDonald, Rabbitt, and Sutcliffe (2000) administered the 24-item DBQ to 1,989 drivers between 49 and 90 years of age (mean 66 years). Principal components analysis was again used to identify an error factor, which accounted for 21.1% of the total response variance, an aggressive violation factor, which accounted for 9.4% of total variance, a lapse factor, which accounted for 5.6% of the variance, and two additional factors which included a second violation factor (e.g., drunk-driving, speeding), and a factor which loaded on a remaining lapse item and a remaining violation item. Separate regression analyses to determine the associations between active (i.e., striking vehicle) and passive accidents (i.e., struck vehicle, such as violating another vehicle's ROW by pulling out from a stop sign) and these factors, were carried out. Age and annual mileage were also included as independent variables. In the restricted age range of the sample, age was not a significant predictor of prior accidents. After annual mileage, the error factor and lapse factor significantly predicted active accident liability (with errors and lapses contributing about equally to the model's predictive power), and the lapse factor significantly predicted passive accidents. Parker et al. calculated that drivers in the top fifth percentile for error and lapse scores were 3.42 times more likely to have been liable for an active accident than drivers in the bottom fifth percentile. In contrast to the full age samples which reported a predominance of violations, the older driver sample reported a predominance of errors, which loaded most strongly on questionnaire items dealing with failures of attention or detection such as not noticing pedestrians, not seeing yield signs

and nearly hitting a vehicle with the ROW, nearly hitting a cyclist to the side, underestimating the time to collision of an approaching vehicle when attempting a pass, and nearly rear-ending a vehicle to the front when trying to merge into traffic.

In summary, Parker et al. (1995) tested over a full age span and found that older drivers committed relatively more unintentional errors or lapses, while young and middle-aged drivers committed relatively more intentional violations, while Parker et al. (2000) tested only older drivers and determined that their elevated accident risk was strongly associated with unintentional errors or lapses.

The Manchester Driver Behaviour Questionnaire has been validated repeatedly by numerous researchers and in several different countries (Lajunen, Parker and Summala, 2004; Owsley, McGwin & McNeil, 2003; Özkan, Lajunen, & Summala, 2006; Özkan, Lajunen, Chliaoutakis, Parker, & Summala, 2006; Reimer, D'Ambrosio, Coughlin, Kafrissen, & Biederman, 2006; Verschuur & Hurts, 2008). De Winter and Dodou (2010) carried out a recent meta-analysis of 174 studies which used the DBQ, and showed that both DBQ errors and violations significantly predict self-reported accidents.

Driving Habits Questionnaire. Owsley, Stalvey, Wells, and Sloane (1999) developed and used the Driving Habits Questionnaire as part of their assessment of the impact of cataract on driving habits and crash risk. The questions ask mostly for concrete assessments of driving activity, with very few questions requiring any self-assessment of driving ability. The questionnaire is appended to Owsley et al. (1999) along with an assessment of test-retest reliability. Ball, Owsley and coworkers often use the questionnaire in their UFOV studies.

Visual Activities Questionnaire (VAQ). The VAQ (Sloane, Ball, Owsley, Bruni, & Roenker, 1992) was designed specifically for the older population, and contains 33 questions about problems carrying out everyday visual tasks, with responses given on a 5-point fully anchored rating scale spanning “never” to “always”. Ten items relate directly to the driving task. Factor analysis was used during the questionnaire’s development to identify 8 visual function factors, including peripheral vision, visual search, and visual processing speed. A battery of 9 visual function tests was also administered to 294 older drivers (mean age 71, range 56 to 90) during VAQ development as a test of criterion validity. Sloane et al. reported 51 significant correlations ($p < .05$) between the 8 VAQ Factor Composites (average scores of VAQ items loading on each factor) and the 9 clinical tests of visual function, with 4 correlations falling between .3 and .4, 19 between .2 and .3, and 28 under .2. Strangely, the highest correlation of .37 was between the VAQ factor “Acuity/Spatial Vision” and the “Contrast Sensitivity” visual function test. Sloane et al. wrote that the VAQ has “reasonable validity given the complexity of self-report judgments about health and behavior problems” (p. 13), that older adults self-reporting visual difficulties tend to demonstrate visual deficits on clinical tests, and that the VAQ may be a useful assessment tool in clinical settings and for epidemiological research.

Perceptions of Driving Skills Questionnaire. As discussed in the section on other motion sensitivity measures, Conlon and Herkes (2008) developed an 11 item questionnaire to measure older drivers’ self-assessed driving performance, and in particular their visual performance on numerous driving tasks and situations. Five of the questions were adapted from the Visual Activities Questionnaire developed by Sloane et

al. (1992). An exploratory factor analysis was used to uncover three factors. Only the first factor was robust, "... consisting of seven items dealing with reported difficulties with the perception of other vehicles or road signs" (p. 457).

In summary, several self-report questionnaires have proven very useful as a dependent measure of driving risk, and of visual deficits in general. The Manchester Driver Behaviour Questionnaire (DBQ) in particular has become the gold standard of self-reported accident risk, and is widely used by many researchers.

Review Summary and Research Rationale

Fatal accidents of older drivers per kilometre increase with age over 65 or 70 years of age, and that rate accelerates with age. At-fault fatal accidents per kilometre increase even more steeply with age than does overall fatal accident rate. Transportation researchers and policy-makers have expressed concern regarding this age-related accident risk, as the population over 65 will more than double over the next 30 years, and an increasing proportion of that population will be active drivers. Although frailty accounts for some of the age-related fatality increase, insurance-only crashes also show the same rising curve with age, albeit less extreme.

Older drivers are over-represented in multiple vehicle crashes at intersections, most often after they have committed the right-of-way (ROW) violation that caused the crash. Given an accident, the age of an older driver predicts the likelihood that they will be cited for a right-of-way violation. Of the five most common driving errors leading to accidents, only failure to yield ROW increases with age. Errors of attention (i.e., detection failures) are the primary age-related causal factor of intersection accidents. A

logical conclusion is that an age-related visual deficit is the underlying causal factor for much of the increase in accident rate with age.

Numerous vision measures have been used in an attempt to identify higher-risk drivers. Visual acuity is the most widely used and the least useful. Dynamic visual acuity (the ability to resolve a small fast-moving visual pattern) has a very slight but statistically significant relation to older driver accident rate. Contrast sensitivity charts (e.g., Pelli-Robson, Vistech) are convenient and fast assessment tools of the contrast sensitivity function for stationary targets in central vision, and some researchers have reported a significant correlation between chart scores and driving performance.

Useful Field of View is the most powerful and useful visual predictor of older driver accident risk to date, and shows that processing of dynamic stimuli in the visual periphery is an important function that is strongly related to driving safely. However, because UFOV subtests task not only low-level sensory functions, but also higher-level perceptual and cognitive functions associated with attention and decision-making, they overlap substantially with other more specialized assessment tools, and do not have sufficient sensitivity and specificity to use as a screening instrument for older drivers. Nevertheless, UFOV provides a strong indication that the age-related visual deficit associated with older driver accident risk involves processing of dynamic stimuli in the visual periphery.

Several researchers have developed other random dot or bespoke motion stimuli and tasks that also predict driving performance. Questionnaire measures have been found to yield reliable and valid measures of visual function and driving performance outside

the laboratory. The most rigorously designed and tested, and the most widely used, is the Manchester Driver Behaviour Questionnaire (DBQ).

Outside the driving domain, numerous investigators have demonstrated age-related deficits in contrast sensitivity for stationary low spatial frequency sine wave gratings in peripheral vision, drifting or counter-phase flickering low spatial frequency gratings in central vision, and coherence thresholds for random dot stimuli drifting in peripheral and central vision at a retinal velocity similar to that of the driving environment. The age-related contrast sensitivity decline at low spatial frequencies and high temporal frequencies is likely due to magnocellular channels' decline with age. The magnocellular channels are responsible for detecting movement, identifying its retinal location, and allocating attention to that location. Age-related magnocellular channel deficiencies would be expected to impair that function, which is precisely the visual function drivers use to detect and respond to approaching vehicles.

An optimal magnocellular channel stimulus is a low spatial frequency high temporal frequency sine wave grating. I propose therefore that the age-related deficit in orienting on and detecting approaching vehicles will be captured by measuring contrast sensitivity (or contrast threshold) for an optimal magnocellular channel stimulus presented in the visual periphery. If that deficit accounts for the increased accident risk of older drivers, then contrast sensitivity (or contrast threshold) will predict their driving performance and accident risk as measured by questionnaire responses and simulator performance.

III. Introduction to the First Study

The first study was the initial attempt to relate a newly developed measure of visual function to a new measure of accident risk, which had been constructed according to my hypothesis that some older drivers were experiencing their driving environment differently due to age-related changes in a low-level visual function that I proposed drove bottom-up or stimulus-driven visual attention. Further, I thought that those older drivers might attribute the change to external factors rather than to internal factors. Accordingly, the largest portion of the questionnaire asked about perceived changes to the speed of other vehicles, and only five questions asked directly about their experience rather than about expected misattributions. Although the questionnaire bears many similarities to some of the questionnaires cited in the literature review, it was in fact written from a blank sheet. I had completed its design by 1991, before any of the cited questionnaires except DBQ had been published, and DBQ was not applied specifically to an older population until 1995. I was not aware of the DBQ when I drafted the bespoke questionnaire.

I chose to test peripheral motion processing with drifting sine wave grating stimuli rather than with moving random dot stimuli. A random dot stimulus is visually complex, being composed of a broad range of spatial and temporal frequencies, while a drifting sine wave grating is composed of a single spatial and temporal frequency, which can be selected so as to make an optimal stimulus for the near peripheral visual field (Devalois and Devalois, 1990).

The personal experience that first presented me with the question of older drivers' visual functions and accident risk was a motorcycle accident that I was involved in at the

age of 19, when a driver 78 years of age turned left across my path on the highway, catapulting me through the air over his car and trailer until I impacted the road 75 feet from the initial collision. When I later met him and we discussed the accident, I came to understand that he had not seen me at all. That accident was prototypic of the accidents discussed in the literature review above, and it spurred my interest in a very important and deceptively simple question. That is, if most of the information needed to drive safely comes through visual channels, why have researchers not identified the visual function or functions that are critical for driving safely and that degrade with age?

**IV. Peripheral Motion Contrast Sensitivity and
Older Drivers' Detection Failure Accident Risk**

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Abstract

Eighteen older drivers (66-88) and their passengers both reported on the drivers' performance using detection deficit questionnaires that elicited responses related to attention and to speed and accuracy of object motion perception. The measure of detection deficit was an equally weighted combination of standardized responses from the 17-item driver questionnaire and the 11-item passenger questionnaire. Peripheral stationary and drifting contrast sensitivity was determined for 0.4 cycles per degree sine wave gratings at fifteen degrees eccentricity. The temporal two-alternative forced choice staircase procedure consisted of randomly interleaved left and right visual field grating presentations. The correlation between log10 motion contrast sensitivity and detection deficit was $-.63$ ($p < .01$), between age and detection deficit was $.56$ ($p < .05$), and between age and log10 motion contrast sensitivity was $-.54$ ($p < .05$). The partial correlation between log10 motion sensitivity and detection deficit, independent of age, was $-.47$ ($p = .054$). We concluded that some age-related driving performance deficits are

associated with reduced sensitivity to motion in the visual periphery. Peripheral motion contrast sensitivity was discussed in relation to “useful field of view” (UFOV®) measures of visual function, and offered as a primary deficit of high risk drivers with mild Alzheimer's disease.

Introduction

Drivers more than sixty years of age are more likely than younger drivers to have fatal accidents, given equal mileage-estimated risk exposure (NHTSA, 2001; Yanik, 1986), and daytime fatality risk is higher for drivers over seventy-five than for any other age group (Massie, Campbell & Williams, 1995). Physical frailty accounts for some of the fatality risk increase (Evans, Gerrish, & Taheri, 1998; Li, Braver, & Chen, 2003). However, older drivers are also more likely to be found at fault if they are involved in a multi-vehicle accident (Cooper, 1989; Stamatiadis & Deacon, 1995), which may in part reflect a bias of accident investigators or police to attribute fault to older drivers.

Furthermore, mileage-based estimates of risk exposure can yield exaggerated accident risk estimates for older drivers (Janke, 1991). First, mileage estimates are usually based on self-reported data, which is likely to be inaccurate, and second, different driving environments expose drivers to widely differing levels of accident risk not captured in mileage-based estimates.

A number of researchers have compared accident responsibility ratio (an induced exposure technique) across age groups to overcome the biases inherent in mileage-based accident rates. If a group has a ratio of at-fault accidents to not-at-fault accidents greater than one, then the group is involved in more than its expected share of two-vehicle accidents. Accident responsibility ratio increases at an accelerating rate after the age of

sixty-five (Cooper, 1989, 1990; Janke, 1991; Stamatiadis & Deacon, 1995; Verhaegen, Toebat, & Delbeke, 1988). The proportion of right of way (ROW) violations to total traffic convictions by age also follows a similar rising curve (Cooper, 1990).

The age-related increases in both ROW violations and accident responsibility may result from failure to detect other vehicles in the right-of-way. Accident characteristics support this hypothesis. Young drivers' accidents are mostly single-vehicle crashes, while older drivers' accidents most frequently involve an undetected crossing vehicle at an intersection (Staplin, Gish, et al., 1998; Staplin, Lococo, et al., 1998; Viano, Culver, Evans, Frick, & Scott, 1990). Furthermore, Summala and Mikkola (1994) found that only "failures of attention" (including detection) increase with age, among the five largest categories of primary non-alcohol causal factors for 1,357 fatal multi-vehicle accidents.

Some of the increase in driver accident responsibility with age may be caused by older drivers' reduced sensitivity to peripheral motion. In central vision, imparting motion enhances the contrast sensitivity of low spatial frequency sine wave gratings (below the CSF peak between 2 and 4 cycles/degree) by a factor of 4 or more. Motion enhancement (the ratio of drifting to stationary contrast sensitivity) begins to decrease after about 60 years of age, and may have fallen by a factor of 2 by the age of 70 (Owsley, Sekuler, & Siemsen, 1983; Sekuler & Owsley, 1982).

If motion sensitivity in the peripheral visual field follows a time course similar to motion sensitivity in central vision, then some of the characteristic failure of detection accidents of older drivers may arise from a peripheral motion processing (PMP) deficit that reduces the power of a moving stimulus to attract visual attention (Steinman, Steinman, Trick, & Lehmkuhle, 1994) and to produce a reflexive saccadic eye movement

toward it (Fuchs, Kaneko, & Scudder, 1985; Stein, 1984). According to this hypothesis, a PMP deficit reduces the salience of a moving object, thus disrupting the preattentive stage of scan-path generation and serial search.

We carried out a correlational test of the hypothesis that self and peer-reported detection deficit in older drivers is related to a PMP deficit that reduces the ability of a moving stimulus to trigger reflexive visual attention. In other words, a measured decrease in PMP will increase reports of detection deficit among susceptible older drivers. Because groups of older drivers are highly variable on both vision measures and driving performance measures, if there is such a correlation between a vision measure (PMP in this case) and driving performance, it will be strongest among older drivers (Shinar & Schieber, 1991). Another advantage of studying older drivers is that they have relatively few accidents involving alcohol (NHTSA, 2004).

Method

Participants

Eighteen licensed and active drivers (66-88, $M = 74.3$, $SD = 5.6$) and their passengers filled out respective driving performance questionnaires. All participants were unpaid volunteers recruited from senior citizen's services or church groups.

Procedure

Motion processing measure. Pilot testing of gratings presented at 15 degrees nominal eccentricity found motion enhancement ratios (MERs) of 3 to 4 for 0.4 cycles per degree gratings, comparable to central vision MERs for gratings of 1 cycles per degree (Sekuler & Owsley, 1982), while MERs were usually less than 2 for 0.8 cycles per degree gratings presented at that eccentricity.

Accordingly, contrast sensitivity was determined for 0.4 cycles per degree stationary and drifting sine wave gratings. Moving gratings were drifted centripetally at a rate of 13.75 degrees per second (5.5 hz), which is the optimal motion enhancement velocity (i.e., the temporal contrast sensitivity peak) for that spatial frequency (Kelly, 1979, 1984), given eccentricity scaling. Gratings generated by a purpose-built display driver (Cushman, 1992) were presented on two display monitors 57 cm distant from the head fixation point. The monitors had 10.2 cm wide by 8.2 cm high nongridded rectangular oscilloscope screens (P31 fast phosphor, .038 msec decay constant), spanning 10 degrees to 20 degrees of visual eccentricity on either side of an eye-level red LED fixation point. A temporal two-alternative forced choice (t2afc) staircase method was used. A single stimulus consisted of a vertical sine-wave grating presented in a raised cosine temporal window of 1.5 seconds duration, preceded and followed by a 0.5 second blank interval. During a trial, the participant looked directly ahead at the lit LED fixation point, and indicated whether a grating stimulus appeared in the first or the second 2.5 second temporal interval (i.e., “before or after the double beep” separating the intervals). A trial was discarded before evaluation if the participant made an anticipatory eye movement.

Left and right visual field staircases were randomly interleaved. Within a staircase, the grating contrast increased after an incorrect response, and decreased after five successive correct responses, oscillating about the contrast yielding 89% correct responses (i.e., where $p^5 = 5(1-p)$).

The participant was blind to temporal interval and grating location, and the experimenter was blind to temporal interval. A trial block continued for at least 20 trials

within each staircase after four contrast reversals within each staircase, and the threshold measure for each block was the mean grating contrast of the final 20 or more trials. The stationary grating block always preceded the moving grating block. A block usually took 40 minutes to 1 hour.

Initial grating contrast was determined by the method of increasing contrast. For six randomly ordered (by side) test trials, the participant looked at the central red LED, and responded “left” or “right” as soon as a grating of gradually increasing contrast appeared on either the left or right oscilloscope screen. Then, 2afc training trials with high-contrast stimuli were conducted until 100% response accuracy was achieved for eight trials (usually within the first eight trials).

Driving performance measures. Driving performance was assessed by a two-part (driver and passenger responses) driving perception questionnaire designed to elicit information about the subjective effects of reduced detection distances and/or an increased probability of detection errors. The passenger, selected by the driver, sealed the completed passenger questionnaire into a supplied envelope before returning it to the driver, who brought both the driver’s and passenger’s completed questionnaires to the vision test session.

The 17 driver questions related to perceptions of traffic speed, their own driving speed relative to several standards, self-ratings of own driving performance relative to several standards, and self-report of how often they were surprised by a range of driving events. The 11 passenger questions asked for judgments of average speed of the driver relative to city and highway traffic, the driver’s relative performance and safety, how often the passenger detected various situations before the driver, and the passenger’s

overall state of mind. The 28 questions were combined by orienting the responses so that higher values reflected higher hypothetical risk (i.e., detection deficit), converting responses for each question to z-scores across drivers, and then computing the average z-score for each driver. This procedure is equivalent to assigning equal weights in a regression equation, involves no capitalization on chance, and is unaffected by missing answers (Wainer, 1976).

Experimental Hypothesis

Within a group of older drivers, peripheral motion contrast sensitivity would correlate significantly ($p < .05$) with detection deficit as assessed by questionnaire scores.

Results

Table 1.

Pearson Product Correlations between Age, Contrast Sensitivity, and Questionnaire Scores (N = 18)

{PRIVATE }	Age	Questionnaire scores	Driver questionnaire	Passenger questionnaire
Age	---	.56*	.50*	.43
Log ₁₀ contrast sensitivity (drifting)				
Right visual field	-.70**	-.55*	-.53*	-.39
Left visual field	-.37	-.64**	-.64**	-.42
Average across fields	-.54*	-.63**	-.62**	-.43
Log ₁₀ contrast sensitivity (stationary)				
Right visual field	-.34	-.04	-.08	.01
Left visual field	-.29	-.25	-.34	-.07
Average across fields	-.35	-.18	-.26	-.04

*p < .05. **p < .01.

Mean log₁₀ contrast sensitivity was 1.68 (SD = 0.17) for stationary 0.4 cycles per degree sine wave grating stimuli, and 2.15 (SD = 0.18) for drifting grating stimuli.

Correlations of interest are shown in Table 1. The partial correlation between motion sensitivity and detection deficit questionnaire score, independent of age, was -.47 (p =

.054). As well, driver and passenger questionnaire scores just failed to correlate significantly with each other ($r = .41$, $p < .1$).

Discussion

Test and remediation. Note particularly that the correlation between peripheral motion processing and questionnaire score is stronger than their correlations with age, indicating that peripheral motion contrast sensitivity may therefore be used to identify drivers at higher risk for detection failure accidents without regard for age, fulfilling the requirement that such tests not be age-based.

Although older drivers do compensate for age-related visual and driving deficits (Slzyk, Seiple, & Viana, 1995), they are poor at assessing their own visual processing skills and at detecting gradual visual losses occurring over time. They are unlikely to recognize the situations, intersections in particular, that are most dangerous for them (Holland, 1993). However, when informed of specific visual deficits by an eye care practitioner, older drivers willingly adopt compensatory strategies. Peripheral motion processing tests could be used to identify the deficit, and perhaps at-risk drivers could be taught to consciously scan the visual field at regular intervals and when approaching intersections, rather than having to rely on a reduced or absent reflexive orienting response to movement. (Note that flight instructors spend significant time instructing their students to consciously scan the visual field outside the aircraft.) Indeed, Schieber (1994) stated that research should be conducted to determine if drivers with peripheral vision deficits might benefit from training in eye movement strategies.

Useful Field of View. Ball, Owsley, and co-workers have proposed that a primary deficit causing driving performance decline is an age-related reduction in useful field of

view (UFOV®) (Ball & Owsley, 1991; Ball, Owsley, Sloane, Roenker, & Bruni, 1993; Ball & Rebok, 1994; Owsley, Ball, & Keeton, 1995; Owsley, Ball, Sloane, Roenker, & Bruni, 1991). UFOV® test participants perform simultaneous peripheral target localization and central target discrimination. Stimulus duration is shorter than saccade latency, preventing serial search of the visual field. Visual Attention Analyzer results can significantly predict prior accident involvement.

Ball, Owsley, and co-workers have suggested that pure sensory measures do not improve the fit of the regression model over UFOV® measures alone because they do not capture the complexity of the cluttered driving environment. Clinical ophthalmology tests (most particularly contrast sensitivity) typically isolate measurements of sensory function from perceptual and cognitive influences, assess only central vision, do not require concurrent use of central and peripheral vision, and incorporate no positional or temporal uncertainty in the test stimulus (Ball & Owsley, 1991; Ball et al., 1993; Owsley et al., 1991). However, the sensory measure of peripheral motion processing described above does minimize perceptual and cognitive influences, while using peripheral vision during central fixation, and incorporating both positional and temporal uncertainty into the test stimulus.

The PMP test and the UFOV® test are complimentary measures of the visual attention required to drive safely. The (sensory) PMP test evaluates the power of motion to produce a saccade target (i.e., bottom-up scan-path generation), and the (attentional) UFOV® test evaluates the extent of information available for visual search within a fixation. PMP and UFOV® measures are not entirely independent, as the second sub-test

of the UFOV® test requires peripheral localization of a solitary step-onset stimulus, a task that probably overlaps with motion detection under spatial uncertainty.

Scialfa, Thomas, and Joffe (1994) found that age-related shrinkage of UFOV increases the serial component of search tasks (parallel to serial compensation). Older participants increased visual search reaction time by requiring more saccades to identify search targets. Therefore, a relatively more sensitive PMP system and more accurate saccade generator will help compensate for UFOV shrinkage (due to age or stroke) and mitigate its impact on driving performance. Conversely, a large UFOV likely reduces the need for accurate saccades. Therefore, including the PMP test in a test battery could reduce false positives by “deselecting” drivers better able to compensate for a UFOV deficit, thereby improving identification of high-risk drivers.

Alzheimer’s disease, PMP, and accident risk. Estimates of increased crash risk for drivers with Alzheimer’s disease (AD) compared to age-matched controls range from a factor of 5 (Friedland et al., 1988), to a factor of 2.5 (Tuokko, Tallman, Beattie, Cooper, & Weir, 1995). Although researchers have considered the elevated accident risk of AD patients to be a function of cognitive impairment (Fitten et al., 1995; Kraszniak, Keyl, & Albert, 1991; Parasuraman & Nestor, 1991; Tuokko et al., 1995), crashing and non-crashing AD drivers are not distinguishable by neuropsychological tests or by symptom severity at initial diagnosis (Lucas-Blaustein, Filipp, Dungan, & Tune, 1988; Tuokko et al., 1995). We contend for the following reasons that PMP deficit causes elevated accident risk in some AD drivers.

Visual deficits are now recognized by clinical researchers as a primary deficit of AD (Cronin- Golomb, 1995). One clinical subgroup of early AD patients displays

Balint's syndrome (a visuospatial and motion processing deficit) as the first symptom of AD (Hof et al., 1993). Motion detection pathways, including middle temporal cortex, appear to be "dramatically affected in these cases" (p. 215). Some mildly demented early AD patients show profound visual deficits for temporally modulated stimuli. Detection thresholds are higher for drifting or flickering sine wave gratings (Gilmore, Wenk, Naylor, & Koss, 1994; Hutton, Morris, Elias, & Poston, 1993) and for 700 msec presentations of step-onset gratings (Cronin-Golomb et al., 1991; Nissen et al., 1985) relative to healthy age-matched controls.

Some researchers have shown that correlated motion thresholds for random dot stimuli are more than double for AD patients (Gilmore et al., 1994; Silverman, Tran, Zimmerman, & Feldon, 1994; Trick & Silverman., 1991). However, Mendola, Cronin-Golomb, Corkin, and Growdon (1992, 1995) found no threshold increase using the correlated motion paradigm, perhaps because their stimuli could evoke correct "blindsight" responses from AD patients. This is made more plausible because Silverman et al. (1994) detected optokinetic nystagmus (OKN) for undetected random-dot motion, demonstrating relative sparing of accessory optic system processing in AD relative to cortical dysfunction. Increased visual evoked potential (VEP) latencies of P2 (indicating defective secondary visual processing), and temporal contrast sensitivity losses have also been reported (Wright, Drasdo, & Harding, 1987).

If a sensory visual attention deficit is the cause of elevated crash risk in some early AD patients, then a variant of the PMP test (perhaps modified into a spatial two-alternative task to eliminate any memory demand) may reliably distinguish between crashing and non-crashing AD drivers. If so, diagnosis of probable early Alzheimer's

disease need not mean termination of a patient's right to drive, as early AD drivers with low risk of sensory attention deficit could continue to drive until precluded by later AD deficits.

Future steps. The validity and reliability of peripheral motion processing measures and the driving perception questionnaire for predicting accident risk should be tested using accident data and driving simulator performance measures. We hope that further development of the forced-choice method and test equipment will reduce test time sufficiently to make peripheral motion processing assessment practical for driving examiners, medical professionals, and transportation researchers.

By means such as these, we hope that personal mobility commensurate with functional vision may be preserved by mitigating functional deficits through appropriate training interventions, by restricting licenses when necessary, and perhaps eventually by developing effective visual prostheses or other technological countermeasures for visual function deficits not yet recognized.

References

- Ball, K., & Owsley, C. (1991). Identifying correlates of accident involvement for the older driver. *Human Factors*, 33(5), 583-595.
- Ball, K., Owsley, C., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1993). Visual attention problems as a predictor of vehicle crashes in older drivers. *Investigative Ophthalmology & Visual Science*, 34(11), 3110-3123.
- Ball, K., & Rebok, G. (1994). Evaluating the driving ability of older adults. *The Journal of Applied Gerontology*, 13(1), 20-38.
- Cooper, P. J. (1989). Differences in accident characteristics among elderly drivers and between elderly and middle-aged drivers. *Proceedings of the 33rd Conference of the American Association for Automotive Medicine*, 33, 153-167.
- Cooper, P. J. (1990). Different ages, different risks: The realm of accident statistics. In J. P. Rothe (Ed.), *The Safety of Elderly Drivers: Yesterday's Young in Today's Traffic*, 85-133. New Brunswick: Transaction Publishers.
- Cronin-Golomb, A. (1995). Vision in Alzheimer's disease. *The Gerontologist*, 35(3), 370-376.
- Cronin-Golomb, A., Corkin, S., Rizzo, J. F., Cohen, J., Growdon, J. H., & Banks, K. S. (1991). Visual dysfunction in Alzheimer's disease: relation to normal aging. *Annals of Neurology*, 29, 41-52.
- Cushman, W. B. (1992). A low-cost spatial contrast sensitivity display driver. *Behavior Research Methods, Instruments, & Computers*, 24(3), 461-463.
- Evans, L., Gerrish, P. H., & Taheri, B. (1998). Epidemiology of the older driver - some preliminary findings from data through 1996. *Proceedings of the 16th*

International Conference on the Enhanced Safety of Vehicles, Windsor, Canada,
1-4 June 1998.

- Fitten, L. J., Perryman, K. M., Wilkinson, C. J., Little, R. J., Burns, M. M., Pachana, N., Mervis, J. R., Malmgren, R., Siembieda, D. W., & Ganzell, S. (1995). Alzheimer and vascular dementias and driving: a prospective road and laboratory study. *Journal of the American Medical Association*, 273(17), 1360-1365.
- Friedland, R. P., Koss, E., Kumar, A., Gaine, S., Metzler, D., Haxby, J. V., & Moore, A. (1988). Motor vehicle crashes in dementia of the Alzheimer type. *Annals of Neurology*, 24, 782-786.
- Fuchs, A. F., Kaneko, C. R. S., & Scudder, C. A. (1985). Brainstem control of saccadic eye movements. *Annual Review of Neuroscience*, 8, 307-337.
- Gilmore, G. C., Wenk, H. E., Naylor, L. A., & Koss, E. (1994). Motion perception and Alzheimer's disease. *Journal of Gerontology: Psychological Sciences*, 49(2), 52-57.
- Hof, P. R., Archin, N., Osmand, A. P., Dougherty, J. H., Wells, C., Bouras, C., & Morrison, J. H. (1993). Posterior cortical atrophy in Alzheimer's disease: analysis of a new case and re-evaluation of a historical report. *Acta Neuropathologica*, 86(3), 215-223.
- Holland, C. A. (1993). Self-bias in older drivers' judgments of accident likelihood. *Accident Analysis & Prevention*, 25(4), 431-441.
- Hutton, J. T., Morris, J. L., Elias, J. W., & Poston, J. N. (1993). Contrast sensitivity dysfunction in Alzheimer's disease. *Neurology*, 43, 2328-2330.

- Janke, M. K. (1991). Accidents, mileage and the exaggeration of risk. *Accident Analysis & Prevention*, 23(2/3), 183-188.
- Kelly, D. H. (1979). Motion and vision. II. Stabilized spatio-temporal threshold surface. *Journal of the Optical Society of America*, 69, 1340-1349.
- Kelly, D. H. (1984). Retinal inhomogeneity. I. Spatiotemporal contrast sensitivity. *Journal of the Optical Society of America*, A, 1(1), 107-113.
- Kraszniak, A.W., Keyl, P. M., & Albert, M. S. (1991). Dementia and the older driver. *Human Factors*, 33(5), 527-537.
- Li G., Braver E. R., Chen L. H. (2003). Fragility versus excessive crash involvement as determinants of high death rates per vehicle-mile of travel among older drivers. *Accident Analysis and Prevention*, 35(2), 227-235.
- Lucas-Blaustein, M. J., Filipp, L., Dungan, C., & Tune, L. (1988). Driving in patients with dementia. *Journal of the American Geriatrics Society*, 36, 1087-1091.
- Massie, D. L., Campbell, K. L., & Williams, A. F. (1995). Traffic accident involvement rates by driver age and gender. *Accident Analysis and Prevention*, 27(1), 73-87.
- Mendola, J. D., Cronin-Golomb, A., Corkin, S., & Growdon, J. H. (1992). Vision in Alzheimer's disease: prevalence of deficit. *Society for Neuroscience Abstracts*, 18, 736.
- Mendola, J. D., Cronin-Golomb, A., Corkin, S., & Growdon, J. H. (1995). Prevalence of visual deficits in Alzheimer's disease. *Optometry and Vision Science*, 72, 155-167.
- National Highway Traffic Safety Administration (2001). *Traffic Safety Facts 2000: Older Population*. DOT HS 809 328.

- National Highway Traffic Safety Administration (2004). Traffic Safety Facts 2003: Older Population. DOT HS 809 766.
- Nissen, M. J., Corkin, S., Buonanno, F. S., Growdon, J. H., Wray, S. H., & Bauer, J. (1985). Spatial vision in Alzheimer's disease: general findings and a case report. *Archives of Neurology*, 42, 667-671.
- Owsley, C., Ball, K., & Keeton D. M. (1995). Relationship between visual sensitivity and target localization in older adults. *Vision Research*, 35(4), 579-587.
- Owsley, C., Ball, K., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1991). Visual/cognitive correlates of vehicle accidents in older drivers. *Psychology and Aging*, 6(3), 403-415.
- Owsley, C., Sekuler, R., & Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision Research*, 23(7), 689- 699.
- Parasuraman, R., & Nestor, P.G. (1991). Attention and driving skills in aging and Alzheimer's disease. *Human Factors*, 33(5), 539-557.
- Schieber, F. (1994). Recent developments in vision, ageing and driving 1988-1994. Report No. UMTRI-94-26. Ann Arbor, MI: University of Michigan, Transportation Research Institute. Viewed April 20, 2005 at: <http://people.usd.edu/~schieber/pdf/umtri.pdf>
- Scialfa, C. T., Thomas, D. M., & Joffe, K. M. (1994). Age differences in the useful field of view: an eye movement analysis. *Optometry and Vision Science*, 71(12), 736-742.

- Sekuler, R., & Owsley, C. (1982). The spatial vision of older humans. In R. Sekuler, D. Kline, & K. Dismukes (Eds.), *Aging and Human Visual Function* (pp. 185-202). New York: Alan R. Liss, Inc.
- Shinar, D. & Schieber, F. (1991). Visual requirements for safety and mobility of older drivers. *Human Factors*, 33(5), 507-519.
- Silverman, S. E., Tran, D. B., Zimmerman, K. M., & Feldon, S.E. (1994). Dissociation between the detection and perception of motion in Alzheimer's disease. *Neurology*, 44, 1814-1818.
- Stamatiadis, N. & Deacon, J. A. (1995). Trends in highway safety: Effects of an aging population on accident propensity. *Accident Analysis and Prevention*, 27(4), 443-459.
- Staplin, L., Gish, K. W., Decina, L. E., Lococo, K., & McKnight, A. S. (1998). *Intersection Negotiation Problems of Older Drivers, Volume I: Final Technical Report*. USDOT/NHTSA Contract No. DTNH22-93-C-05237. Washington, DC.
- Staplin, L., Lococo, K., McKnight, A. J., McKnight, A. S., & Odenheimer, G. (1998). *Intersection Negotiation Problems of Older Drivers, Volume II: Background Synthesis on Age and Intersection Driving Difficulties*. USDOT/NHTSA Contract no. DTNH22-93-C05237. Washington, DC.
- Stein, B. E. (1984). Development of the superior colliculus. *Annual Review of Neuroscience*, 7, 95-125.
- Steinman, S. B., Steinman, B. A., Trick, G. L., & Lehmkuhle, S. (1994). A sensory explanation for visual attention deficits in the elderly. *Optometry and Vision Science*, 71(12), 743-749.

- Summala, H., & Mikkola, T. (1994). Fatal accidents among car and truck drivers: Effects of fatigue, age, and alcohol consumption. *Human Factors*, 36(2), 315-326.
- Szlyk, J. P., Seiple, W., & Viana, M. (1995). Relative effects of age and compromised vision on driving performance. *Human Factors*, 37(2), 430-436.
- Trick, G. L., & Silverman, S. E. (1991). Visual sensitivity to motion: Age-related changes and deficits in senile dementia of the Alzheimer type. *Neurology*, 41, 1437-1440.
- Tuokko, H., Tallman, K., Beattie, B. L., Cooper, P., & Weir, J. (1995). An examination of driving records in a dementia clinic. *Journal of Gerontology: Social Sciences*, 50B(3), S173-S181.
- Verhaegen, P. K., Toebat, K. L., & Delbeke, L. L. (1988). Safety of older drivers: A study of their overinvolvement ratio. *Proceedings of the 32nd Conference of the Human Factors Society*, 185-188.
- Viano, D. C., Culver, C. C., Evans, L., Frick, M., & Scott, R. (1990). Involvement of older drivers in multi-vehicle side impact crashes. *Accident Analysis & Prevention*, 22(2), 177-188.
- Wainer, H. (1976). Estimating coefficients in linear models: It don't make no nevermind. *Psychological Bulletin*, 83(2), 213-217.
- Wright, C. E., Drasdo, N., & Harding, G. F. A. (1987). Pathology of the optic nerve and visual association areas: information given by the flash and pattern visual evoked potential, and the temporal and spatial contrast sensitivity function. *Brain*, 110, 107-120.

Yanik, A. J. (1986). What accident data reveal about elderly drivers. (SAE Technical Paper #851688). Warrendale, PA: Society of Automotive Engineers.

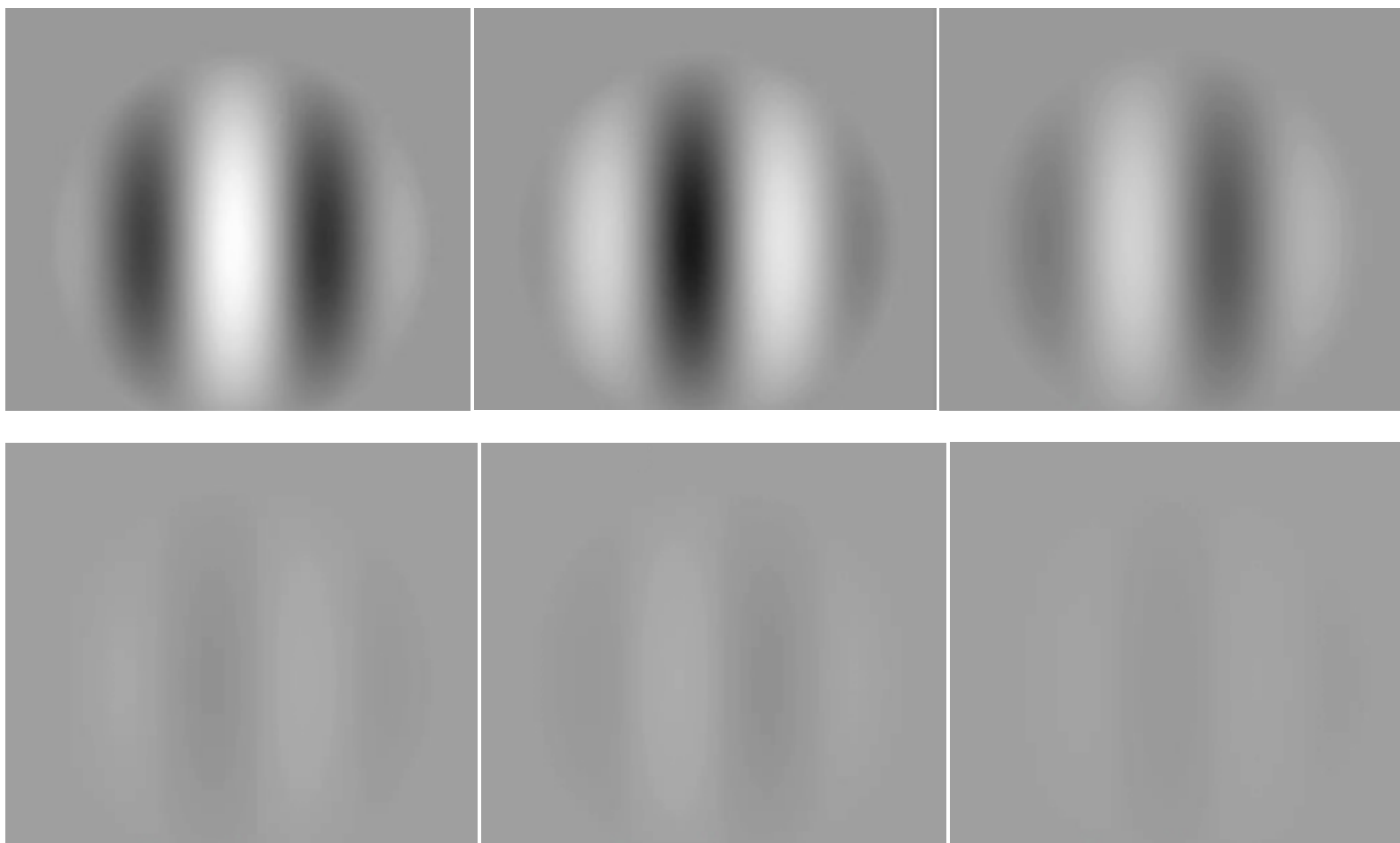


Figure 12. Gabor stimuli with high (upper) and low (lower) contrast.

V. Introduction to the Second Study

The second study, which was carried out in the Psychology Department of the University of Ottawa in collaboration with Dr. Sylvain Gagnon, and Dr. Charles Collin, was designed to cover substantial new ground. First, the bespoke questionnaire was tested for validation against the Manchester Driver Behaviour Questionnaire, which is the self-report metric most widely accepted in the field of older driver human factors as a valid measure of driver safety and accident risk. Second, the relations among peripheral motion detection threshold, accident risk, and UFOV® (the most successful visual function predictor of older driver accident risk to date) were analyzed, and the extent to which the two visual measures task the same visual functions was determined.

An applied advance was the replacement of the rectangular-windowed sine wave grating stimuli (which were bounded by step transients or square wave edges) by the more widely used and mathematically simpler Gabor stimuli (i.e., sine wave gratings within a spatial Gaussian window – that is, the contrast of the sine wave grating is attenuated by a Gaussian function of the distance from the centre of the window), as shown in Figure 12.

This study was intended to replicate the first study, and in addition to validate both the vision measure and the driving risk self-report measure against the most widely accepted metrics of a similar type. However, an unintentional change from the first study was that through a programming error that was discovered after a substantial number of participants had been tested, the drift rate of the grating stimulus was 11 hz, or 27.5

degrees per second, rather than the intended 5.5 hz of the first study. We elected to complete the study using the 11 hz drift rate.

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**VI. Near Peripheral Motion Detection Threshold Correlates with
Self-reported Failures of Attention in Younger and Older Drivers**

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Abstract

Motion contrast thresholds for 0.4 cycle/degree drifting Gabor stimuli were assessed at 15 degrees eccentricity in the right and left visual fields for 16 younger drivers (ages 24 to 42), and 15 older drivers (ages 65 to 84), using a temporal two alternative forced choice staircase procedure. Two self-report questionnaires that assess failures of attention while driving—the Driver Perception Questionnaire (DPQ5), and an abridged Aging Driver Questionnaire (ADQ15)—were administered. The three UFOV® sub-tests of attention and processing speed were also administered. Mean peripheral motion contrast threshold (PMCT) of older drivers was significantly higher than that of younger drivers. When controlling for age, PMCT thresholds correlated significantly with both DPQ5 and ADQ15 while the UFOV® subtests were found not to correlate with PMCT results. The potential value of the PMCT as an assessment of drivers' hazard detection capacity is discussed. [141 words]

peripheral motion contrast threshold older drivers visual function
accident risk

Introduction

The rate of collisions per kilometer begins to increase after the age of 65, and accelerates substantially after the age of 70 (Dellinger et al., 2002; Eberhard, 2008; Li et al., 2003; NHTSA, 2001). Although these statistics may be biased regarding older drivers for several reasons (Hakamies-Blomqvist, 2004), including overexposure to collision risk from compensatory changes to driving practices (Janke, 1991) and moderate driving exposure (Langford et al., 2006), studies controlling for such factors continue to find an increased risk of accident in the elderly (Ross et al., 2009; Freund et al., 2005). Of particular importance to the current study are findings of age-related increases in both right-of-way violations and accident responsibility (Di Stefano and Macdonald, 2003; Langford et al., 2005; Massie et al., 1995; Mayhew et al., 2006; Stamatiadis and Deacon, 1995). These kinds of incidents may arise from failures to notice other vehicles in the right-of-way (ROW), suggesting that part of the increased accident risk exhibited by older drivers arises from an increase in detection failures.

Research on accident characteristics also supports the detection failure hypothesis, finding that older drivers' accidents most frequently involve an undetected crossing vehicle at an intersection (Braitman et al., 2007; Caird et al., 2005; Retting et al., 2003; Staplin, Gish et al., 1998; Staplin, Lococo, et al., 1998). Summala and Mikkola (1994) reported that rigorous and immediate on-site expert team investigations of 1357 fatal multi-vehicle accidents (not involving alcohol) determined that of the five largest categories of primary causal factors, only “failures of attention” (i.e., detection failures) increased with age. Braitman et al. (2007) studied 92 ROW violation intersection crashes and reported that detection failure was the predominant error, leading to more than half

the incidents examined. Inadequate search was found to account for most of the detection failure errors committed by the 70+ year old drivers, while distraction and inadequate search accounted for equal numbers of detection failures in the 35-54 year old control group.

Research has indicated that visual acuity, although widely used by most licensing authorities around the world to assess drivers, is a poor predictor of crash risk and driving ability (Sivak, 1996; Desapriya et al., 2008; Wood and Owens, 2005). In contrast, stronger results have been achieved with attention-based visual assessments such as UFOV® (Ball et al., 2006; Clay et al., 2005) and with sensory-based measures of contrast sensitivity (CS), such as the Pelli-Robson Low-Contrast Letter Chart or VISTECH gratings. For instance, Horswill and coworkers (2008) reported that Pelli-Robson contrast sensitivity and UFOV2 scores predicted 22% of the variance in hazard detection performance of 84 older drivers viewing videos of traffic conflict scenarios.

Of particular importance to the current study is research examining sensitivity to motion as a predictor of driving ability (Wood et al., 2008). Motion contrast sensitivity in central vision is known to decline with age (Owsley et al., 1983; Sekuler and Owsley, 1982) as does speed discrimination of high contrast drifting gratings (Raghuram et al., 2005). A number of studies have shown a correlation between these declines and driving performance. For instance, De Raedt and Ponjaert-Kristoffersen (2000) tested 84 older drivers using a commercial visual assessment device (Ergovision, ESSILOR., now of Bristol, UK) which assessed movement perception by presenting moving arrow structures. They found that movement perception significantly predicted on-road test score. Similarly, Raghuram et al. (2006) tested a small sample of 15 older drivers and

found that a speed discrimination task significantly predicted driving difficulty as assessed by a questionnaire. More recently, Conlon and Herkes (2008) found that performance on a comparative speed judgment between two adjacent moving random dot patches was significantly related to a questionnaire-based measure of perception of other vehicles and road signs. Finally, Wood et al. (2008) carried out a stepwise regression analysis to assess the predictive value of a battery of 20 visual, cognitive and physical performance measures and found that motion detection—as measured by minimum coherent dot displacement—was the only significantly predictive visual performance variable.

Although the above studies all suggest that visual motion processing can be predictive of driving performance, comparing and generalizing their findings is difficult due to the wide array of tasks employed. In the current study, we aimed to design a motion test whose characteristics are based on what is known about how motion is processed in the brain and how visual motion perception degrades with age. To do so, we considered the characteristics of the magnocellular pathway, which is widely understood to be responsible for detecting movement, identifying its retinal location position, and allocating attention to that location (Chikashi et al., 1999; Horwitz and Newsome, 1999; Livingstone and Hubel, 1988; Steinman et al., 1997). This pathway exhibits the following basic characteristics: It is optimally responsive to low spatial frequencies (below about 1.5 cpd; Skottun, 2000); it is responsive to relatively higher temporal frequencies than the sustained, form-processing parvocellular pathway (Skottun and Skoyles, 2008); and it is relatively more peripherally distributed than the parvocellular pathway.

Ganglion cells with transient receptive fields also comprise a more primitive, retinotectal pathway to the superior colliculus (SC). The retinotectal pathway strongly contributes to reflex orienting of visual attention (Brietmeyer and Ganz, 1976; Livingstone and Hubel, 1988; Rafal et al., 1991; Schneider and Kastner, 2005). Indeed, recent high resolution fMRI research has confirmed that the retinotectal pathway to SC is the predominant neural pathway for visual orienting (Sylvester et al., 2007). Furthermore, the human SC is highly sensitive to low stimulus contrast and highly responsive to stimulus motion, similar to M pathway responses (Schneider and Kastner, 2005). SC is also very responsive to random dot motion (Horwitz and Newsome, 1999).

Based on the above characteristics of motion processing in the human visual system we suggest that an optimal stimulus to test both transient pathways (i.e. geniculostriate and tectopulvinar) may be a low spatial frequency, high temporal frequency sine wave grating in the near visual periphery. Contrast detection threshold for such a stimulus involves contrast and movement, which Wood et al. (2008) identify as the relevant cues for driving, thus providing face validity to motion sensitivity as an accident risk metric.

Motion enhances contrast sensitivity by a factor of three or four for a 1 cycle per degree (cpd) sine wave grating in central vision (Sekuler and Owsley, 1982). Pilot testing at 10 to 20 degrees of eccentricity found the same motion enhancement factor for a 0.4 cpd grating, consistent with retinal scaling, compared to a motion enhancement factor of only two for a 0.8 cpd grating, indicating that 0.4 cpd is an appropriate spatial frequency for the test stimulus.

Henderson and Donderi (2005) proposed that a reduction in peripheral motion sensitivity might degrade an older driver's visual orienting reflex toward moving objects that are away from the point of central fixation. This capacity would be essential to detect vehicles or other road users in the right of way. They reported a significant correlation between peripheral motion contrast sensitivity threshold (PMCT) and their self-report measure of driving risk (the Driver Perception Questionnaire, or DPQ5). The DPQ5 was designed to elicit information about the subjective effects of reduced detection distances and increased probability of detection errors, as a measure of detection failure accident risk. Thus, there is preliminary evidence that sensitivity to motion in the near periphery is related to self-reported failures of attention and self-reported driving performance and that it could therefore potentially be a predictor of crash risk in older drivers.

Many issues need to be addressed in order to further validate the relationship between PMCT and accident risk. As a first step, it is essential to document age-related differences in PMCT. Secondly, the findings obtained using the DPQ5 developed by Henderson and Donderi (2005) need to be confirmed and contrasted with a validated self-report assessment of driving abilities and risk of crash. Thirdly, the value of PMCT as a predictor of detection failures and accident risk needs to be compared to the widely used UFOV®, which has been found to correlate with self-report assessments of driving ability (van Rijn et al., 2002) and with crash risk (Clay et al., 2005). Both the UFOV® and the PMCT assess the ability of participants to detect stimuli in the near periphery, with an essential difference between the two tests being that, while the UFOV® presents static targets, the PMCT involves detecting primitive motion signals.

The current study was conducted to determine if PMCT predicts detection failure accident risk—as reflected in self-reported failures of attention—at any age, and if PMCT deteriorates with age. We had two additional goals. The first goal was to determine if the DPQ measures substantially the same driver competencies as a subset of questions (selected a priori based on their face validity in reference to detection failure accident risk) from the well-validated and widely used Manchester Driver Behavior Questionnaire (DBQ) (Parker et al., 2000; Parker, 2005). DBQ error and lapse scores significantly predict older drivers' accident involvement (Parker et al., 2000; Assailly et al., 2006; Obriot-Claudé and Gabaude, 2004), the DBQ has been validated cross-culturally (Lajunen et al., 2004), and the DBQ has acceptable test-retest reliability (Özkan et al., 2006; Parker et al., 1995). Parker et al. (2000) and Assailly et al. (2006) referred to the DBQ as the Aging Driver Questionnaire (ADQ) in their older driver articles, and we will also follow that practice.

The second goal was to determine the degree to which the PMCT test assesses the same performance factors as the UFOV® test battery (Ball et al., 2006), especially with regard to the divided attention version of the task (UFOV2), which presents static stimuli in the periphery. We examined the comparative power of both instruments to predict accident risk resulting from detection failures.

Method

Participants

The convenience sample of 31 volunteer participants consisted of 16 younger drivers and 15 older drivers. The younger drivers included 9 men and 7 women between 24 and 42 years of age ($M = 29.4$, $SD = 4.36$) with 11.3 years ($SD = 5.02$) of driving

experience on average. The older drivers included 8 men and 7 women between 65 and 84 years of age ($M = 73.1$, $SD = 5.36$) with 48 years ($SD = 8.0$) of driving experience on average. All participants reported good mental and physical health with no history of neurological, psychiatric or substance abuse problems, and all were tested with their normal visual correction. All were residents of the Ottawa area and received twenty dollars for their participation.

Driving Questionnaires

Participants completed a modified and abridged Aging Driver Questionnaire (ADQ15) containing 8 questions from Parker et al. (2000) and seven additional questions from the augmented ADQ set of 42 questions (Parker, 2005). From Parker et al. (2000) questions 4, 9, 11, 13, 14, 17, 20, and 21 were selected as they were judged to be related to detection failures. The additional seven questions taken from Parker (2005) because of their relevance to detection failures were:

How often do you:

- find that the distance you have allowed for stopping is too short,
- turn left onto a main road into the path of an oncoming vehicle from the right that you hadn't seen, or whose speed you misjudged,
- fail to notice a green left turn arrow,
- fail to notice when a traffic signal turns green,
- turn right onto a main road into the path of an oncoming vehicle from the left that you hadn't seen, or whose speed you had misjudged.
- turn left onto a main road into the path of an oncoming vehicle from the left that you hadn't seen, or whose speed you had misjudged.

- miss your exit off the highway.

All participants also answered the five driver perception questions¹ (DPQ5) from the Driver Perception Questionnaire (see Appendix A; Henderson and Donderi, 2005). ADQ15 as well as DPQ5 response scores to each question were standardized across all participants within each age group and then averaged across questions for each participant. To conduct statistical analyses on the entire sample of participants irrespective of the age group, DPQ5 scores and ADQ15 scores for each participant were also calculated by standardizing question responses across all participants before averages across items were computed. This standardization procedure is equivalent to assigning equal weights in a regression equation, involves no capitalization on chance, and is unaffected by missing answers (Wainer, 1976).

Vision Measures

Peripheral motion contrast threshold (PMCT). PMCT was determined for 0.4 cycles per degree Gabor stimuli, which consisted of a vertical sine wave grating that drifted centripetally at 27.5°/sec within a half-sine window. The stimuli were presented at 15° eccentricity, within a raised cosine temporal window of 1.5 seconds duration, preceded and followed by a 0.5 second blank interval. Gratings were presented on two

¹ Thesis note: All 17 questions of the Driver Perception Questionnaire were asked, but only the 5 direct questions provided an estimate of detection failure errors. Therefore the questions relating to mis-attribution to external factors were not included in the analysis.

CRT monitors² 74 cm distant from the head fixation point. The stimuli were generated using WinVis and MATLAB software on an IBM PC running Windows XP.

A temporal two-alternative forced choice staircase method, similar to that used by Henderson and Donderi (2005) was employed. This psychophysical technique is designed to help untrained participants to maintain central fixation. The procedure consisted of four randomly interleaved 2-down/1-up staircases rather than two randomly interleaved 4-down/1-up staircases, but was otherwise unchanged. During a single staircase trial, a participant looked directly ahead at a lit LED fixation point, and indicated whether the Gabor stimulus appeared in the first or the second 2.5 second temporal interval. The division between the two temporal intervals was signaled by a double beep, and participants were instructed to indicate—via one of two buttons on a response box—whether the stimulus was seen before or after this sound cue. Within a staircase, grating contrast increased after an incorrect response, and decreased after two successive correct responses. A tester sat opposite to the participant and observed their eyes throughout all trials. A trial was discarded before evaluation if the participant made an eye movement. The participant was blind to temporal interval and grating location. Peripheral motion contrast thresholds (dB) were averaged across the four staircases for each participant. All participants were able to complete the PMCT procedure within 20 minutes.

² Thesis note: Monitors were gamma-corrected. Luminance resolution was increased two bits by spatial jittering – the smallest luminance increase was by a single bit in a single pixel of each 2x2 pixel area. Stimulus frames were interleaved with blank frames of the same overall luminance, effectively doubling luminance resolution (i.e., adding one bit) by halving contrast range.

Useful Field of View (UFOV®). All UFOV® subtests of visual attention (speed of processing, divided attention, selective attention) were administered to all participants. These tests are known to be valid and reliable instruments for predicting older drivers' motor vehicle collision (Ball et al., 2006; Clay et al., 2005). The same procedure is applied in all three subtests. In the speed of processing subtest, participants are required to indicate whether they perceive the silhouette of a car or truck in the center of the monitor. Display time of the stimulus is manipulated across trials. The divided attention subtest requires the participant to simultaneously locate a car presented eccentrically while identifying the central stimulus (a car or a truck). In the selective attention subtest, the peripheral and central stimuli are surrounded with visual distracters (triangles), with the same response as in the divided attention subtest. Performance (milliseconds) corresponds to the threshold at which a participant is able to detect the target information.

Results

To test the hypothesis that PMCT declines with age, we calculated the mean PMCT of younger participants (-39.3 ± 3.00 dB, $n = 16$) and older participants (-33.8 ± 3.05 dB, $n = 15$). A t-test for independent groups showed that this difference was significant ($t(29) = -5.09$, $p < .001$). Within the older group, but not the younger group (as expected), age and PMCT were significantly correlated ($n = 15$, $r = .49$, $p < .05$). To determine if these declines in PMCT are related to accident risk due to detection failures, we calculated the correlation between PMCT and scores on our two self-report measures (DPQ5, ADQ15), while partialing out age as a covariate. The results of this analysis are shown in Table 1. Our analyses indicate that PMCT is significantly related to scores on both the DPQ5 and the ADQ15 when age is factored out. This suggests that the PMCT

test measures a factor that is correlated with self-reported failures of attention regardless of age. Furthermore, within the younger group, where no age effect was found, PMCT and DPQ5 are strongly related ($n = 16$, $r = .62$, $p < .01$). Table 1 also shows that the correlation between PMCT measures and UFOV® scores is not significant when age is partialled out. The relative difference in age mediation of the relationships of PMCT and UFOV® to the self-reported driving measures suggests that PMCT and UFOV® measure different performance factors.

Table 1

Partial Correlations for Peripheral Motion Contrast Threshold by Selected Variables, Factoring out Age ($n = 31$)

	Partial r
PMCT ^a by:	
DPQ5 ^b	.549***
ADQ15 ^c	.389*
UFOV ^d Category	-.062
UFOV1	.02
UFOV2	.192

^a PMCT = peripheral motion contrast threshold

^b DPQ5 = driver perception questionnaire, 5 questions

^c ADQ15 = aging driver questionnaire, 15 questions
(i.e. Manchester Driver Behavior Questionnaire)

^d UFOV® = Useful Field of View

* $p < .05$, ** $p < .01$, *** $p < .001$, one-tailed.

To further examine the relationship between PMCT, UFOV, DPQ5, ADQ15, and age, we calculated the simple product moment correlations between these factors without partialing out age. The results of these analyses are shown in Table 2. As shown, UFOV® subtests that require processing of peripheral stimuli are very strongly related to age, and less strongly to PMCT, while UFOV1 (processing speed) is significantly related to age but not to PMCT. None of the UFOV® subtest scores is related to any questionnaire score. Taken together, these results (along with those shown in Table 1) suggest that, to the degree that UFOV® and PMCT measure a similar risk factor, it is a factor related to age. Moreover, our results suggest that the DPQ5, ADQ15, and PMCT are also measuring an orthogonal factor unrelated to age but related to the driver's self-reported crash risk resulting from detection failures.

Table 2

Correlations Across Vision Measures, Age, and Questionnaire Scores for Younger and Older Drivers (n = 31)

	Age	PMCT ^a	DPQ5 ^b	ADQ15 ^c
UFOV1 ^d (processing speed)	.303*	.136	-.074	.009
UFOV2 (divided attention)	.671****	.561***	.184	.095
UFOV3 (selective attention)	.796****	.577***	.108	.002
UFOV Category	.606***	.385*	.087	.019

^a PMCT = peripheral motion enhancement threshold,

^b DPQ5 = driver perception questionnaire, 5 questions

^c ADQ15 = aging driver questionnaire, 15 questions

(i.e. Manchester Driver Behavior Questionnaire)

^d UFOV® = Useful Field of View

* p<.05, ** p<.01, *** p<.001, **** p<.0001, one-tailed.

Finally, to validate our DPQ instrument against the ADQ15, we calculated the correlation between scores on these two questionnaires within groups and overall. The results show a very strong correlation in all cases (overall, n = 31, r = .63, p < .001; younger drivers, n = 16, r = .59, p < .01; older drivers, n = 15, r = .73, p < .01). These

results validate the accident risk assessment utility of our questionnaire (DPQ5) against well-validated items of the widely used Aging Driver Questionnaire.

Discussion

Our findings suggest that a test of peripheral motion detection may be a potentially useful element of older driver assessment. In agreement with our predictions, our data show that the visual capacity of peripheral motion processing diminishes with age and that it correlates well with self-reported failure to detect hazards while driving. Specifically, we found a significant difference in PMCT between older and younger drivers, and significant partial correlations between PMCT and relevant elements of both the DPQ (Henderson and Donderi, 2005) and ADQ (Parker et al., 2000; Parker, 2005). Our findings show that the relationship between PMCT and self-reported detection failures while driving is not simply related through age, emerging more strongly when the latter is partialled out. This suggests that our instrument measures a visual processing component that is associated with safe driving across the lifespan, and is not biased against older drivers. Because age *per se* is not a reliable indicator of drivers' ability to operate a car safely (but see Horswill et al., 2008), driver assessment researchers strive to develop effective predictors of driving performance regardless of age. Indeed, Staplin et al. (2003) called for "...*improved detection of deficits in the functional abilities most important for safe driving. ... without regard to age per se*" (p.4, italics theirs). Our findings suggest that PMCT may potentially be a fair assessment tool for identifying drivers with relatively higher detection failure accident risk at any age. However, larger-scale tests will be required to determine if PMCT is a valid and reliable predictor of accident risk, and warrants inclusion in driving assessment test batteries.

Our motion detection task differed from other driving researchers' motion processing tasks in a number of important ways. First, we used Gabor stimuli, which comprise only a single spatial and temporal frequency. These are thus very simple and focused visual elements that are thought to activate a very specific set of early visual detectors in primary visual cortex and beyond (Devalois and Devalois, 1990). In contrast, the dots in a dot-motion task are comparatively complex, composed of a broad range of spatial and temporal frequencies. They thus activate a wide range of mechanisms in early vision. Therefore, the visual system may show greater robustness in detecting dot stimuli than Gabors as the visual system ages. That is, Gabor stimuli may allow a greater sensitivity to aging effects. Future studies would do well to compare the two techniques.

A second important difference between the PMCT and dot motion tasks is that the former tests peripheral vision while the latter tests central vision. Peripheral visual function is arguably more relevant to assessing drivers' inattention to road hazard occurring away from the point of fixation. Klauer et al. (2006) reported that 80 percent of the crashes and 65 percent of the near crashes recorded during the 100-car Naturalistic Driving Study involved the driver looking away from the forward roadway just prior to the onset of the conflict. If drivers tend to schedule their long glances away from the roadway in the apparent absence of a developing critical situation, a driver with relatively better PMCT may more likely detect a situation more than two seconds before its arrival and postpone their glance. However, a driver with deficient PMCT may be more likely to misallocate attention away from the forward roadway as an undetected critical situation develops.

The UFOV® test also involves the detection of stimuli in the periphery (subtests 2 and 3) as well as higher cognitive processes such as divided and selective attention. It has been widely used in the literature and has been found to correlate with driving performance on closed (Wood, 2002; Wood and Troubeck, 1995) and open road circuits (De Raedt and Ponjaert-Kristoffersen, 2000), and is a valid and reliable predictor of crash risk (Clay et al., 2005). Surprisingly, our results indicate that the PMCT and the UFOV® have little overlap when age is partialled out. Moreover, UFOV® was found not to correlate significantly with the two self-report measures of accident risk, which contrasts substantially with the strong relation between PMCT scores and these questionnaires. This finding may initially seem surprising, as UFOV® has been found to correlate with self-report measures in previous studies. For example, van Rijn et al. (2002) found that vision tests correlated with the responses of participants, some with vision impairments at the time of testing. They also found that UFOV® scores correlated significantly with self-reported assessment of the ability to drive in unfamiliar settings, and concluded that driving in unfamiliar settings likely required the use of attentional processes assessed by UFOV®. The apparent discrepancy between their study and ours may be explained by differences in the specific factors examined by the self-report instruments. In the current study, our participants answered questions relating to a failure to detect information (i.e. hazards) suddenly presented in the periphery. The DPQ5 questions as well as the selected ADQ questions were unrelated to driving in unfamiliar settings. Thus, UFOV® and PMCT may be measuring orthogonal performance factors, with the latter more related to simple visual detection and the former more related to the cognitive load of driving in new environments. In agreement with previous research (e.g. Wood et al., 2008), we

suggest that a battery incorporating multiple assessment tools will likely be necessary to confidently determine if a person is able to drive safely. The present study suggests that both PMCT and UFOV® could be useful elements of such a battery, although substantially more validation of PMCT is clearly necessary first.

A secondary goal of this study was to validate the DPQ5 questionnaire against questions selected a priori from the Aging Driver Questionnaire, chosen because they relate to a driver's ability to detect relevant information in the periphery. Our results showed that the two questionnaire scores were strongly related, validating our DPQ5 questionnaire.

Given the very preliminary nature of the current research initiative, we consider that the significant correlations of PMCT with self-report assessments of driving performance should be considered a legitimate first step toward identifying peripheral motion processing as an important visual function for safe driving. This finding definitely strengthens the hypothesized link between peripheral motion contrast threshold and accident risk resulting from failures of detection.

We propose that the next step will be to correlate PMCT findings with on road or simulator assessment performance in a large-scale study that incorporates a broader range of demographic variables and functional assessments of driver capabilities. Simulation scenarios presenting detection failure opportunities such as right-of-way incursions, left turns, and complex intersections are potentially fruitful options to further evaluate and validate PMCT against the risk for detection failure or motion processing error accidents most likely to involve older drivers. Our aim is to eventually achieve full validation of PMCT as an effective and reliable predictor of accident risk. We also plan to reduce the

time required to administer the test, making it practical for inclusion in driving assessment test batteries, thereby allowing at-risk drivers to be identified and their accident risks mitigated.

Author Note

This study has received approval from the University of Ottawa Ethics Review Committee and was conducted in compliance with the regulations to govern research on human participants. This study was financially supported by an Ontario Neurotrauma Foundation grant and a National Sciences and Engineering Research Council grant to Dr. Sylvain Gagnon, and by a National Sciences and Engineering Research Council grant to Dr. Charles Collin. Alexandre Bélanger was also funded by the National Sciences and Engineering Research Council as a Ph.D. graduate student.

References

- Assailly, J.P., Bonin-Guillaume, S., Mohr, A., Parola, A., Grandjean, R., Frances, Y.M., 2006. Les conducteurs âgés en bonne santé font plus d'erreurs et d'oublis que d'infractions. Enquête auprès de 904 volontaires. *La Presse Médicale* 35, 941-947.
- Ball, K.K., Roenker, D.L., Wadley, V.G., Edwards, J.D., Roth, D.L., McGwin, G., Raleigh, R., Joyce, J.J., Cissell, G.M., Dube, T., 2006. Can high-risk older drivers be identified through performance-based measures in a department of motor vehicles settings? *The American Geriatrics Society* 54, 77-84.
- Braitman, K.A., Kirley, B.B., Ferguson, S., Chaudhary, N.K., 2007. Factors leading to older drivers' intersection crashes. *Traffic Injury Prevention* 8, 267-274.

- Brietmeyer, B.G., Ganz, L., 1976. Implications of sustained and transient channels for theories of visual pattern masking, saccadic suppression, and information processing. *Psychological Review* 83, 1-36.
- Caird, J.K., Edwards, C.J., Creaser, J.I., Horrey, W.J., 2005. Older driver failures of attention at intersections: Using change blindness methods to assess turn decision accuracy. *Human Factors* 47, 235-249.
- Chikashi, M., Okubo, M., Mugishima, M.O., 1999. Effects of background color on the global and local processing of hierarchically organized stimuli. *Journal of Cognitive Neuroscience* 11, 1-8.
- Clay, O.J., Wadley, V.G., Edwards, J.D., Roth, D.L., Roenker, D.L., Ball, K.K., 2005. Cumulative meta-analysis of the relationship between useful field of view and driving performance in older adults: Current and future implications. *Optometry and Vision Science* 82, 724–731.
- Conlon, E., Herkes, K., 2008. Spatial and temporal processing in healthy aging: Implications for perceptions of driving skills. *Aging, Neuropsychology, and Cognition* 15, 446-470.
- Dellinger, A.M, Langlois, J.A., Li, G., 2002. Fatal crashes among older drivers: decomposition of rates into contributing factors. *American Journal of Epidemiology* 155, 234–241.
- De Raedt, R., Ponjaert-Kristoffersen, I., 2000. Can strategic and tactical compensation reduce crash risk in older drivers. *Age and Ageing* 29, 517-521.

- Desapriya, E., Subzwari, S., Fujiwara, T., Pike I., 2008. Conventional vision screening tests and older driver motor vehicle crash prevention. *International Journal of Injury Control and Safety Promotion* 15, 124–126.
- De Valois, R., De Valois, K., 1980. *Spatial vision*. Oxford University Press: New York..
- Di Stefano, M., Macdonald, W., 2003. Assessment of older drivers: Relationships among on-road errors, medical conditions, and test outcome. *Journal of Safety Research* 34, 415-429.
- Eberhard, J., 2008. Older drivers' 'high per mile crash involvement' - the implications for licensing authorities. *Traffic Injury Prevention* 9, 284-290.
- Freund, B., Colgrove, L.A., Burke, B.L., McLeod, R., 2005. Self-rated driving performance among elderly drivers referred for driving evaluation. *Accident Analysis and Prevention* 37, 613–618.
- Hakamies-Blomqvist, L., 2004. Safety of Older Persons in Traffic. In: *TRB's Conference Proceedings 27 Transportation in an Aging Society: A Decade of Experience*.
- Henderson, A.S., Donderi, D.C., 2005. Peripheral motion contrast sensitivity and older drivers' detection failure accident risk. In: *Proceedings of the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, Rockport, Maine, 41-50.
- Horswill, M.S., Marrington, S.A., McCullough, C.M., Wood, J., Pachana, N.A., McWilliam, J., Raikos, M.K., 2008. The hazard perception ability of older drivers. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences* 63, 212-218.

- Horwitz, G.D., Newsome, W.T., 1999. Separate signals for target selection and movement specification in the superior colliculus. *Science* 284, 1158-1161.
- Janke, M.K., 1991. Accidents, mileage and the exaggeration of risk. *Accident Analysis and Prevention* 23, 183-188.
- Klauer, S.G., Dingus, T.A., Neale, V.L., Sudweeks, J.D., Ramsey, D.J., 2006. The Impact of Driver Inattention on Near-Crash/Crash Risk: An Analysis Using the 100-Car Naturalistic Driving Study Data. Report DOT HS 810 594. National Highway Traffic Safety Administration. Washington, DC.
- Lajunen, T., Parker, D., Summala, H., 2004. The Manchester Driver Behaviour Questionnaire: a cross-cultural study. *Accident Analysis and Prevention* 42, 1-8.
- Langford, J., Andrea, D., Fildes, B., Williams, T., Hull, M., 2005. Assessing responsibility for older drivers' crashes. Austroads Project RS.UB.507, Sydney, Australia.
- Langford, J., Methorst, R., Hakamies-Blomqvist, L., 2006. Older drivers do not have a high crash risk-a replication of low mileage bias. *Accident Analysis and Prevention* 38, 574-578.
- Li, G., Braver, E., Chen, L., 2003. Fragility versus excessive crash involvement as determinants of high death rates per vehicle-mile of travel among older drivers. *Accident Analysis and Prevention* 35, 227-235.
- Livingstone, M., Hubel, D., 1988. Segregation of form, color, movement, and depth: Anatomy, physiology, and perception. *Science* 240, 740-749.
- Massie, D.L., Campbell, K.L., Williams, A.F., 1995. Traffic accident involvement rates by driver age and gender. *Accident Analysis and Prevention* 27, 73-87.

- Mayhew, D.R., Simpson, H.M., Ferguson, S.A., 2006. Collisions involving senior drivers: high-risk conditions and locations. *Traffic Injury Prevention* 7, 117-124.
- National Highway Traffic Safety Administration, 2001. *Traffic Safety Facts 2000: Older Population*. DOT HS 809 328.
- Obriot-Claudet, F., Gabaude, C., 2004. The Driver Behaviour Questionnaire: A French Study Applied to Elderly Drivers. French National Institute for Transport and Safety Research, Laboratory of Ergonomics and Cognitive Science applied to Transport, France.
- Owsley, C., Sekuler, R., Siemsen, D., 1983. Contrast sensitivity throughout adulthood. *Vision Research* 23, 689-699.
- Özkan, T., Lajunen, T., Summala, H., 2006. Driver Behaviour Questionnaire: A follow-up study. *Accident Analysis and Prevention* 38, 386-395.
- Parker, D., 2005. Personal communication. December, 2005.
- Parker, D., McDonald, L., Rabbitt, P., Sutcliffe, P., 2000. Elderly drivers and their accidents: The Aging Driver Questionnaire. *Accident Analysis and Prevention* 32, 751-759.
- Parker, D., Reason, J.T., Manstead, A.S.R. and Stradling, S.G., 1995. Driving errors, driving violations and accident involvement. *Ergonomics* 38, 1036-1048.
- Rafal, R., Henik, A., Smith, J., 1991. Extrageniculate contributions to reflex visual orienting in normal humans: A temporal hemifield advantage. *Journal of Cognitive Neuroscience* 3, 322-328.

- Raghuram, A., Lakshminarayanan, V., 2006. Motion perception tasks as potential correlates to driving difficulty in the elderly. *Journal of Modern Optics* 53, 1343-1362.
- Raghuram, A., Lakshminarayanan, V., Khanna, R., 2005. Psychophysical estimation of speed discrimination. II. Aging effects. *Journal of the Optical Society of America A* 22, 2269-2280.
- Retting, R. A., Weinstein, H. B., Solomon, M., 2003. Analysis of motor-vehicle crashes at stop signs in four US cities. *Journal of Safety Research* 34, 485-489.
- Ross, L.A., Clay, O.J, Edwards, J.D., Ball, K., Wadley, V.G., Vance, D.E., Cissell, G.M., Roenker, D.L., Joyce, J.J., 2009. Do older drivers at risk for crashes modify their driving over time? *Journals of Gerontology: Psychological Sciences* 64B, 163-170.
- Schneider, K.A., Kastner, S., 2005. Visual responses of the human superior colliculus: A high-resolution functional magnetic resonance imaging study. *Journal of Neurophysiology* 94, 2491-2503.
- Sekuler, R., Owsley, C., 1982. The spatial vision of older humans. In R. Sekuler, D. Kline, K. Dismukes (Eds.), *Aging and Human Visual Function*, 185-202. New York: Alan R. Liss.
- Sivak, M., 1996. The information that drivers use: Is it indeed 90% visual? *Perception* 25, 1081–1089.
- Skottun, B.C., 2000. The magnocellular deficit theory of dyslexia: the evidence from contrast sensitivity. *Vision Research* 40, 111-127.

- Skottun, B.C., Skoyles, J.R., 2008. Temporal frequency and the magnocellular and parvocellular systems. *Neuro-Ophthalmology* 32, 43-48.
- Stamatiadis, N., Deacon, J.A., 1995. Trends in highway safety: Effects of an aging population on accident propensity. *Accident Analysis and Prevention* 27, 443-459.
- Staplin, L., Gish, K. W., Decina, L.E., Lococo, K., McKnight, A.S., 1998. Intersection Negotiation Problems of Older Drivers, Volume I: Final Technical Report. USDOT/NHTSA Contract No. DTNH22-93-C-05237. Washington, DC.
- Staplin, L., Lococo, K., McKnight, A.J., McKnight, A.S., Odenheimer, G., 1998. Intersection Negotiation Problems of Older Drivers, Volume II: Background Synthesis on Age and Intersection Driving Difficulties. USDOT/NHTSA Contract no. DTNH22-93-C-05237. Washington, DC.
- Staplin, L., Lococo, K., Gish, K. W., Decina, L.E., 2003. Model Driver Screening And Evaluation Program Final Technical Report, Volume 1: Project Summary And Model Program Recommendations. USDOT HS 809 582.
- Steinman, B.A., Steinman, S.B., Lehmkuhle, S., 1997. Transient visual attention is dominated by the magnocellular stream. *Vision Research* 37, 17-23.
- Summala, H., Mikkola, T., 1994. Fatal accidents among car and truck drivers: Effects of fatigue, age, and alcohol consumption. *Human Factors* 36, 315-326.
- Sylvester, R., Josephs, O., Driver, J., Rees, G., 2007. Visual fMRI responses in human superior colliculus show a temporal–nasal asymmetry that is absent in lateral geniculate and visual cortex. *Journal of Neurophysiology* 97, 1495-1502.

- van Rijn, L. J., Wilhelm, H., Emesz, M., Kaper, R., Heine, S., Nitsch, S., Grabner, G., Volker-Dieben, H. J., 2002. Relation between perceived driving disability and scores of vision screening tests. *British Journal of Ophthalmology* 86, 1262-1264.
- Wainer, H., 1976. Estimating coefficients in linear models: It don't make no nevermind. *Psychological Bulletin* 83, 213-217.
- Wood, J.M., 2002. Age and visual impairment decrease driving performance as measured on a closed-road circuit. *Human Factors* 44, 482–494.
- Wood, J., Anstey, K. J., Kerr, G., Lord, S. R., Lacherez, P., 2008. A multi-domain approach for predicting older driver safety under in-traffic road conditions. *Journal of the American Geriatric Society* 56, 986-993.
- Wood, J.M., Owens, D.A., 2005. Visual acuity does not predict drivers' recognition performance but contrast sensitivity does. *Optometry and Vision Science* 82, 698-705.
- Wood, J.M., Troutbeck, R., 1995. Elderly drivers and simulated visual impairment. *Optometry and Vision Science* 72, 115-124.

Additional Study 2 Results and Discussion

Although Study 2 was published in *Accident Analysis & Prevention* in 2010, an earlier version was presented as a poster and paper at the 4th International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design (Driving Assessment 2007). (The poster content is shown in Appendix B, including two additional tables, and two figures.) With the exceptions of PMCT difference between the two age cohorts, and the correlation of age with UFOV subtests, the AA&P article shown above focused on the relations between the vision measures and the driving measures independent of age. The poster contains additional interesting information. For example, Figure B-1 is an interesting scatterplot of PMCT by age.

In addition, Table B-1 shows that across all 31 participants, PMCT and DPQ5 had a correlation of .484 ($p < .01$), but when age was partialled out, their correlation increased to .549 ($p < .001$), as shown in Table VI-1 (duplicated in Table B-4). Similarly, Table B-1 shows that across all 31 participants, PMCT and ADQ15 were not significantly correlated ($r = .252$), but with age partialled out, Table 1 (and Table B-4) show a significant partial correlation of .389 ($p < .05$). Inspection of Figure B-2 shows that the trendlines of DPQ5 on PMCT within the younger and older cohorts have a similar slope, and that the older driver group is simply displaced to the right along the horizontal axis relative to the younger drivers. Partialing out the age variable removed that between-group variance and effectively shifted the two groups together along the axis. Given the within-group correlations between DPQ5 and PMCT of .61 and .55 for younger and older drivers respectively, removing the between-group variance led to the significant

correlation increase. That is, a systematic effect of age group on DPQ5 vs. PMCT underlies some of the partialled out age effects.

Note that the PMCT standard deviation of the younger participants (3.00 dB) was not different from that of the older participants (3.05 dB). However, Table B-1 shows that the older drivers' correlation between PMCT and DPQ5 was much lower than the younger drivers' correlation (.492 versus .619 respectively). Perhaps the *unrecognized* age-related change in older drivers' PMCT added additional variance to their DPQ5 self-reports, making it a less accurate assessment of detection failure accident risk. Then why is there not additional age-related variance in PMCT? Perhaps the older drivers with the lowest (i.e., best) PMCT are more likely to incur age-related loss relative to their cohort, which would shift the distribution without spreading it out. A longitudinal study of PMCT and age would be required to test that hypothesis. However, looking ahead to Study 3, PMCT variance of the older drivers was more than four times that of the younger drivers, so perhaps the equal PMCT variance across groups in Study 2 was simply a statistical anomaly arising from the small sample size.

VII. Introduction to the Third Study

Lee, Cameron, and Lee (2003) assessed 129 older drivers using both a simulator and an on-road test. Simulator driving performance explained over two-thirds of the variance in on-road test performance. Driving simulators also enable the introduction of challenging scenarios that could never be safely used in on-road tests, and of course experimenters are able to control simulator scenarios much more exactly than circumstances can be managed during an on-road test. Although our previous studies used self-report measures of accident risk, as have numerous other well-accepted studies linking visual function with driver safety, questionnaire measures requiring self-knowledge clearly add an additional source of variability to the dependent measure. Furthermore, many practicing professionals in the field of driving safety will be more likely to accept a simulator assessment of driving performance as a valid dependent measure of accident risk than they would a self-report questionnaire assessment.

In addition, the third study gave a further opportunity to increase the usability of the PMCT test by shortening the test time in two ways. First, we changed the temporal forced choice to a spatial forced choice. Second, we changed from a staircase methodology to the method of descending limits. Together these changes reduced test time to ten minutes from twenty minutes, bringing the test closer to a practical length for DMV staff and medical practitioners.

VIII. Near Peripheral Motion Contrast Threshold

Predicts Older Drivers' Simulator Performance

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Abstract

Our group has previously demonstrated that peripheral motion contrast threshold (PMCT) is significantly associated with self-reported accident risk of older drivers (questionnaire assessment), and with Useful Field of View® subtest 2 (UFOV2). It has not been shown, however, that PMCT is significantly associated with driving performance. Using the method of descending limits (spatial two-alternative forced choice) we assessed motion contrast thresholds of 28 young participants (25–45), and 21 older drivers (63–86) for 0.4 cycle/degree drifting Gabor stimuli at 15 degrees eccentricity and examined whether it was related to performance on a simulated on-road test and to a measure of visual attention (UFOV® subtests 2 and 3). Peripheral motion contrast thresholds (PMCT) of younger participants were significantly lower than older participants. PMCT and UFOV2 significantly predicted driving examiners' scores of older drivers' simulator performance, as well as number of crashes. Within the older group, PMCT correlated significantly with UFOV2, UFOV3, and age. Within the younger group, PMCT was not significantly related to either UFOV® scores or age. Partial correlations showed that: substantial

association between PMCT and UFOV2 was not age-related (within the older driver group); PMCT and UFOV2 tapped a common visual function; and PMCT assessed a component not captured by UFOV2. PMCT is potentially a useful assessment tool for predicting accident risk of older drivers, and for informing efforts to develop effective countermeasures to remediate this functional deficit as much as possible.

Introduction

Collisions per mile begin to increase after the age of 65, and more so after the age of 70 (Carsten, 1981; Cerrelli, 1973; Chipman et al., 1993; Dellinger et al., 2002; Eberhard, 2008; HLDI, 2005; Li et al., 2003; Massie et al., 1995; NHTSA, 2001; Rallabandi & Dissanayake, 2009). However, accidents per licensed driver do not increase until about the age of 85, due to the downward trend in driving miles with age (Braver & Trempe, 2004; Chipman et al., 1993). Numerous cohort effects, aging effects, technological advances and demographic trends are impacting on older drivers' safety. The older population is increasing in absolute terms and in proportion of the population as the first members of the Baby Boom generation reached 65 years of age in 2010. The U.S. population aged 65 and older is expected to more than double in the next thirty years, from 40.2 million in 2010 to 81.2 million by 2040 (U.S. Census Bureau, 2008). The proportion of the older population who are active drivers is increasing (Cheung & McCartt, 2011), and the annual mileage of each older driver is increasing (Burkhardt et al., 1998).

Although some researchers had predicted from these projections that fatalities involving older drivers would increase by a factor of up to three or more by 2030 (Burkhardt et al., 1998; Hu et al., 2000; Lyman et al., 2002), Cheung and McCartt (2011)

examined fatalities per licensed driver from 1997 to 2008, broken out into four age cohorts. While middle-aged drivers experienced a 23% drop in fatality rate, the 70-74 year old rate dropped by 30%, the 75-79 year old rate by 35%, and the 80+ year old rate by 47%. They concluded that the steeper fatality rate decline with age was due to declining crash rate and to more robust health and lower frailty relative to earlier cohorts. However, the proliferation of vehicles equipped with side airbags also offer a preferential benefit to older drivers, who tend to be involved in multiple vehicle side impact crashes at intersections, as noted below.

Consistent with Cheung and McCartt's analysis, fatality counts for vehicle occupants (including drivers, passengers, and motorcyclists) aged 65 or more have been trending downward since 1998, according to Fatality Analysis Reporting System (FARS) data (NHTSA, 2011), while overall vehicle occupant fatalities only began trending downward in 2006. However, from 2007 to 2009, when fatalities to occupants 65 and older declined by 11%, fatalities to occupants under 65 declined by 20%.

Regarding crash rates for any severity, Cheung and McCartt reported that all police-reported property-only crashes also declined more for older drivers than for the 35-54 year old comparison group, to demonstrate older drivers' reduced crash propensity. However, insurance claim data show no such relative decrease. The Highway Loss Data Institute (HLDI) (2009) reported that from 1997 to 2006, insurance collision claims per 1000 insured vehicle years declined by 9% for middle-aged drivers, but only 5-7% for older drivers. An alternate explanation for this discrepancy is that some older drivers may be filing insurance claims after an accident without reporting the accident to the police. In addition, changing economic conditions may even have encouraged some licensed older

drivers to become inactive drivers, inflating Cheung and McCartt's exposure estimate (i.e., licensed drivers) but not the HLDI exposure estimate (i.e., ensured vehicles).

Biases

Several biases inflate the fatality rate per distance of older drivers.

Frailty bias. First, older drivers are frailer, and more likely to die than a younger driver in a crash of a given energy (Evans, 1988). Dellinger et al. (2002) applied a “decomposition” analysis to determine the relative influences of frailty, accident risk per distance driven, and exposure in older drivers' overall fatality risk, and determined that frailty (fatal crashes per 1,000 crashes) had a lesser influence on older driver fatality rate than either crash propensity or annual mileage. On the other hand, Li et al. (2003) also used decomposition analysis to determine the contribution of frailty to older drivers' over-representation in fatal accidents per distance travelled, and estimated that 60% of the elevated fatality rate of drivers 85 and over was related to frailty. However, they used police-reported crashes from National Automotive Sampling System (NASS) / General Estimates System (GES) – a database containing a sample of approximately 50,000 representative police-reported accidents each year – to estimate crash propensity, which may underestimate property-damage-only crashes as noted above, increasing the frailty metric by shrinking the denominator, and decreasing the crash propensity metric by shrinking the numerator, leading to an overestimation of the frailty contribution to the fatality rate of older drivers.

Low-mileage bias. Langford et al. (2006) analyzed self-reported travel distance and accident survey data gathered from 47,502 Dutch drivers between 1990 and 2003, and concluded that the age-related accident rate increase was due entirely to the

increasing accident rate incurred by the 10% of older drivers who drove fewer than 3,000 km a year, and that all other drivers showed decreasing accident rates as they got older. However, the conclusion can be critiqued on several points. First, Staplin et al. (2008) observed that Langford et al. relied entirely on self-reported collision and risk exposure (i.e., annual mileage) data for their analysis. Those data are notoriously inaccurate. Mileage estimates are extremely inaccurate (Betz & Lowenstein, 2010; Huebner et al., 2006; Staplin, Gish, et al., 2003), as are accident self-report data (McGwin et al., 1998). A further reason to question the self-reported mileage estimates reported by Langford et al. stated that the cohort of drivers 75 and over had the *smallest* proportion of low-mileage drivers compared to younger age groups, which is certainly not characteristic of North American driver demographics, and suggests that the oldest drivers overestimated their annual mileage most of any cohort.

Second, Langford et al. acknowledged that despite the overall size of their sample, the results were not statistically significant, because the analysis rested on an average of eight accidents per year incurred by low-mileage drivers 75 years and older. The final point against the low mileage bias is more theoretical than empirical. Janke (1991) suggested that causality might go in the other direction, and that less competent drivers may tend to drive less. In that case, the low mileage bias becomes a simple observation of drivers self-limiting their risk, perhaps due to recognition of their diminishing functional capabilities.

Urban driving. Although traffic experts consider limited access highways to be safer because they offer far fewer opportunities for traffic conflict than urban streets do (Bédard, Weaver, et al., 2008) and Ontario drivers living in rural areas have a

significantly lower accident rate by distance traveled or by traveling time than Ontario drivers living in urban areas (Chipman et al., 1993), older drivers tend to avoid highways and other high-speed roads, increasing their accident rate relative to younger drivers (Dissanayake & Perera, 2009; Di Stephano & MacDonald, 2003; Janke, 1991). (However, the lower energy of urban crashes will somewhat mitigate the effect of frailty.)

Chipman et al. (1993) proposed that driving time rather than driving distance as a risk exposure metric would eliminate some of the bias against drivers who travel more in urban, intersection-dense high-risk environments, and against older drivers who prefer to drive in that environment.

Accident Characteristics.

Accident-involved older drivers are more likely to have committed causal right-of-way violations and to be assigned accident responsibility (Clarke et al., 2010; Di Stefano & Macdonald, 2003; Langford et al., 2005; Massie et al., 1995; Mayhew et al., 2006; Stamatiadis & Deacon, 1995), and older drivers are most significantly overrepresented in motor vehicle crashes involving undetected crossing vehicles at intersections (Bao & Boyle, 2009; Braitman et al., 2007; Caird et al., 2005; Clarke et al., 2009; Clarke et al., 2010; Daigneault et al., 2002; Dissanayake & Perera, 2009; Edwards et al., 2003; Hellinga, 1999; Langford & Koppel 2006; Levin et al., 2009; Oxley et al., 2006; Raglund & Zabyshny , 2003; Retting et al., 2003; Schlag 1993; Skyving et al., 2009; Stamatiadis & Deacon, 1995; Staplin, Gish et al., 1998: Staplin, Lococo et al., 1998; Subramanian & Lombardo, 2007). Consistent with older drivers' tendency to have multivehicle collisions at intersections, older drivers are particularly at risk of incurring side impact crashes (Austin & Faigin, 2003; Viano et al., 1990). Given accident

involvement, older drivers are more likely to have committed a right of way (ROW) violation and to be found at fault for the accident (Bédard, Porter et al., 2008; Braitman et al., 2007; Clarke et al., 2009; Clarke et al., 2010; Dissanayake & Perera, 2009; Di Stefano & Macdonald, 2003; Eustace & Wei, 2010; Hakamies-Blomqvist, 1993; Langford et al., 2005; Levin et al., 2009; Massie et al., 1995; Mayhew et al., 2006; NHTSA, 2010; Rabbitt & Parker, 2002; Rallabandi & Dissanayake, 2009; Retting et al., 2003; Schlag, 1993; Stamatiadis & Deacon, 1995; Strauss, 2005; Subzwari et al. 2009; Williams & Shabanova, 2003).

A Finnish study involving immediate and rigorous investigation of 1357 fatal multi-vehicle accidents (not involving alcohol) by an on-site expert team determined that of the five largest categories of primary causal factors, only visual attention failures (i.e., "... the drivers missed one or more other vehicles, according to the conclusion of the investigation team. (p. 320") increased with driver age (Summala & Mikkola, 1994).

Vision Measures and Driving

Most of the information necessary to drive safely is acquired through the visual system, although of course many cognitive and physical functions are also critical to safe driving. However, impairment of a critical function of visual perception may well affect critical functions later in the information processing continuum (from sensory to perceptual to cognitive).

Visual acuity (VA) declines strongly and monotonically with age from the age of 18 (Owsley et al., 1983; Salthouse, 1996). However, although widely used by most licensing authorities around the world to assess older drivers, VA is a poor predictor of older driver performance (Wood & Owen, 2005) or accident risk (Cross et al., 2009;

Keffe et al., 2002), although Rabbitt and Parker (2002) did find that VA was significantly associated with older driver performance, although not with their accident involvement.

In contrast, stronger results have been achieved with attention-based visual assessments such as UFOV®. These tests are known to be valid and reliable instruments for identifying older drivers with a history of prior accidents (Ball et al., 1993; Clay et al., 2005; Goode et al., 1998; Owsley et al., 1991; Sims et al., 1998), predicting subsequent motor vehicle collisions (Ball et al., 2006; Clay et al., 2005; Cross et al., 2009; Rubin et al., 2007; Sims et al., 2000), and predicting performance in a driving simulator (Roenker et al., 2003). UFOV® has also been found to correlate with driving performance on closed (Wood, 2002; Wood & Troubeck, 1995) and open road circuits (De Raedt & Ponjaert-Kristoffersen, 2000; Roenker et al., 2003), and to correlate with self-report assessments of driving ability (van Rijn et al., 2002). See Clay et al. (2005) for a meta-analysis of much of that work.

Stronger results have also been achieved using sensory-based measures of contrast sensitivity (CS) such as the Pelli-Robson Low-Contrast Letter Chart or VISTECH gratings (Horswill et al., 2008; Wood & Owens, 2005), although the association between stationary central contrast sensitivity measures and driving safety remains equivocal (Owsley & McGwin, 2010).

Visual motion sensitivity is a strong predictor of driving ability (Wood, 2002; Wood et al., 2008), and motion contrast sensitivity in central vision is known to decline with age (Owsley et al., 1983; Sekuler & Owsley, 1982) as does speed discrimination of high contrast drifting gratings (Raghuram et al., 2005). Other researchers have also found that age-related motion processing declines correlate strongly with driving performance

(Conlon & Herkes, 2008; De Raedt & Ponjaert-Kristoffersen, 2000; Gabaude & Ficout, 2005; Raghuram & Lakshminarayanan, 2006). These researchers used central or near-central motion stimuli, according to the model that an age-related decline in motion perception may reduce some older drivers' ability to discriminate complex motion patterns in order to understand their driving environment, judge appropriately, and respond to changes safely and in a timely manner. However, our model proposes that a critical visual function is to detect and orient on novel stimuli, and that measuring that function will help to identify high-risk drivers.

Henderson and Donderi (2005) proposed that an age-related decline in motion contrast sensitivity in the near periphery, analogous to the known decline in motion contrast sensitivity in central vision (Owsley et al., 1983; Sekuler & Owsley, 1982) may reduce the power of a moving stimulus to attract visual attention (Steinman et al., 1997) and to produce a reflexive saccadic eye movement towards it (Fuchs et al., 1985; Stein, 1984), thereby impairing some older drivers' visual orienting reflex toward unexpected objects. Henderson and Donderi found that peripheral motion contrast thresholds (PMCT) correlated significantly with self-report accident risk questionnaires.

Our group's earlier work (Henderson et al., 2007, 2010) replicated and extended those findings. We again used self-report accident risk questionnaires. We designed a motion test whose characteristics were based on what is known about how motion is processed in the brain and how visual motion perception degrades with age. To do so, we considered the characteristics of the magnocellular pathway, which is widely understood to be responsible for detecting movement, identifying its retinal location position, and allocating attention to that location (Chikashi et al., 1999; Horwitz & Newsome, 1999;

Livingstone & Hubel, 1988; Steinman et al., 1997). The magnocellular pathway is optimally responsive to spatial frequencies below about 1.5 cpd (Skottun, 2000); it is responsive to relatively higher temporal frequencies than the sustained, form processing parvocellular pathway (Skottun & Skoyles, 2008); and it is relatively more peripherally distributed than the parvocellular pathway. The magnocellular pathway also manifests age-related deficits (Scheffrin et al., 1999). Henderson et al. (2010) explained why a peripheral low spatial high temporal frequency sine wave grating is an optimal magnocellular stimulus, and provided a detailed rationale for using a peripheral motion contrast threshold test to probe older driver performance. Our results showed that the visual capacity of peripheral motion processing (as measured by PMCT) diminished with age and that it correlated well with self-reported failure to detect hazards while driving. We also found that PMCT correlated strongly with UFOV® subtest 2 (divided attention) and subtest 3 (selective attention), although those UFOV® subtests were not significantly related to self-reported accident risk.

Driving simulators provide a powerful, flexible means to manipulate driving scenarios in a controlled and safe environment, thereby taxing the visual functions that are important for mitigating traffic conflicts and safely negotiating the driving environment and reacting to hazards. Accordingly, in the current study we tested for relations between older drivers' PMCT scores and driving simulator performance scores (i.e., rater scores and crashes). We tested for an age-related decline in PMCT across two age groups, and within a sample of older drivers. We also tested for a relation between rater scores and number of crashes in the simulator. This was done because Owsley and McGwin (2010) observed that there is little empirical evidence of a link between

evaluated driving performance and subsequent crash involvement. Finally, we administered all UFOV® subtests (Ball et al, 2006) in order to assess their relationship with the PMCT measure.

Method

Participants

A younger driver sample of 28 volunteer participants consisted of 16 men and 12 women between 25 and 45 years of age ($M = 30.1$, $SD = 6.51$). The initial older driver sample consisted of 23 men and 5 women between 63 and 86 years of age ($M = 70.1$, $SD = 4.99$), but 5 participants did not finish the testing due to simulator adaptation syndrome, and 2 participants did not complete the questionnaires. The final sample of 21 older drivers consisted of 17 men and 4 women between 63 and 82 years of age ($M = 69.0$, $SD = 4.20$). Gender distributions within the samples precluded testing for gender effects.

All participants had at least 5 years of driving experience, and all reported good mental and physical health with no history of neurological, psychiatric or substance abuse problems. Participants were tested while wearing their normal visual correction. The participants were Ottawa residents and received 20 dollars for their participation.

Vision Measures

Peripheral motion contrast threshold (PMCT). PMCT was determined for 0.4 cycles per degree Gabor stimuli (a vertical sine wave grating drifted centripetally at 13.75 degrees/sec within a Gaussian window spanning approximately ten degrees) presented at fifteen degrees horizontal eccentricity and five degrees vertical eccentricity (i.e., four possible stimulus locations), within a half-sine temporal window of 1.5 seconds duration, preceded and followed by a 0.5 second blank interval. Gratings were presented on two

gamma-corrected CRT monitors 65 cm distant from the head fixation point. Mean luminance was 53.9 candelas per meter². Luminance resolution was increased two bits by spatial jittering – the smallest luminance increase was a single bit in a single pixel of each 2x2 pixel area. Stimulus frames were also interleaved with blank frames of the same overall luminance, effectively doubling luminance resolution (i.e., adding one bit) by truncating the upper half of the contrast range.

The stimuli were generated using MATLAB software on an IBM PC running Windows XP. Stimulus contrast was recorded in decibel units (dB), which is $20 \cdot \log(\text{Michelson contrast})$.

The method of descending limits procedure consisted of eight blocks (four left and four right) of descending contrast spatial two-alternative forced choice trials. A block began at well above threshold contrast. Two blocks were run simultaneously – that is, left and right trials were randomly interleaved. In the first four blocks, contrast decreased 2 dB from the last trial on that side, and in the last four blocks, contrast decreased 1 dB from the last trial on that side. During a single trial, a participant looked directly ahead at a lit LED fixation point, a Gabor stimulus was presented at one of the four possible locations, a horizontal line was then presented to indicate the side of the stimulus presentation, and the participant indicated whether the Gabor stimulus had appeared above or below the line's location. A trial was discarded if the participant made an eye movement before the line appeared. The two blocks ended when an error had been made on each side. Contrast threshold was recorded as one contrast step higher than the stimulus contrast for the first error on that side (because the infinite geometric series describing error probability below threshold converges to one). Peripheral motion

contrast thresholds (dB) were averaged across the two sides and eight blocks for each participant. All participants were able to complete the PMCT procedure within 10 minutes.

Useful Field of View (UFOV®). All UFOV® subtests of visual attention (speed of processing, divided attention, selective attention), which are known to be a valid and reliable test for predicting older drivers' crashes and at fault accidents (Ball et al, 2006), were also administered to younger and older participants.

Driving Performance Measure³

A high fidelity STISIM driving simulator (Systems Technology Inc., Build 2.08.04) presented a virtual roadway environment on three wide screens using three NEC projectors to yield a field of view of 80 degrees. The simulator software allows the experimenter to design urban and suburban roadway environments including interactive vehicles on all lanes, buildings, traffic control devices, and pedestrians through advanced vehicle dynamics and image generation. The virtual environment is supplemented with realistic audio effects providing acceleration cues. The software was run on a Windows XP operating system and Intel x86 Model 15 Family computers with a processing speed of 2394 MHz (four systems required).

Participants completed a 10-minute training session of increasing complexity followed by a 20-minute evaluation course. The evaluation course was patterned after a standard on-road driving test in residential, highway, and commercial environments. The

³ Thesis note: Participants also completed the 5 direct questions from the Driver Perception Questionnaire and the 15 questions from the Manchester Driver Behaviour Questionnaire, but their self-report responses did not relate at all to the vision measures or to simulator performance. Therefore the questionnaire data were not included in the analysis.

experimenter assessed drivers' simulator performance using the evaluation procedure employed by Bédard, Porter, et al. (2008) – that is, the experimenter used an instrument developed for on-road evaluation of driving fitness to assign demerit points (RaterScore) for driving errors involving starting, stopping, signal violations, vehicles moving on roadway, passing, speed, and turning. Crashes were also recorded by the STISIM drive software.

Results

Pearson Product-Moment correlations, step-wise regressions, and associated tests of significance were calculated across age, visual function (PMCT, UFOV®), and driving simulator performance using SAS Version 9.1. Where appropriate, tests were directional (i.e., one-tailed). A p-value of $< .05$ was considered statistically significant for statistical tests.

Table 1 shows group statistics and between-group analyses of independent variables (vision measures) and dependent variables (driving measures).

Table 1

Between-Group Statistics and Analyses

	Younger drivers	Older drivers	t-statistics
	Mean (SD)	Mean (SD)	(unequal variances)
<i>n</i>	28	21	
Age	30.1 (6.51)	69.0 (4.20)	
PMCT ^a (dB)	-47.0 (1.8)	-43.3 (3.79)	4.11***
UFOV ^b 1	16.7 (0)	26.4 (28.7)	1.55
UFOV2	24.8 (19.3)	86.5 (93.6)	2.98**
UFOV3	70.7 (58.9)	193.0 (57.4)	7.30***
Crash	0.61 (1.07)	0.62 (.80)	0.04
RaterScore	52.3 (24.3)	65.1 (43.4)	1.21

^a PMCT (dB): peripheral motion enhancement threshold (decibels)

^b UFOV: Useful Field of View.

* $p < .05$, one-tailed.

** $p < .01$, one-tailed.

*** $p < .001$, one-tailed.

Younger drivers had significantly lower PMCT than older drivers (lower values indicate better performance for all measures). Note also that the PMCT variance of the older group was more than four times higher than that of the younger group, which is consistent with other studies showing that performance variability increases with age (Landy, 1992; Tsang, 1997, 2003). UFOV1 was not significantly different between

groups, likely due to a floor effect for younger drivers. Younger drivers' UFOV2 scores were moderately lower than older drivers' scores, and younger drivers' UFOV3 scores were much lower than older drivers' scores. Driving measures were not significantly different between groups.

Table 2 shows correlations among age, vision measures and driving measures for the older driver group. Age was found to be strongly related to PMCT and UFOV2 and moderately to UFOV3 within the older driver group. As expected, no significant effect of age on PMCT was found within the younger group. Within the younger group, neither PMCT nor any UFOV subtest was associated with any driving measure.

Table 2

Pearson Product Moment Correlations between Visual Function Measures, Age, and Simulator Performance (Older, N = 21)

	PMCT	Age	Crash	RaterScore
PMCT ^a	1	.73***	.63***	.66***
Age	.73***	1	.33	.40*
UFOV ^b 1	.09	-.1	.16	-.05
UFOV2	.74***	.48*	.72***	.58**
UFOV3	.50**	.44*	.45*	.29

^a PMCT: peripheral motion enhancement threshold

^b UFOV: Useful Field of View.

* $p < .05$, one-tailed.

** $p < .01$, one-tailed.

*** $p < .001$, one-tailed.

For older drivers, PMCT was very strongly associated with UFOV2, suggesting that the two vision measures tap common or overlapping visual functions, as we have suggested before (Henderson et al., 2007). PMCT was very strongly associated with crashes and with drivers' overall assessed simulator performance (RaterScore). UFOV2 was also very strongly associated with crashes and strongly associated with RaterScore. Age was very strongly correlated with PMCT, and moderately correlated with UFOV2 (divided attention), UFOV3 (selective attention), and RaterScore.

Not shown in the tables is the correlation between RaterScore and Crash for older drivers ($n=21$, $r=.73$, $p<.001$) and for younger drivers ($n=28$, $r=.03$, ns), showing that for older drivers in a simulator, driving performance evaluation score is a very strong indicator of simulator accident risk.

Figure 13 shows the compelling relation between PMCT and older drivers' simulator performance (higher RaterScore and PMCT scores indicate poorer performance.) In addition to showing scored simulator performance plotted against PMCT, Figure 13 also shows the number of crashes incurred by each driver. Note that three of the four two-crash drivers (triangles) had the three poorest PMCT scores, and that the six poorest RaterScores included the four two-crash drivers.

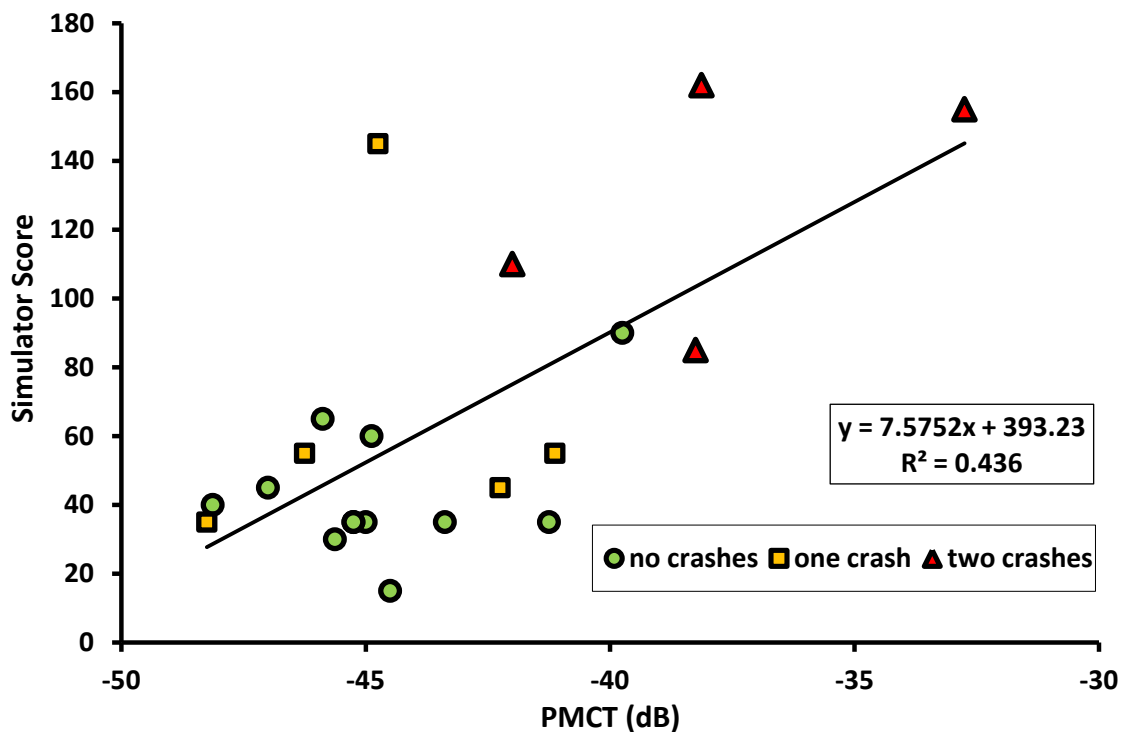


Figure 13. Simulator score on PMCT (older drivers)

(Note that two points are co-located at -45.25, 35)

Table 3 shows partial correlations of vision measures on driving simulator performance, holding single independent variables constant, to assess age mediation of vision measures to driving performance, and to determine if UFOV2 and PMCT are measuring the same visual function.

Table 3

Partial Correlations between Selected Variables (Older, N = 21)

Age constant	UFOV2	UFOV3	Crash	RaterScore
PMCT ^a	.650***	.295	.599**	.593**
UFOV ^b 2	1	.558**	.673***	.484*
PMCT constant	Age	UFOV3	Crash	RaterScore
UFOV2	-.133	.479*	.482*	.183
UFOV3	.479*	1	.192	-.061
UFOV2 constant	Age	PMCT	Crash	RaterScore
PMCT	.641**	1	.212	.424*
UFOV3	.193	.047	-.040	-.136

^a PMCT: peripheral motion enhancement threshold

^b UFOV: Useful Field of View.

* $p < .05$, two-tailed.

** $p < .01$, two-tailed.

*** $p < .001$, two-tailed.

Table 2 shows high correlations ($p < .001$) of PMCT and UFOV2 with RaterScore. In comparison, Table 3 shows that controlling for age, both PMCT and UFOV2 were significantly related to RaterScore ($p < .01$ and $p < .05$ respectively). Thus, within this group of older drivers, Age mediates some of the associations between the vision measures and RaterScore. Correlations of PMCT and UFOV2 with Crash remain high when Age is held constant, indicating that Age does not substantially mediate the high correlations between those variables.

Controlling for PMCT, UFOV2 was unrelated to RaterScore, but was related (with lower significance) to Crash, indicating that PMCT accounted for all the variance in RaterScore explained by UFOV2, and some of the variance in Crash explained by UFOV2. Controlling for UFOV2, PMCT was no longer significantly related to Crash, indicating that PMCT does not account for any additional variance over UFOV2.

Controlling for UFOV2, PMCT was moderately related to RaterScore. Therefore, as PMCT mediates the correlation between UFOV2 and RaterScore, PMCT may capture a component of driving-critical visual function that UFOV2 does not, perhaps associated with bottom-up scan-path generation (Henderson & Donderi, 2005).

Controlling for either UFOV2 or PMCT, UFOV3 was unrelated to any simulator performance measure.

Discussion

For the first time, PMCT has been associated with older drivers' accident risk and driving performance in a driving simulator. In addition, PMCT has again been validated against UFOV® measures, which have been the only visual function measures to be

associated repeatedly against retrospective and prospective accident records, simulator performance and on-road driving performance.

Owsley and McGwin (1999) observed that standard visual sensory tests do not relate strongly to accident risk, in part because they do not present the visual complexity of the driving environment, use static rather than dynamic stimuli, do not involve peripheral visual processing, and do not involve higher-level cognitive processes of attention. They recommended that an effective visual test might address the critical role that peripheral vision appears to play, that contrast sensitivity is worthy of further study, and that “tests of sensitivity for dynamic visual events require a closer look in terms of their association with driving problems” (p. 539). PMCT, although a visual sensory test, appears to follow these recommendations in that it taxes peripheral vision, it is a contrast sensitivity test, and it involves a primitive motion stimulus in standard use in visual psychophysics. Although not in any way a cognitive test of attention, it also requires a participant to attend to four visual locations, none of which is being fixated. Furthermore, while not a measure of attentional processing, it is potentially a measure of a threshold for initiating a bottom-up visual orienting response, which is certainly important for detecting unexpected events in the driving environment.

PMCT is a pure test of sensory visual function which we have found to predict driving performance and accident risk equally as well as UFOV2 in a self-report study and a driving simulation study (Henderson & Donderi, 2005; Henderson et al., 2007, 2010). We suggest that PMCT likely overlaps very little with other tests that may be included in a test battery for assessing older drivers’ fitness to drive. Therefore, if its effectiveness continues to be supported by further research and it is included as a

potential test in future test battery development studies similar to that of Wood et al. (2008), we expect that PMCT will likely remain in the final model of a parsimonious test battery as a significantly predictive visual performance variable. (UFOV2, although the strongest visual measure predictor of on-road driving performance among 20 candidate measures, was dropped from the test battery during stepwise regression using backward elimination because it overlapped with other cognitive tests in the battery, rendering it redundant (Wood et al., 2008).)

The finding that RaterScore and Crash were very strongly associated for older drivers but not younger drivers may be an artifact of Bedard's driving examiner protocol, which was developed specifically for evaluating older drivers. Parker et al. (1995, 2000) found that older drivers committed relatively more unintentional errors or lapses, while young and middle-aged drivers committed relatively more intentional violations. Therefore, Bedard's driving evaluation may be more sensitive to the involuntary errors and lapses of older drivers than to the intermittent, intentional voluntary violations of younger drivers that led to crashes. For older drivers at least, we found Bedard's driving performance measure to be strongly associated with driving safety in a simulator.

We did not set as an objective of this study to determine when age-related decline in peripheral motion sensitivity might begin. However, a purely post-hoc exploratory estimate can be made by substituting the mean younger driver PMCT of -47.0 dB into the older driver regression equation of Age on PMCT ($PMCT = -89.02 + 0.662 \text{ Age}$). Solving for Age yields 63.5 years as the best estimate of the age at which PMCT begins to decline, assuming a linear trend. Further research with much larger numbers of drivers

will be necessary to determine the actual timecourse of peripheral motion processing changes and how much decline may occur before driving safety is affected.

The *spatial two-alternative forced choice method of descending limits* procedure yielded as valid a measure of peripheral motion contrast threshold as did the previously reported *temporal two-alternative forced choice staircase method* (Henderson & Donderi, 2005; Henderson et al, 2007, 2010), while requiring only half as much time to complete (i.e., ten minutes). Time savings result from: a) a spatial forced choice stimulus presentation is half as long as a temporal forced choice presentation; b) the method of limits reduces contrast after each correct response, while the staircase method reduces contrast after two correct responses; and 3) the method of limits terminates after a single error on each side, while a staircase terminates after a criterion number of reversals.

However, two minutes is the average functional capacity test duration that Staplin et al. (2003) determined to be feasible for an overall twenty-minute DMV first tier screening battery for older drivers. We are currently developing a two-minute PMCT test, which will be usable by DMV staff, driving examiners, medical practitioners who must assess their patients' driving safety, and occupational therapists tasked with teaching their clients how to drive more safely.

Although older drivers are poor at assessing their visual functions and detecting gradual visual losses occurring over time, when informed of a functional deficit, they may adopt compensatory strategies for age-related visual and driving deficits (Holland, 1993; Szlyk, Seiple, & Viana, 1995; Stalvey & Owsley, 2000). For example, at-risk drivers could be trained to restrict the length of their glances away from the driving environment to well under two seconds (Henderson et al., 2007). In addition, research

should be conducted to determine if training in voluntary scanning techniques (Schieber, 1994) offers an effective countermeasure for this age-related peripheral motion processing deficit.

Staplin et al. (2003) stated that “functional capacity screening with older drivers ... [should] support remediation of functional limitations if possible ... within a larger context of helping to preserve and extend the mobility of older persons” (abstract). Therefore, if future research validates motion processing in the visual periphery as a critical visual function for safe driving and replicates our finding that an age-related functional deficit affects some drivers, then a concerted research effort will be required to develop effective countermeasures to maintain safe driving if possible. Only as a last resort should driving privileges be restricted or suspended.

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This study has received approval from the University of Ottawa Ethic’s review committee and was conducted in compliance with the regulations to govern research on human participants. This study was financially supported by an Ontario Neurotrauma Foundation grant and a National Sciences and Engineering Research Council grant to Dr. Sylvain Gagnon, and by a National Sciences and Engineering Research Council grant to Dr. Charles Collin.

References

- Austin, R. A., & Faigin, B. M. (2003). Effect of vehicle and crash factors on older occupants. *Journal of Safety Research*, 34, 441-452.
- Ball, K., Owsley, C., Sloane M. E., Roenker D. L., & Bruni J. R.(1993). Visual attention problems as a predictor of vehicle crashes in older drivers. *Investigative Ophthalmology and Visual Science*, 34, 3110–23.
- Ball, K., Roenker, D. L., Wadley, V. G., Edwards, J. D., Roth, D. L., McGwin, G., Raleigh, R., Joyce, J. J., Cissell, G. M., & Dube, T. (2006). Can high-risk older drivers be identified through performance-based measures in a Department of Motor Vehicles setting? *Journal of the American Geriatrics Society*, 54, 77-84.
- Bédard, M., Porter, M., Marshall, S., Isherwood, I., Riendeau, J., Weaver, B., Tuokko, H, Molnar, F., & Miller-Polgar, J. (2008). The combination of two training approaches to improve older adults' driving safety. *Traffic Injury Prevention*, 9, 70–76.
- Bédard, M., Weaver, B., Dārzinš P., & Porter, M. (2008). Predicting driving performance in older adults: We are not there yet! *Traffic Injury Prevention*, 9, 336-341.
- Betz, M. E., & Lowenstein, S. R. (2010). Driving patterns of older adults: Results from the second injury control and risk survey. *Journal of the American Geriatrics Society*, 58, 1931-1935.
- Braitman, K. A., Kirley, B. B., Ferguson, S., & Chaudhary, N. K. (2007). Factors leading to older drivers' intersection crashes. *Traffic Injury Prevention*, 8, 267-274.

- Braver, E. R., & Trempe, R. E. (2004). Are older drivers actually at higher risk of involvement in collisions resulting in deaths or non-fatal injuries among their passengers and other road users? *Injury Prevention, 10*, 27–32.
- Burkhardt, J., Berger, A. M., Creedon, M., & McGavock, A. (1998). *Mobility and Independence: Changes and Challenges for Older Drivers*. Bethesda, MD: Ecosometrics, Inc.
- Caird, J. K., Edwards, C. J., Creaser, J. I., & Horrey, W. J. (2005). Older driver failures of attention at intersections: Using change blindness methods to assess turn decision accuracy. *Human Factors, 47*, 235-249.
- Carsten, O. (1981). Use of the Nationwide Personal Transportation Study to calculate exposure, *HSRI Research Review, 11*, 1-8.
- Cerrelli, E. C. (1973). Driver exposure: The indirect approach for obtaining relative measures. *Accident Analysis and Prevention, 5*, 147-156.
- Cheung, I., & McCartt, A. T. (2011). Declines in fatal crashes of older drivers: Changes in crash risk and survivability. *Accident Analysis and Prevention, 43*, 666-674.
- Chikashi, M., Okubo, M., & Mugishima, M. O. (1999). Effects of background color on the global and local processing of hierarchically organized stimuli. *Journal of Cognitive Neuroscience, 11*, 1-8.
- Chipman, M. L., MacGregor, C. G., Smiley, A. M., & Lee-Gosselin, M. (1993). The role of exposure in comparisons of crash risk among different drivers and driving environments. *Accident Analysis & Prevention, 25*, 207-211.
- Clarke, D. D., Ward, P., Bartle, C., & Truman, W. (2010). Older drivers' road traffic crashes in the UK. *Accident Analysis and Prevention, 42*, 1018-1024.

- Clarke, D. D., Ward, P., Truman, W. & Bartle, C. (2009). *Collisions Involving Older Drivers: An In-depth Study*. Road Safety Research Report 109. London: Department for Transport.
- Clay, O. J., Wadley, V. G., Edwards, J. D., Roth, D. L., Roenker, D. L., & Ball, K. K. (2005). Cumulative meta-analysis of the relationship between useful field of view and driving performance in older adults: Current and future implications. *Optometry and Vision Science*, 82, 724–731.
- Conlon, E. & Herkes, K. (2008). Spatial and temporal processing in healthy aging: Implications for perceptions of driving skills. *Aging, Neuropsychology, and Cognition*, 15, 446-470.
- Cross, J. M., McGwin, G., Jr., Rubin, G. S., Ball, K. K., West, S. K., Roenker, D. L., & Owsley, C. (2009). Visual and medical risk factors for motor vehicle collision involvement among older drivers. *British Journal of Ophthalmology*, 93, 400–404.
- Daigneault, G., Joly, P., & Frigon, J. (2002). Executive functions in the evaluation of accident risk of older drivers. *Journal of Clinical and Experimental Neuropsychology*, 24, 221 – 238.
- Dellinger, A.M., Langlois, J.A., & Li, G. (2002). Fatal crashes among older drivers: decomposition of rates into contributing factors. *American Journal of Epidemiology*, 155, 234–241.
- De Raedt, R. & Ponjaert-Kristoffersen, I. (2000). Can strategic and tactical compensation reduce crash risk in older drivers. *Age and Ageing*, 29, 517-521.

- Desapriya, E., Subzwari, S., Fujiwara, T. & Pike I. (2008). Conventional vision screening tests and older driver motor vehicle crash prevention. *International Journal of Injury Control and Safety Promotion*, 15, 124–126.
- Dissanayake, S., & Perera, L. (2009). *Highway Safety Issues of Older Drivers in Kansas*. Kansas Department of Transportation Report No. K-TRAN: KSU-07-3. Retrieved from http://ntl.bts.gov/lib/31000/31200/31208/KSU-07-03_FinalReport.pdf
- Di Stefano, M. & Macdonald, W. (2003). Assessment of older drivers: Relationships among on-road errors, medical conditions, and test outcome. *Journal of Safety Research*, 34, 415-429.
- Eberhard, J. (2008). ‘Older drivers’ ‘high per mile crash involvement’—the implications for licensing authorities. *Traffic Injury Prevention*, 9, 284–290.
- Edwards, C. J., Creaser, J. I., Caird, J. K., Lamsdale, A. M., & Chisholm, S. L. (2003). Older and younger drive performance at complex intersections: Implications for using perception-response time and driving simulation. *Proceedings of the Second International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*. July 21-24, 2003, Park City, Utah. Retrieved from http://drivingassessment.uiowa.edu/DA2003/pdf/7_Creaserformat.pdf
- Eustace, D., & Wei, H. (2010). The role of driver age and gender in motor vehicle fatal crashes. *Journal of Transportation Safety and Security*, 2, 28-44.
- Evans, L., (1988). Older drivers involvement in fatal and severe traffic accidents. *Journal of Gerontology*, 43, 186–193.

- Freund, B., Colgrove, L. A., Burke, B. L., & McLeod, R. (2005). Self-rated driving performance among elderly drivers referred for driving evaluation. *Accident Analysis & Prevention*, 37, 613–618.
- Fuchs, A. F., Kaneko, C. R. S., & Scudder, C. A. (1985). Brainstem control of saccadic eye movements. *Annual Review of Neuroscience*, 8, 307-337.
- Gabaude, C., & Paire-Ficout, L. (2005). Toward a driving competency assessment encouraging elderly's automobility: A French point of view. *Proceedings of the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*. June 27-30, Rockport, Maine. Retrieved from http://drivingassessment.uiowa.edu/DA2005/PDF/48_gabaudeformat.pdf
- Goode, K. T., Ball, K. K., Sloane, M., Roenker, D. L., Roth, D. L., Myers, R. S., & Owsley, C. (1998). Useful field of view and other neurocognitive indicators of crash risk in older adults. *Journal of Clinical Psychology in Medical Settings*, 5, 425-440.
- Hakamies-Blomqvist, L. (1993). Fatal accidents of older drives. *Accident Analysis & Prevention*, 25, 19-27.
- Hakamies-Blomqvist, L. (2004). Safety of older persons in traffic. In: *TRB's Conference Proceedings 27 Transportation in an Aging Society: A Decade of Experience*.

- Hellinga, B., & MacGregor, C. (1999). Towards modeling the impact of an ageing driver population on intersection design and traffic management. Paper prepared for presentation at the 1999 Annual Conference of the Transportation Association of Canada, Saint John, New Brunswick. Retrieved from <http://www.civil.uwaterloo.ca/bhellinga/publications/Publications/TAC-%201999%20Modelling%20Older%20Drivers%20v2.PDF>
- Henderson, A. S. & Donderi, D. C. (2005). Peripheral motion contrast sensitivity and older drivers' detection failure accident risk. *Proceedings of the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, 41-50, Rockport, Maine 2005.
- Henderson, A. S, Gagnon, S., Bélanger, A., Tabone, R., & Collin, C. (2007). Near peripheral motion detection threshold predicts detection failure accident risk in younger and older drivers. *Proceedings of the Fourth International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, 191-198, Stevenson, Washington.
- Henderson, A. S, Gagnon, S., Bélanger, A., Tabone, R., & Collin, C. (2010). Near peripheral motion detection threshold correlates with self-reported failures of attention in younger and older drivers. *Accident Analysis & Prevention*, 42, 1189–1194.
- Highway Loss Data Institute (2009). Older driver trends. *Highway Loss Data Institute Bulletin*, 26(8), 1-12.
- Holland, C. A. (1993). Self-bias in older drivers' judgments of accident likelihood. *Accident Analysis and Prevention*, 25(4), 431-441.

- Horswill, M. S., Marrington, S. A., McCullough, C. M., Wood, J., Pachana, N. A., McWilliam, J., & Raikos, M. K. (2008). The hazard perception ability of older drivers. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, 63, 212-218.
- Horwitz, G. D., & Newsome, W. T. (1999). Separate signals for target selection and movement specification in the superior colliculus. *Science*, 284, 1158-1161.
- Hu, P. S., Jones, D. W., Reuscher, T., Schmoyer, R. S. & Truett, L. F. (2000) *Projecting Fatalities in Crashes Involving Older Drivers, 2000–2025*. Oak Ridge National Laboratory, U.S. Department of Energy. (Report ORNL-6963).
- Huebner, K. D., Porter, M. M. & Marshall, S. C. (2006). Validation of an electronic device for measuring driving exposure. *Traffic Injury Prevention*, 7, 76-80.
- Janke, M. K. (1991). Accidents, mileage and the exaggeration of risk. *Accident Analysis & Prevention*, 23, 183-188.
- Keffe, J. E., Jin, C. F., Weih, L.M., McCarty, C. A., & Taylor, H. R. (2002). Vision impairment and older drivers: Who's driving? *British Journal of Ophthalmology*, 86, 1118-1121
- Landy, F. J. (1992). *Alternatives to chronological age in determining standards of suitability for public safety jobs. Volume I: Technical report*. University Park, PA: Center for Applied Behavioral Sciences.
- Langford, J., Andrea, D., Fildes, B., Williams, T., & Hull, M. (2005). *Assessing Responsibility for Older Drivers' Crashes*. Austroads Project RS.UB.507, Sydney, Australia.

- Langford, J. & Koppel, S. (2006). Epidemiology of older driver crashes – identifying older driver risk factors and exposure patterns. *Transportation Research Part F*, 9, 309-321.
- Langford, J., Methorst, R., & Hakamies-Blomqvist, L. (2006). Older drivers do not have a high crash risk-a replication of low mileage bias. *Accident Analysis & Prevention*, 38, 574-578.
- Levin, L., Dukic, T., Henriksson, P., Mårdh, S., & Sagberg, F. (2009). *Older Car Drivers in Norway and Sweden: Studies of Accident Involvement, Visual Search Behavior, Attention and Hazard Perception*. VTI Report No. 656A. Retrieved from <http://www.vti.se/EPiBrowser/Publikationer%20-%20English/R656A.pdf>
- Li, G., Braver, E., & Chen, L. (2003). Fragility versus excessive crash involvement as determinants of high death rates per vehicle-mile of travel among older drivers. *Accident Analyses and Prevention*, 35, 227-235.
- Livingstone, M., & Hubel, D. (1988). Segregation of form, color, movement, and depth: Anatomy, physiology, and perception. *Science*, 240, 740-749.
- Lyman, S., Ferguson, S. A., Braver, E. R., & Williams, A. F. (2002). Older driver involvements in police reported crashes and fatal crashes: Trends and projections. *Injury Prevention*, 8, 116 – 120.
- Massie, D. L., Campbell, K. L., & Williams, A. F. (1995). Traffic accident involvement rates by driver age and gender. *Accident Analysis and Prevention*, 27, 73-87.
- Mayhew, D. R., Simpson, H. M., & Ferguson, S. A. (2006). Collisions involving senior drivers: high-risk conditions and locations. *Traffic Injury Prevention*, 7, 117-124.

- McGwin, G., Jr., Owsley, C., & Ball, K. (1998). Identifying crash involvement among older drivers: Agreement between self-report and state records. *Accident Analysis & Prevention, 30*, 781–791.
- Myers, R. S., Ball, K. K., Kalina, T. D., Roth, D. L., & Goode, K. T. (2000). Relation of useful field of view and other screening tests to on-road driving performance. *Perceptual and Motor Skills, 91*, 279-290.
- National Highway Traffic Safety Administration (2001). *Traffic Safety Facts 2000: Older Population*. DOT HS 809 328.
- National Highway Traffic Safety Administration (2010). *Traffic Safety Facts 2009 (Early Edition)*. Retrieved from <http://www-nrd.nhtsa.dot.gov/Pubs/811402EE.pdf>
- National Highway Traffic Safety Administration (2011). *Fatality Analysis Reporting System (FARS)*. Available at <http://www.nhtsa.gov/FARS>
- Owsley, C., Ball, K., McGwin, G., Jr., Sloane, M. E., Roenker, D. L., White, M. F. & Overley, E. T. (1998). Visual processing impairment and risk of motor vehicle crash among older adults. *Journal of the American Medical Association, 279*, 1083–1088.
- Owsley, C., Ball, K., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1991) Visual/ cognitive correlates of vehicle accidents in older drivers. *Psychology and Aging, 6*, 403–415.
- Owsley, C., & McGwin, G. (1999); G. Vision impairment and driving. *Survey of Ophthalmology, 43*, 535–550.
- Owsley, C., & McGwin, G. (2010). Vision and driving. *Vision Research, 50*, 2348-2361.

- Owsley, C., McGwin, G., Jr. & Ball, K. (1998). Vision impairment, eye disease, and injurious motor vehicle crashes in the elderly. *Ophthalmic Epidemiology*, 5, 101–113
- Owsley, C., Sekuler, R., & Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision Research*, 23, 689-699.
- Oxley, J., Fildes, B., Corben, B., & Langford, J. (2006). Intersection design for older drivers. *Transportation Research Part F*, 9, 335-346.
- Parker, D., McDonald, L., Rabbitt, P., & Sutcliffe, P. (2000). Elderly drivers and their accidents: the aging driver questionnaire. *Accident Analysis and Prevention*, 32, 751–759.
- Parker, D., Reason, J. T., Manstead, A. S. R., & Stradling, S. G. (1995). Driving errors, driving violations and accident involvement. *Ergonomics*, 38, 1036–1048.
- Rabbitt, P., & Parker, D. (2002). *The Ageing Driver: A Programme of Research*. Road Safety Research Report No. 29. Department for Transport: London. Retrieved from <http://webarchive.nationalarchives.gov.uk/+/http://www.dft.gov.uk/pgr/roadsafety/research/rsrr/theme3/theageingdriveraprogrammeofr4777>
- Raghuram, A., & Lakshminarayanan, V. (2006). Motion perception tasks as potential correlates to driving difficulty in the elderly. *Journal of Modern Optics*, 53, 1343-1362.
- Raghuram, A., Lakshminarayanan, V., & Khanna, R..(2005). Psychophysical estimation of speed discrimination. II. Aging effects. *Journal of the Optical Society of America A*, 22, 2269-2280.

- Ragland, D. R., & Zabyshny, A. A. (2003). *Intersection Decision Support Project: Taxonomy of Crossing-Path Crashes at Intersections Using GES 2000 Data*. UC Berkeley: UC Berkeley Traffic Safety Center. Retrieved from:
<http://escholarship.org/uc/item/0201j0v2>
- Rallabandi, A., & Dissanayake, S. (2009). Fatality risk of older drivers under different conditions based on vehicle miles traveled. *Proceedings of the 2009 Mid-Continent Transportation Research Symposium*. August 2009, Ames, Iowa.
Retrieved from
<http://www.intrans.iastate.edu/pubs/midcon2009/RallabandiElderly.pdf>
- Retting, R. A., Weinstein, H. B., & Solomon, M. (2003). Analysis of motor-vehicle crashes at stop signs in four US cities. *Journal of Safety Research*, 34, 485-489.
- Rizzo, M., Reinach, S., McGehee, D., & Dawson, J. (1997). Simulated car crashes and crash predictors in drivers with Alzheimer disease. *Archives of Neurology*, 54, 545-551.
- Roenker, D. L., Cissell, G. M., Ball, K. K., Wadley, V. G. & Edwards, J. D. (2003). Speed of- processing and driving simulator training result in improved driving performance. *Human Factors*, 45, 218-233.
- Ross, L. A., Clay, O. J, Edwards, J. D., Ball, K., Wadley, V. G., Vance, D. E., Cissell, G. M., Roenker, D. L., & Joyce, J. J. (2009). Do older drivers at risk for crashes modify their driving over time? *Journals of Gerontology: Psychological Sciences*, 64B, 163-170.

- Rubin, G. S., Ng, E. S., Bandeen-Roche, K., Keyl, P. M., Freeman, E. E., & West, S. K. (2007). A prospective, population-based study of the role of visual impairment in motor vehicle crashes among older drivers: The SEE study. *Investigative Ophthalmology and Visual Science*, 48, 1483–1491.
- Salthouse T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, 103, 403-428.
- Scheffrin, B. E., Tregear, S. J., Harvey Jr, L. O., & Werner, J. S. (1999). Senescent changes in scotopic contrast sensitivity. *Vision Research*, 39, 3728–3736.
- Schieber, F. (1994). *Recent developments in vision, ageing and driving 1988-1994*. Technical Report No. UNMTRI-94-26. Ann Arbor, MI.
- Schlag, B. (1993). Elderly drivers in Germany – fitness and driving behaviour. *Accident Analysis and Prevention*, 25, 47 – 56.
- Sekuler, R., & Owsley, C. (1982). The spatial vision of older humans. In R. Sekuler, D. Kline, & K. Dismukes (Eds.), *Aging and Human Visual Function*, 185-202. New York: Alan R. Liss.
- Sims, R. V., McGwin, G., Jr., Allman, R. M., Ball, K. & Owsley, C. (2000). Exploratory study of incident vehicle crashes among older drivers. *Journal of Gerontology:Medical Sciences*, 55A(1), M22–M27.
- Sims, R. V., Owsley, C., Allman, R. M., Ball, K. & Smoot, T. M. (1998). A preliminary assessment of the medical and functional factors associated with vehicle crashes in older adults. *Journal of the American Geriatrics Society*, 46, 556–561.
- Sivak, M. (1996). The information that drivers use: is it indeed 90% visual? *Perception*, 25, 1081–1089.

- Skottun, B. C. (2000). The magnocellular deficit theory of dyslexia: the evidence from contrast sensitivity. *Vision Research*, 40, 111-127.
- Skottun, B. C. & Skoyles, J. R. (2008). Temporal frequency and the magnocellular and parvocellular systems. *Neuro-Ophthalmology*, 32, 43-48.
- Skyving, M., Berg, H. & Laflamme, L. (2009) A pattern analysis of traffic crashes fatal to older drivers. *Accident Analysis and Prevention*, 41, 253–258.
- Stalvey, B. T., & Owsley, C. (2000). Self-Perceptions and Current Practices of High-Risk Older Drivers: Implications for Driver Safety Interventions. *Journal of Health Psychology*, 5, 441-456.
- Stamatiadis, N. & Deacon, J. A. (1995). Trends in highway safety: Effects of an aging population on accident propensity. *Accident Analysis and Prevention*, 27, 443-459.
- Staplin, L., Gish, K. W., Decina, L.E., Lococo, K. & McKnight, A. S. (1998). *Intersection Negotiation Problems of Older Drivers, Volume I: Final Technical Report*. USDOT/NHTSA Contract No. DTNH22-93-C-05237. Washington, DC.
- Staplin, L., Gish, K.W., & Joyce, J. (2008). “Low mileage bias” and related policy implications—A cautionary note. *Accident Analysis & Prevention*, 40, 1249-1252.
- Staplin, L., Gish, K., & Wagner, E. (2003). MaryPODS revisited: Updated crash analysis and implications for screening program implementation. *Journal of Safety Research*, 34(4), 389-397.

- Staplin, L., Lococo, K. H., Gish, K. W., & L. Decina, L. (2003). *Model Driver Screening and Evaluation Program Final Technical Report. Volume 1: Project Summary and Model Program Recommendations*. U.S. DOT/NHTSA Publication No. DOT HS 809 582, U.S. Department of Transportation, Washington, DC.
- Staplin, L., Lococo, K. H., McKnight, A. J., McKnight, A. S. & Odenheimer, G.L. (1998). Intersection Negotiation Problems of Older Drivers, Volume II: Background Synthesis on Age and Intersection Driving Difficulties. HS-808 850, Volume II,; Report No. 1446/FR,; Background Synthesis, National Technical Information Service.
- Stein, B. E. (1984). Development of the superior colliculus. *Annual Review of Neuroscience*, 7, 95-125.
- Steinman, B. A., Steinman, S. B., & Lehmkuhle, S. (1997). Transient visual attention is dominated by the magnocellular stream. *Vision Research*, 37, 17-23.
- Strauss, S. H. (2005). *SPR 559 - New, Improved, Comprehensive, and Automated Driver's License Test and Vision Screening System*. Arizona Department of Transportation Report No. FHWA-AZ-04-559(1). Retrieved from http://grandcanyonairport.info/TPD/ATRC/publications/project_reports/PDF/AZ559.pdf
- Subzwari, S., Desapriya, E., Babul-Wellar, S., Pike, I., Turcotte, K., & Rajabali, F., et al. (2009). Vision screening of older drivers for preventing road traffic injuries and fatalities (Review). The Cochrane Collaboration, Issue 1. Art. No.: CD006252. doi:10.1002/14651858. CD006252. pub2.

- Summala, H., & Mikkola, T. (1994). Fatal accidents among car and truck drivers: Effects of fatigue, age, and alcohol consumption. *Human Factors*, 36, 315-326.
- Szlyk, J. P., Seiple, W., & Viana, M. (1995). Relative effects of age and compromised vision on driving performance. *Human Factors*, 37(2), 430-436.
- Tsang, P. S. (1997). Age and pilot performance. In R.A. Telfer & P.J. Moore (Eds.), *Aviation Training: Learners, Instruction and Organization* (pp. 21-40). Brookfield, VT: Avebury.
- Tsang, P. S. (2003). Assessing cognitive aging in piloting. In P. S. Tsang & M. A. Vidulich (Eds.), *Principles and Practices of Aviation Psychology* (pp. 507-540).
- van Rijn, L. J., Wilhelm, H., Emesz, M., Kaper, R., Heine, S., Nitsch, S., Grabner, G., & Volker-Dieben, H. J., (2002). Relation between perceived driving disability and scores of vision screening tests. *British Journal of Ophthalmology*, 86, 1262-1264.
- Viano, D. C., Culver, C. C., Evans, L., Frick, M., & Scott, R. (1990). Involvement of older drivers in multi-vehicle side impact crashes. *Accident Analysis & Prevention*, 22(2), 177-188.
- Williams, A. F., & Shabanova, V. I. (2003). Responsibility of drivers, by age and gender, for motor-vehicle crash deaths. *Journal of Safety Research*, 34, 527-531.
- Wood, J. M. (2002). Age and visual impairment decrease driving performance as measured on a closed-road circuit. *Human Factors*, 44, 482-494.

- Wood, J. M., Anstey, K. J. , Kerr G. K., Lacherez, P. F. & Lord, S. (2008). A multidomain approach for predicting older driver safety under in-traffic road conditions. *Journal of the American Geriatrics Society*, 56(6), 986-993.
- Wood, J. M. & Owens, D. A. (2005). Standard measures of visual acuity do not predict drivers' recognition performance under day or night conditions. *Optometry and Vision Science*, 82, 698-705.
- Wood, J. M. & Troutbeck, R. (1995). Elderly drivers and simulated visual impairment. *Optometry and Vision Science*, 72, 115–24.

Additional Study 3 Results and Discussion

Age-related PMCT deficit. Figure 14 shows the relation between age and PMCT. For descriptive purposes only, a cubic trend line has been added to the scatterplot. By curving upward at about the age of 65, the line captures 60% of the variance in PMCT.

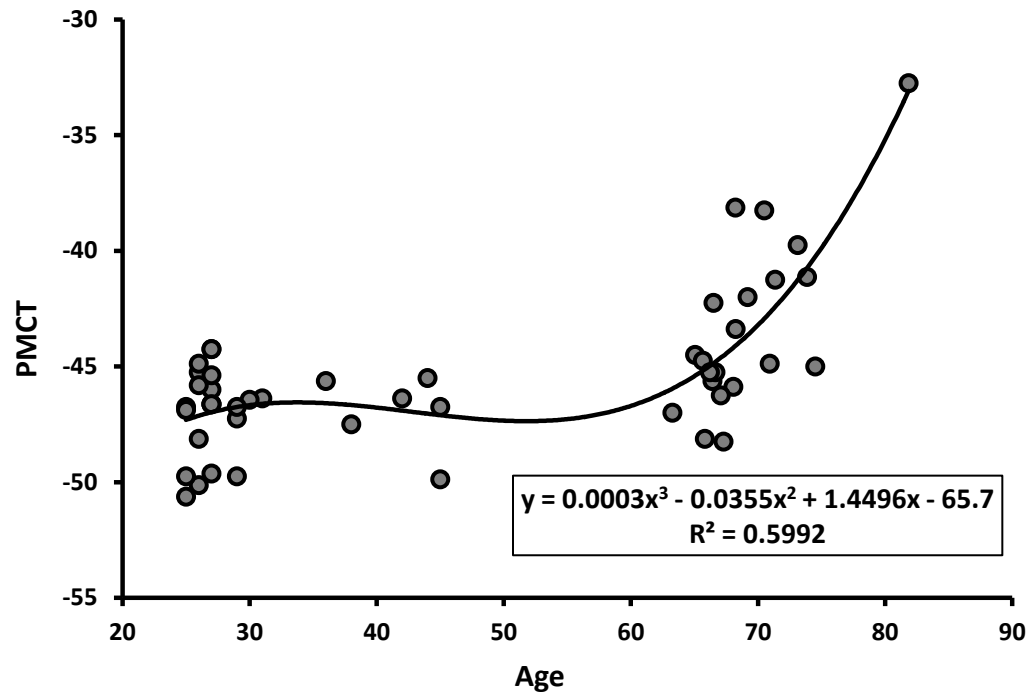


Figure 14. Motion processing on age (all drivers).

PMCT and UFOV2 ROC curves. Although the sample size is far too small to provide more than a suggestion regarding sensitivity and specificity of the two vision measures, receiver operating characteristic (ROC) curves that show Hits (sensitivity) and False alarms (1-specificity) for every potential cutoff value of vision measure illustrates the predictive power of PMCT and UFOV2. Table 4 shows individual driver records, ordered by PMCT or by UFOV2, that were used to generate the ROC curves shown in Figure. The predictor variable is PMCT in the left figures and UFOV2 in the right

figures. The outcome variable is simulator crashes, with a criterion of two crashes (below) or at least 1 crash (next page). Figures 15 and 16 below show that according to the area under the curve, PMCT and UFOV2 were equally able to effectively predict which drivers will crash two times in the simulator scenario (which was the baseline scenario for another study, and was expected not to present many opportunities for crashes). However, in keeping with the concept that crashes are somewhat random events, neither measure is particularly effective at identifying all drivers who crashed in the scenario, although UFOV2 is slightly more effective than PMCT, as shown in Figures 17 and 18. The diagonal line indicates chance performance.

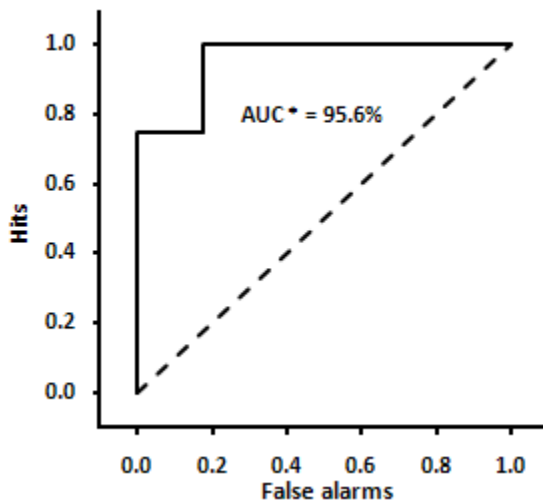


Figure 15. PMCT 2 crash ROC curve
*AUC = area under curve.

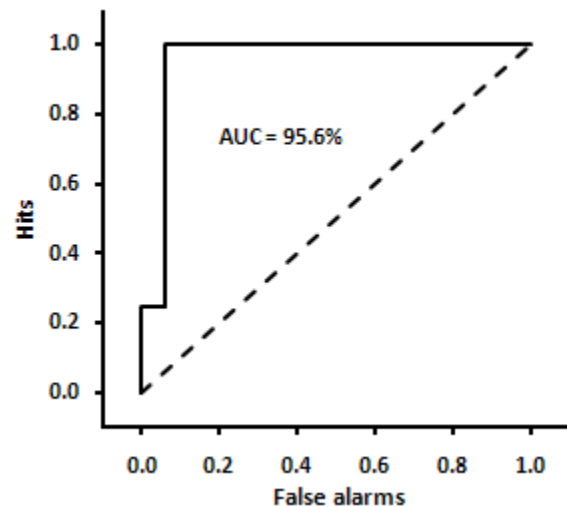


Figure 16. UFOV2 2 crash ROC curve.

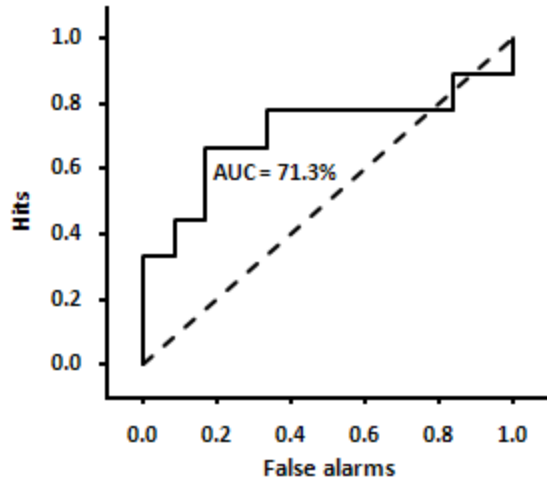


Figure 17. PMCT 1+ crash ROC curve.

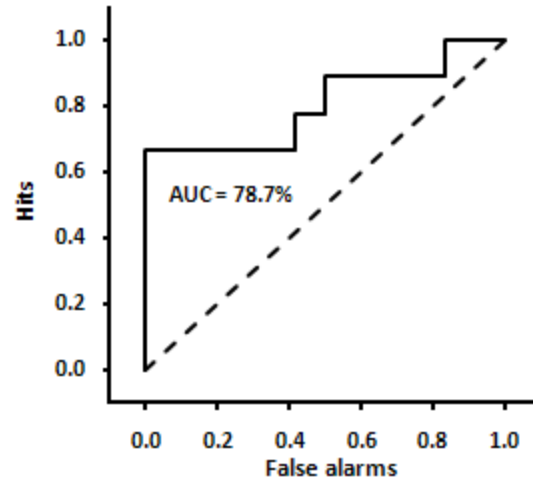


Figure 18. UFOV2 1+ crash ROC curve.

Table 4. Ordered data for ROC curves, with suggested cutpoints

PMCT	Crash	UFOV2	Crash
-32.75	2	330.1	2
-38.13	2	293.3	1
-38.25	2	203.3	2
-39.75	0	176.5	2
-41.13	1	136.6	2
-41.25	0	133.4	1
-42	2	110.1	0
-42.25	1	60	0
-43.38	0	53.3	0
-44.5	0	46.8	0
-44.75	1	40.1	0
-44.88	0	36.7	1
-45	0	33.4	0
-45.25	0	30.1	1
-45.25	0	26.7	0
-45.63	0	23.4	0
-45.88	0	16.7	0
-46.25	1	16.7	0
-47	0	16.7	0
-48.13	0	16.7	0
-48.25	1	16.7	1

IX. General Discussion

Robust replication. The three studies presented above all utilized small samples due to a decision that my supervisor and I made before beginning the first study. We decided that a sample of 20 participants was sufficient to yield a statistically significant result if the effect size was large enough to make PMCT theoretically interesting and practically important. As Cohen (1992) made clear in his very accessible paper on statistical power analysis, statistical power is a function of sample size (N), significance criterion (α), and population effect size (ES). Our decision was vindicated by the robust results of all three studies, as shown in Table 1 below. This program of research has clearly and repeatedly shown that an aging visual system's ability to process a spatiotemporally optimal peripheral stimulus strongly indicates that visual system's capability to effectively detect potentially conflicting objects in the dynamic visual environment of driving.

Table 1.

Effect size and predictive strength of PMCT across studies

Study	PMCT(dB): mean(sd)	Outcome variable	N	R^2	p (1-tailed)
1	-43.0 (3.70)	DPQ28	18	.396	.0026
2	-33.8 (3.05)	DPQ5	15	.255	.027
3	-43.3 (3.79)	Simulator Score	21	.435	.00057
3	-43.3 (3.79)	Crashes	21	.394	.0012

Note that PMCT shows a stronger relation to Simulator Score, a direct measure of driving performance, than to the questionnaire measures of accident risk, likely as a result of the additional self-report variance.

Non-optimal drift rate. As noted earlier, the sine wave stimulus used in the second study was drifted at two times the optimal rate, due to a programming error, and that may explain at least to some degree the relatively weaker result found in that study. Given probable individual differences in both the location and the spread of the temporal contrast sensitivity function, testing away from the peak of the spatiotemporal contrast sensitivity function likely introduced an additional source of variance to obscure the relation between PMCT and accident risk. Care should therefore be taken to constrain a test stimulus presented at a nominal eccentricity of 15 degrees to the optimal spatial and temporal frequencies of 0.4 cycles/degree and 5.5 hz (13.75 degrees/second) respectively, to yield the strongest result.

Gabor stimulus effectiveness. Note that the Gabor stimulus, which contained only two sine wave cycles and spanned 5 degrees VA, yielded the same contrast threshold as the rectangular grating patch containing 4 full cycles of the same spatial and temporal frequency in a spatial window spanning 10 degrees VA.

TSB safety deficiency identification process. At the Transportation Safety Board of Canada (TSB), where I have worked as a human factors investigator and research analyst since 1999, the mandate is to enhance transportation safety by investigating accidents and emerging safety issues to identify safety deficiencies, and then to inform change agents about those deficiencies so that they can be eliminated or reduced, or their impact mitigated. The TSB definition of a safety deficiency is a systemic underlying factor (the unsafe condition at the deepest level of analysis) for which defenses are inadequate. (See Appendix C for an informal description of the TSB's methodology applied to the issue of older driver safety – although the mandate of the

TSB includes the modes of air, marine, pipelines, and railways, but not roads.) That analysis served to identify the following underlying factor: *Some older drivers tend to come into conflict with other road users, pedestrians, or fixed objects, because they are unaware that their visual systems have become relatively less sensitive to moving stimuli in the visual periphery.*

I suggest that no defenses for this underlying factor exist simply because the critical visual function of stimulus-driven orientation on moving peripheral objects, or at least a test for assessing that function, has not been identified until now. Potential defenses could include testing older drivers' PMCT and training functionally deficient drivers in compensatory strategies, such as simulator training to sharpen cognitive functions (Cassavaugh & Kramer, 2009) or scan more effectively at intersections (Romoser & Fisher, 2009). Alternatively, providing them with information about their functional PMCT deficit will enable them to make a more informed decision about driving cessation. A second defense could be the introduction of a 2-minute PMCT assessment as a screening tool to be used by Department of Motor Vehicles staff (see below).

Questionable questionnaires. As indicated in the footnotes, in Study 2 the questionnaire items that depended on attribution of older drivers' perceptions to an external factor (i.e., faster traffic) rather than an internal age-related change, no longer captured detection failure accident risk. The differences between participant pools across the two studies may explain the loss of those questions' effectiveness. First, Study 1 was conducted in Montreal, where traffic is quite fast-moving and dense, and somewhat anarchic, while Study 2 was conducted in Ottawa, where traffic is much more sedate,

traffic less often strains the capacity of the road system, drivers usually travel closer to the speed limit, and the driving environment is relatively less stressful. Second, the Montreal participant pool was drawn mainly from churches, and appeared to span the full range of normal competence. However, the participant pool in Ottawa was composed of a very high-achieving group, including former or current medical doctors, professors, and airline pilots, who may therefore have been more confident in their driving abilities, and more knowledgeable about the driving environment. Third, a nearly 10 year interval separated Study 1 from Study 2, and substantial information had been communicated to the public about older driver issues, so that older drivers may have become too well-educated and knowledgeable about age-related changes in their vision to attribute changes in traffic perception to changes in traffic.

The differences in questionnaire responses from Study 2 to Study 3 are more difficult to explain. The small size of the sample may simply have led to a Type II error for self-report data. Again, the participant group was composed of high achievers including ex-airline pilots and doctors, who may have been even more overconfident in their abilities than the Study 2 participants. If overconfidence is the reason that self-report no longer indicated accident risk in Study 3, that is consistent with Williams (2003), who reported that most drivers rate their skills as above average. It is also reason for concern, as Freund, Colgrove, Burke, and McLeod (2005) asked older drivers who had been referred for a driving evaluation to estimate how well they would perform on an upcoming driving simulation test. Drivers who rated themselves at least a little bit better than others of their age were more than four times more likely to actually be unsafe

drivers than drivers who believed that they were the same or worse than other drivers of their age.

Perhaps a future study could examine the relation of self-report questionnaire responses to simulator performance: participants with poor scores on both may use compensatory strategies, self-limit their driving to less challenging situations, and perhaps even stop driving altogether; participants with high self-report and simulator scores have likely not yet been affected by age-related functional losses; but drivers who perform poorly in the simulator but self-report high driving abilities are unaware of their own age-related functional decline, likely making them high-risk drivers (Freund et al., 2005), who are most in need of PMCT assessment and compensation training.

Future work.

The findings of the three presented studies strongly indicate that a usable test of peripheral motion detection should be developed for inclusion in older driver test batteries. Driving assessment researchers, professionals such as occupational therapists and medical practitioners, and government transportation policy-makers agree that a usable assessment test must be capable of being completed in less than two minutes to be usable in the field.

We will soon develop and validate such a test, which will allow rapid, accurate and reliable measurement of peripheral motion contrast thresholds. This shorter test will be a rapid, accurate and reliable measurement of peripheral motion contrast thresholds appropriate for deployment at Department of Motor Vehicle locations, in medical practitioners' examining rooms, and in occupational therapy settings.

The test procedure will consist of a series of six to eight increasing contrast trials (Gilmore, Andrist, & Royer, 1991), with the stimulus gradually appearing randomly on the left or right side in each trial, and with the tested driver indicating the correct side as soon as any movement is detected. The two-alternative forced choice aspect of the test prevents drivers from guessing in an attempt to lower their threshold.

If the proposed study concludes with a successful result, the follow-on study will incorporate eye movement monitoring into the prototype test apparatus.

Application to clinical populations who drive. Follow-on tests will also extend testing to clinical driving populations with Alzheimer's disease, Parkinson's disease, stroke, or traumatic brain injury who current scientific literature indicates may also be at risk of deficient visual motion processing.

For example, drivers with Alzheimer's disease exhibit vision-related driving deficits (Rizzo, McGehee, Dawson, & Anderson, 2001). Dawson, Anderson, Uc, Dastrup, and Rizzo (2009) administered a cognitive, visual, and motor test battery and a road test to 40 probable early AD drivers and 115 older drivers without neurological disease, and concluded that tests of visuospatial abilities and motor responses were much better predictors of driving safety than were tests of anterograde memory function (which is the symptom most commonly associated with AD).

Drivers with Parkinson's disease also have increased accident risk, which is associated with visual deficits. Devos, Vandenberghe, Nieuwboer, Tant, Baten, and De Weerdt (2007) tested 40 PD drivers and 40 age- and sex-matched control drivers with an extensive test battery (vision measures included Snellen acuity, Pelli-Robson contrast sensitivity, Ergovision tests of binocular visual acuity and kinetic vision, Humphrey Field

Analyzer visual field, and neuropsychological tests included UFOV® among others). All participants also completed a road test and a driving simulator test and were scored either pass or fail by a professional driving examiner who had expertise in assessing neurologically impaired persons' fitness to drive. The only vision measure included in the final pass-fail prediction model of four predictor variables (and the strongest predictor overall) was Pelli-Robson contrast sensitivity. The prediction model had a specificity (correctly predicted to pass) of 90% and a sensitivity (correctly predicted to fail) of 91%.

Stroke or traumatic brain injury survivors may also have driving difficulties related to visual function impairments. Akinwuntan, Feys, De Weerd, Pauwels, Baten, and Strypstein (2002) administered an extensive and well-selected clinical visual and neuropsychological test battery and road test to 104 stroke survivors. Vision tests included Ergovision tests of near and far visual acuity, depth perception, and kinetic vision acuity (the ability to recognize objects in motion). The eight neuropsychological tests included UFOV, the figure of Rey, divided attention, and scanning, among others. (See Akinwuntan et al. for a detailed description of all tests.) According to road test performance, participants were identified as suitable, not immediately suitable, or not suitable to be permitted to drive. All vision tests and most neuropsychology test scores (including UFOV) were significantly related to final road test score and assigned suitable/not yet suitable/not suitable group. Kinetic vision, figure of Rey, UFOV, reaction time in scanning, and absolute difference in reaction time of visual neglect were significant at $p < .0001$. However, the final four-variable logistic regression model for predicting final group decision ($N = 93$, $R^2 = .53$) contained only kinetic vision and scanning, in addition to side of lesion and road test score.

The two-minute variant of the PMCT test that we intend to soon develop will be a powerful assessment tool for practitioners who work with these clinical populations.

Applications outside the domain of road safety. We anticipate that the test may also prove useful outside the domain of fitness to drive assessment. For example, I will shortly be collaborating with an aviation research group at Carleton University to determine if PMCT can be used to identify which older pilots are less likely to detect other aircraft in their vicinity, or to detect changes in their instruments.

At the opposite end of the performance distribution and outside the domain of assessing deficits in aging or clinical populations, PMCT may also prove useful for identifying people with exceptionally higher sensitivity to peripheral motion who would be well-suited to serve as marine and air search and rescue personnel, terminal air traffic controllers, or professional athletes. Military staffing experts may even be interested in identifying recruits with high peripheral motion sensitivity for training as fighter pilots or urban warfighters with superior ability to detect and react to threats in their visual periphery.

References

- Akinwuntan, A. E., Feys, H., De Weerd, P. T., Pauwels, J., Baten, G., & Strypstein, E. (2002). Determinants of driving after stroke. *Archives of Physical Medicine and Rehabilitation*, 83, 334-341.
- Atchley, P., & Anderson, G. J. (1998). The effect of age, retinal eccentricity, and speed on detection of optic flow components. *Psychology and Aging*, 13, 297-308.
- Austin, R. A., & Faigin, B. M. (2003). Effect of vehicle and crash factors on older occupants. *Journal of Safety Research*, 34, 441-452.
- Ball, K., & Owsley, C. (1991). Identifying correlates of accident involvement for the older driver. *Human Factors*, 33(5), 583-595.
- Ball, K., Beard, B. L., Roenker, D. L., Miller, R. L., & Griggs, D. S. (1988). Age and visual search: Expanding the useful field of view. *Journal of the Optical Society of America A*, 5, 2210-2219.
- Ball, K., Owsley, C., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1993). Visual attention problems as predictor of vehicle crashes in older drivers. *Investigative Ophthalmology and Visual Science*, 34, 3110-3123.
- Ball, K., Roenker, D., Wadley, V., Edwards, J., Roth, D., McGwin, G., et al. (2006). Can high-risk older drivers be identified through performance-based measures in a department of motor vehicles setting? *Journal of the American Geriatric Society*, 54, 77-84.
- Bao, S., & Boyle, L. N. (2009). Age-related differences in visual scanning at median-divided highway intersections in rural areas. *Accident Analysis and Prevention*, 41, 146-152.

- Bédard, M., Porter, M. M., Marshall, S., Isherwood, I., Riendeau, J., Weaver, B., Tuokko, H., Molnar, F., & Miller-Polgar, J. (2008). The combination of two training approaches to improve older adults' driving safety. *Traffic Injury Prevention, 9*, 70–76.
- Bédard, M., Weaver, B., Dārzinš P., & Porter, M. (2008). Predicting driving performance in older adults: We are not there yet! *Traffic Injury Prevention, 9*, 336-341.
- Betz, M. E., & Lowenstein, S. R. (2010). Driving patterns of older adults: Results from the second injury control and risk survey. *Journal of the American Geriatrics Society, 58*, 1931-1935.
- Braitman, K. A., Kirley, B. B., Ferguson, S., & Chaudhary N. K. (2007). Factors leading to older drivers' intersection crashes. *Traffic Injury Prevention, 8*(3), 267-74.
- Braver, E. R., & Trempe, R. E. (2004). Are older drivers actually at higher risk of involvement in collisions resulting in deaths or non-fatal injuries among their passengers and other road users? *Injury Prevention, 10*, 27–32.
- Burg, A. (1964). *An Investigation of Some Relationships Between Dynamic Visual Acuity, Static Visual Acuity and Driving Record*. Department of Engineering Report No. 64-18, University of California, Los Angeles.
- Burg, A. (1967). *Vision test scores and driving records: general findings*. Report No. 67-24. University of California, Los Angeles, Institute of Transportation and Traffic Engineering.
- Burg, A. (1968). *Vision test scores and driving records: Additional findings*. Report No. 68-27. Los Angeles: Department of Engineering, University of California.
- Burg, A. (1971). Vision and driving: A report on research. *Human Factors, 13*, 79-87.

- Burkhardt, J., Berger, A. M., Creedon, M., & McGavock, A. (1998). *Mobility and Independence: Changes and Challenges for Older Drivers*. Bethesda, MD: Ecosometrics, Inc.
- Carsten, O. (1981). Use of the Nationwide Personal Transportation Study to calculate exposure. *HSRI Research Review*, 11, 1-8.
- Cassavaugh, N. D., & Kramer, A. F. (2009). Transfer of computer-based training to simulated driving in older adults. *Applied Ergonomics*, 40, 943-952.
- Centers for Disease Control and Prevention (2009). *CDC Injury Research Agenda, 2009-2018*. Retrieved from www.cdc.gov/Injury/ResearchAgenda/index.html
- Cerrelli, E. C. (1973). Driver exposure: The indirect approach for obtaining relative measures. *Accident Analysis and Prevention*, 5, 147-156.
- Chandraratna, S. & Stamatiadis, N. (2009). Quasi-induced exposure method: evaluation of not-at-fault assumption. *Accident Analysis and Prevention*, 41(2), 308–313.
- Cheung, I., & McCartt, A. T. (2011). Declines in fatal crashes of older drivers: Changes in crash risk and survivability. *Accident Analysis and Prevention*, 43, 666-674.
- Chipman, M. L., MacGregor, C. G., Smiley, A. M., & Lee-Gosselin, M. (1993). The role of exposure in comparisons of crash risk among different drivers and driving environments. *Accident Analysis & Prevention*, 25, 207-211.
- Clarke, D. D., Ward, P., Bartle, C., & Truman, W. (2010). Older drivers' road traffic crashes in the UK. *Accident Analysis and Prevention*, 42, 1018-1024.
- Clarke, D. D., Ward, P., Truman, W. & Bartle, C. (2009). *Collisions Involving Older Drivers: An In-depth Study*. Road Safety Research Report 109. London: Department for Transport.

- Clay, O. J., Wadley, V., Edwards, J. D., Roth, D., Roenker, D. L., & Ball, K. K. (2005). Cumulative meta-analysis of the relationship between Useful Field of View and driving performance in older adults: Current and future implications. *Optometry & Vision Science*, 82, 724-731.
- Cohen, J. (1992). A power primer. *Psychological Bulletin*, 112, 155 – 159.
- Conlon, E. & Herkes, K. (2008). Spatial and temporal processing in healthy aging: Implications for perceptions of driving skills. *Aging, Neuropsychology, and Cognition*, 15, 446-470.
- Cooper, P. J. (1989). Differences in accident characteristics among elderly drivers and between elderly and middle-aged drivers. *Proceedings of the 33rd Conference of the American Association for Automotive Medicine*, 33, 153-167.
- Cooper, P. J. (1990). Different ages, different risks: The realm of accident statistics. In J. P. Rothe (Ed.), *The Safety of Elderly Drivers: Yesterday's Young in Today's Traffic*, 85-133. New Brunswick: Transaction Publishers.
- Coughlin, J. F. (2009). Longevity, lifestyle, and anticipating the new demands of aging on the transportation system. *Public Works Management and Policy*, 13, 301-311.
- Cross, J. M., McGwin, G., Jr., Rubin, G. S., Ball, K. K., West, S. K., Roenker, D. L., & Owsley, C. (2009). Visual and medical risk factors for motor vehicle collision involvement among older drivers. *British Journal of Ophthalmology*, 93, 400–404.
- Daigneault, G., Joly, P., & Frigon, J. (2002). Executive functions in the evaluation of accident risk of older drivers. *Journal of Clinical and Experimental Neuropsychology*, 24, 221 – 238.

- Dawson, J. D., Anderson, S. W., Uc, E. Y., Dastrup, E., & Rizzo, M. (2009). Predictors of driving safety in early Alzheimer disease. *Neurology*, *72*, 521-527.
- De Raedt, R. & Ponjaert-Kristoffersen, I. (2000). Can strategic and tactical compensation reduce crash risk in older drivers? *Age and Ageing*, *29*, 517-521.
- De Valois, R., & De Valois, K. (1980). *Spatial vision*. Oxford University Press: New York.
- De Winter, J. C. F., & Dodou, D. (2010). The Driver Behaviour Questionnaire as a predictor of accidents: a meta-analysis. *Journal of Safety Research*, *41*, 463-470.
- Dellinger, A. M., Langlois, J. A., & Li, G. (2002). Fatal crashes among older drivers: decomposition of rates into contributing factors. *American Journal of Epidemiology*, *155*, 234-241.
- Derefeldt, G., Lennerstrand, G., & Lundh, B. (1979). Age variations in normal human contrast sensitivity. *Acta Ophthalmologica*, *57*, 679-690.
- Devos, H., Vandenberghe, W., Nieuwboer, A., Tant, M., Baten, G., & De Weerd, W. (2007). Predictors of fitness to drive in people with Parkinson disease. *Neurology*, *69*, 1434-1441.
- Di Stefano, M. D., & MacDonald, W. (2003). Assessment of older drivers: Relationships among on-road errors, medical conditions, and test outcome. *Journal of Safety Research*, *34*, 415-429.
- Dissanayake, S., & Perera, L. (2009). *Highway Safety Issues of Older Drivers in Kansas*. Kansas Department of Transportation Report No. K-TRAN: KSU-07-3. Retrieved from http://ntl.bts.gov/lib/31000/31200/31208/KSU-07-03_FinalReport.pdf

- Dobbs, B. (2010). The effects of aging. *Forum on Safety, Mobility and the Aging Driver*, National Transportation Safety Board, November 9, 2010. Retrieved from <http://www.nts.gov/events/Aging-Drivers-2010/Aging-Drivers.html>
- Eberhard, J. (2008). 'Older drivers' 'high per mile crash involvement'—the implications for licensing authorities. *Traffic Injury Prevention*, 9, 284–290.
- Edwards, C. J., Creaser, J. I., Caird, J. K., Lamsdale, A. M., & Chisholm, S. L. (2003). Older and younger drive performance at complex intersections: Implications for using perception-response time and driving simulation. *Proceedings of the Second International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*. July 21-24, 2003, Park City, Utah. Retrieved from http://drivingassessment.uiowa.edu/DA2003/pdf/7_Creaserformat.pdf
- Eustace, D., & Wei, H. (2010). The role of driver age and gender in motor vehicle fatal crashes. *Journal of Transportation Safety and Security*, 2, 28-44.
- Evans, L., (1988). Older drivers involvement in fatal and severe traffic accidents. *Journal of Gerontology*, 43, 186–193.
- Federal Highway Administration (2010). *Travel Monitoring: Traffic Volume Trends*. Available at http://www.fhwa.dot.gov/policyinformation/travel_monitoring/tvt.cfm
- Federal Highway Administration (NHTS). *National Household Travel Survey (NHTS)*, formerly the *Nationwide Personal Transportation Survey (NPTS)*. Available at <http://nhts.ornl.gov/introduction.shtml>

- Freund, B., Colgrove, L. A., Burke, B. L., & McLeod, R. (2005). Self-rated driving performance among elderly drivers referred for driving evaluation. *Accident Analysis & Prevention*, 37, 613–618.
- Gabaude, C., & Paire-Ficout, L. (2005). Toward a driving competency assessment encouraging elderly's automobility: A French point of view. *Proceedings of the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*. June 27-30, Rockport, Maine. Retrieved from http://drivingassessment.uiowa.edu/DA2005/PDF/48_gabaudeformat.pdf
- Gilmore, G. C., Andrist, C. G., & Royer, F. L. (1991). Comparison of two methods of contrast sensitivity assessment with young and elderly adults. *Optometry and Vision Science*, 68(2), 104-109.
- Ginsburg, A. P. (1984). A new contrast sensitivity vision test chart. *American Journal of Optometry and Physiological Optics*, 61, 403-407.
- Goode, K. T., Ball, K. K., Sloane, M., Roenker, D. L., Roth, D. L., Myers, R. S. & Owsley, C. (1998). Useful Field of View and other neurocognitive indicators of crash risk in older adults. *Journal of Clinical Psychology in Medical Settings*, 5, 425-440.
- Hakamies-Blomqvist, L. (1993). Fatal accidents of older drivers. *Accident Analysis & Prevention*, 25, 19-27.
- Hancock, P. A. & Manser, M. P. (1997) Time-to-contact: more than Tau alone. *Ecological Psychology*, 9(4), 265–297.
- Hellinga, B., & MacGregor, C. (1999). Towards modeling the impact of an ageing driver population on intersection design and traffic management. Paper prepared for

- presentation at the 1999 Annual Conference of the Transportation Association of Canada, Saint John, New Brunswick. Retrieved from <http://www.civil.uwaterloo.ca/bhellingsa/publications/Publications/TAC-%201999%20Modelling%20Older%20Drivers%20v2.PDF>
- Henderson, R. & Burg, A. (1974). *Vision and audition in driving*. Technical Report No. TM[L]-5297/000/000. Washington, DC: US Department of Transportation.
- Hennessy, D. F. (1995). *Vision testing of renewal applicants: Crashes predicted when compensation for impairment is inadequate*. Report No. RSS-95-152. Sacramento, CA: California Department of Motor Vehicles. Retrieved from http://www.dmv.ca.gov/about/profile/rd/r_d_report/Section%202/152-Vision%20Testing%20of%20Ren.pdf
- Hennessy, D. F., & Janke, M. K. (2009). *Clearing a road to being driving fit by better assessing driving wellness: Development of California's prospective three-tier driving centered assessment system*. Technical Report No. CAL-DMV-RSS-05-216. Sacramento, CA: Research and Development Division, Licensing Operations Division, California Department of Motor Vehicles.
- Highway Loss Data Institute (2010). *Q&As: Older People*. Retrieved from http://www.iihs.org/research/qanda/older_people.html#2
- Highway Loss Data Institute (2009). Older driver trends. *Highway Loss Data Institute Bulletin*, 26(8), 1-12.
- Highway Loss Data Institute, (2005). *Insurance special report (A-70): Insurance losses by driver age*. Arlington, VA. , cited on the Insurance Institute for Highway

- Safety/Highway Loss Data Institute *Q&A: Older People*, Retrieved from http://www.iihs.org/research/qanda/older_people.html#2
- Hills, B. L. & Burg, A. (1977). *A reanalysis of California driver vision data: General findings*. Report No. 768. Crowthorne, England: Transport and Road Research Laboratory.
- Hoffman, L., DeDowd, J. M., Atchley, P., & Dubinsky, R. (2005). The role of visual attention in predicting driving impairment in older adults. *Psychology and Aging*, 20, 610-622.
- Hu, P. S., Jones, D. W., Reuscher, T., Schmoyer, R. S. & Truett, L. F. (2000) *Projecting Fatalities in Crashes Involving Older Drivers, 2000–2025*. Oak Ridge National Laboratory, U.S. Department of Energy. (Report ORNL-6963).
- Huebner, K. D., Porter, M. M. & Marshall, S. C. (2006). Validation of an electronic device for measuring driving exposure. *Traffic Injury Prevention*, 7, 76-80.
- Hutman, L. P., & Sekuler, R. (1980). Spatial vision and aging. II: Criterion effects. *Journal of Gerontology*, 35, 700-706.
- Janke, M. K. (1991). Accidents, mileage, and exaggeration of risk. *Accident Analysis and Prevention*, 23, 183–188.
- Janke, M. K., & Eberhard, J. W. (1998). Assessing medically impaired older drivers in a licensing agency setting. *Accident Analysis and Prevention*, 30, 347-361.
- Janke, M. K., & Hersch, S. W. (1997). *Assessing the older driver: Pilot studies* (Report No. 172). Sacramento: California Department of Motor Vehicles.

- Keffe, J. E., Jin, C. F., Weih, L.M., McCarty, C. A., & Taylor, H. R. (2002). Vision impairment and older drivers: Who's driving? *British Journal of Ophthalmology*, 86, 1118-1121
- Kirk, A. & Stamatiadis, N. (2001). *Evolution of the Quasi-induced Exposure: Final Report*, for Southeastern Transportation Center, USDOT Transportation Center. Retrieved from <http://stc.ra.utk.edu/STCresearch/completed/PDFs/stc2-001.pdf>
- Lajunen, T., Parker, D., & Summala, H. (2004). The Manchester Driver Behaviour Questionnaire: a cross-cultural study. *Accident Analysis and Prevention*, 42, 1-8.
- Landy, F. J. (1992). *Alternatives to Chronological Age in Determining Standards of Suitability for Public Safety Jobs. Volume I: Technical Report*. University Park, PA: Center for Applied Behavioral Sciences.
- Langford, J. & Koppel, S. (2006). Epidemiology of older driver crashes – identifying older driver risk factors and exposure patterns. *Transportation Research Part F*, 9, 309-321.
- Langford, J., Koppel, S., McCarthy, D., & Srinivasan, S. (2008). In defence of the low mileage bias. *Accident Analysis & Prevention*, 40, 1996–1999.
- Langford, J., Methorst, R., & Hakamies-Blomqvist, L. (2006). Older drivers do not have a high crash risk-a replication of low mileage bias. *Accident Analysis and Prevention*, 38, 574-578.
- Leat, S. J., & Woo, G. C. (1997). The validity of current clinical tests of contrast sensitivity and their ability to predict reading speed in low vision. *Eye*, 11, 893-899.

- Lee, H. C., Cameron, D., & Lee, A. H. (2003). Assessing the driving performance of older adult drivers: On-road versus simulated driving. *Accident Analysis and Prevention*, 35, 797 – 803.
- Levin, L., Dukic, T., Henriksson, P., Mårdh, S., & Sagberg, F. (2009). *Older Car Drivers in Norway and Sweden: Studies of Accident Involvement, Visual Search Behavior, Attention and Hazard Perception*. VTI Report No. 656A. Retrieved from <http://www.vti.se/EpiBrowser/Publikationer%20-%20English/R656A.pdf>
- Levy, D. T. (1995). The relationship of age and state license renewal policies to driving licensure rates. *Accident Analysis and Prevention*, 27, 461-467.
- Li, G., Braver, E., & Chen, L. (2003). Fragility versus excessive crash involvement as determinants of high death rates per vehicle-mile of travel among older drivers. *Accident Analyses and Prevention*, 35, 227-235.
- Lyman, S., Ferguson, S. A., Braver, E. R., & Williams, A. F. (2002). Older driver involvements in police reported crashes and fatal crashes: Trends and projections. *Injury Prevention*, 8, 116 – 120.
- Massie, D. L., Campbell, K. L., & Williams, A. F. (1995). Traffic accident involvement rates by driver age and gender. *Accident Analysis and Prevention*, 27, 73-87.
- Mayhew, D. R., Simpson, H. M., & Ferguson, S. A., (2006). Collisions involving senior drivers: high-risk conditions and locations. *Traffic Injury Prevention*, 7, 117-124.
- McGwin, G., Jr., Owsley, C., & Ball, K. (1998). Identifying crash involvement among older drivers: Agreement between self-report and state records. *Accident Analysis & Prevention*, 30, 781–791.

- McLaughlan & Murtha, 2010; National Automotive Sampling System (NASS) / General Estimates System (GES) data
- National Highway Traffic Safety Administration (2001). *Traffic Safety Facts 2000: Older Population*. DOT HS 809 328.
- National Highway Traffic Safety Administration (2010a). *Traffic Safety Facts 2009 (Early Edition)*. Retrieved from <http://www-nrd.nhtsa.dot.gov/Pubs/811402EE.pdf>
- National Highway Traffic Safety Administration (2010b). *Physician's Guide to Assessing and Counseling Older Drivers*. Retrieved from <http://www.nhtsa.gov/people/injury/olddrive/OlderDriversBook/pages/Contents.html>
- National Highway Traffic Safety Administration (a). *Fatality Analysis Reporting System (FARS)*. Available at <http://www.nhtsa.gov/FARS>
- National Highway Traffic Safety Administration (b). *National Automotive Sampling System (NASS)*. Available at <http://www.nhtsa.gov/NASS>
- National Institute on Aging (2007). *Living Long & Well in the 21st Century: Strategic Directions for Research on Aging*. Retrieved from www.nia.nih.gov/AboutNIA/StrategicDirections
- Nelson, E. A. & Dannefer, D. D. (1992). Aged heterogeneity: Fact or fiction? The fate of diversity in gerontological research. *The Gerontologist*, 32, 17-23.
- Owsley, C., & Sloane, M. E. (1987). Contrast sensitivity, acuity, and the perception of 'real-world' targets. *British Journal of Ophthalmology*, 71, 791-796.

- Owsley, C., Ball, K., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1991) Visual/cognitive correlates of vehicle accidents in older drivers. *Psychology and Aging*, 6, 403–415.
- Owsley, C., McGwin, G., & McNeil, S. F. (2003). Impact of impulsiveness, venturesomeness, and empathy on driving by older adults. *Journal of Safety Research*, 34, 353-359.
- Owsley, C., Sekuler, R., & Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision Research*, 23(7), 689- 699.
- Owsley, C., Stalvey, B., Wells, J., & Sloane, M. E. (1999). Older drivers and cataract: Driving habits and crash risk. *The Journals of Gerontology*, 54A, M203-M211.
- Oxley, J., Fildes, B., Corben, B., & Langford, J. (2006). Intersection design for older drivers. *Transportation Research Part F*, 9, 335-346.
- Özkan, T., Lajunen, T., & Summala, H., (2006). Driver Behaviour Questionnaire: A follow-up study. *Accident Analysis and Prevention*, 38, 386-395.
- Özkan, T., Lajunen, T., Chliaoutakis, J. El., Parker, D., & Summala, H. (2006). Crosscultural differences in driving behaviours: A comparison of six countries. *Transportation Research Part F*, 9, 227–242.
- Parker, D., McDonald, L., Rabbitt, P., & Sutcliffe, P. (2000). Elderly drivers and their accidents: the aging driver questionnaire. *Accident Analysis and Prevention*, 32, 751–759.
- Parker, D., Reason, J. T., Manstead, A. S. R., & Stradling, S. G. (1995). Driving errors, driving violations and accident involvement. *Ergonomics*, 38, 1036–1048.

- Pelli, D. G., Robson, J. G., & Wilkins, A. J. (1988). The design of a new letter chart for measuring contrast sensitivity. *Clinical Vision Sciences*, 2, 187 – 199.
- Rabbitt, P. (1993). Does it all go together when it goes? The nineteenth Bartlett memorial lecture. *The Quarterly Journal of Experimental Psychology Section A*, 46, 385-434.
- Rabbitt, P., & Parker, D. (2002). *The Ageing Driver: A Programme of Research*. Road Safety Research Report No. 29. Department for Transport: London. Retrieved from <http://webarchive.nationalarchives.gov.uk/+/http://www.dft.gov.uk/pgr/roadsafety/research/rsrr/theme3/theageingdriveraprogrammeofr4777>
- Raghuram, A., & Lakshminarayanan, V. (2006). Motion perception tasks as potential correlates to driving difficulty in the elderly. *Journal of Modern Optics*, 53, 1343-1362.
- Ragland, D. R., & Zabyshny, A. A. (2003). *Intersection Decision Support Project: Taxonomy of Crossing-Path Crashes at Intersections Using GES 2000 Data*. UC Berkeley: UC Berkeley Traffic Safety Center. Retrieved from: <http://escholarship.org/uc/item/0201j0v2>
- Rallabandi, A., & Dissanayake, S. (2009). Fatality risk of older drivers under different conditions based on vehicle miles traveled. *Proceedings of the 2009 Mid-Continent Transportation Research Symposium*. August 2009, Ames, Iowa. Retrieved from <http://www.intrans.iastate.edu/pubs/midcon2009/RallabandiElderly.pdf>

- Reason, J., Manstead, A., Stradling, S., Baxter, J., & Campbell, K. (1990). Errors and violations on the roads: A real distinction? *Ergonomics*, 33, 1315–1332.
- Reimer, B., D'Ambrosio, L. A., Coughlin, J. F., Kafrissen, M. E., & Biederman, J. (2006). Using self-reported data to assess the validity of driving simulation data. *Behavioral Research Methods*, 38, 314–324.
- Retting, R. A., Weinstein, H. B., & Solomon, M. (2003). Analysis of motor-vehicle crashes at stop signs in four US cities. *Journal of Safety Research*, 34, 485-489.
- Rizzo, M., McGehee, D. V., Dawson, J. D., & Anderson, S. N. (2001). Simulated car crashes at intersections in drivers with Alzheimer disease. *Alzheimer Disease & Associated Disorders*, 15(1), 10-20.
- Roenker, D. L., Cissell, G. M., Ball, K. K., Wadley, V. G. & Edwards, J. D. (2003). Speed of- processing and driving simulator training result in improved driving performance. *Human Factors*, 45, 218–233.
- Romoser, M. R. E., & Fisher, D. L. (2009). The effect of active versus passive training strategies on improving older drivers' scanning in intersections. *Human Factors*, 51, 652-668.
- Rubin, G. S., Ng, E. S., Bandeen-Roche, K., Keyl, P. M., Freeman, E. E., & West, S. K. (2007). A prospective, population-based study of the role of visual impairment in motor vehicle crashes among older drivers: The SEE study. *Investigative Ophthalmology and Visual Science*, 48, 1483–1491.
- Salthouse T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, 103, 403-428.

- Schefrin, B. E., Tregear, S. J., Harvey Jr, L. O., & Werner, J. S. (1999). Senescent changes in scotopic contrast sensitivity. *Vision Research*, 39, 3728–3736.
- Schieber, F., Kline, D. W., Kline, T. J. B., & Fozard, J. L. (1992). The relationship between contrast sensitivity and the visual problems of older drivers. *SAE Technical Paper 920613*. ISSN 0148-7191.
- Schlag, B. (1993). Elderly drivers in Germany – fitness and driving behaviour. *Accident Analysis and Prevention*, 25, 47 – 56.
- Sekular, R., & Hutman, L. P. (1980). Spatial vision and aging. I: Contrast sensitivity. *Journal of Gerontology*, 35, 692-699.
- Sekular, R., Hutman, L. P., & Owsley, C. J. (1980). Human aging and spatial vision. *Science*, 209, 1255-1256.
- Sekuler, A.B., Bennett, P.J. & Mamelak, M. (2000). Effects of aging on the useful field of view. *Experimental Aging Research*, 26, 103-120.
- Sekuler, R., Kline, D. W., & Kosnik, W. (1988). *Your vision. A survey by the vision laboratories of Northwestern University and the University of Calgary*. The University of Calgary, Department of Psychology.
- Sims, R. V., McGwin, G., Jr., Allman, R. M., Ball, K. & Owsley, C. (2000). Exploratory study of incident vehicle crashes among older drivers. *Journal of Gerontology: Medical Sciences*, 55A(1), M22–M27.
- Sims, R. V., Owsley, C., Allman, R. M., Ball, K. & Smoot, T. M. (1998). A preliminary assessment of the medical and functional factors associated with vehicle crashes in older adults. *Journal of the American Geriatrics Society*, 46, 556–561.

- Sivak, M. (2009). Mechanisms involved in the recent large reductions in US road fatalities. *Injury Prevention*, 15, 205-206.
- Sivak, M., & Schoettle, B. (2010). *Toward Understanding the Recent Large Reductions in U.S. Road Fatalities*. Report No. UMTRI-2010-12. The University of Michigan Transportation Research Institute: Ann Arbor, Michigan. Retrieved from <http://deepblue.lib.umich.edu/bitstream/2027.42/71390/1/102304.pdf>
- Skaar, N., Rizzo, M., & Stierman, L. (2003). Traffic entry judgments by aging drivers. *Proceedings of the Second International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*. July 21-24, Park City, Utah. Retrieved from http://drivingassessment.uiowa.edu/DA2003/pdf/24_Skaarformat.pdf
- Skyving, M., Berg, H. & Laflamme, L. (2009) A pattern analysis of traffic crashes fatal to older drivers. *Accident Analysis and Prevention*, 41, 253–258.
- Sloane, M. E., Ball, K., Owsley, C., Bruni, J. R., & Roenker, D. L. (1992). The visual activities questionnaire: Developing an instrument for assessing problems in everyday visual tasks. *Technical Digest, Noninvasive Assessment of the Visual System*, 1, 26–29.
- Stamatiadis, N. & Deacon, J. A. (1995). Trends in highway safety: Effects of an aging population on accident propensity. *Accident Analysis and Prevention*, 27, 443-459.
- Staplin, L. & Dinh-Zarr, T. B. (2006). Promoting rehabilitation of safe driving abilities through computerbased clinical and personal screening techniques. *Topics in Geriatric Rehabilitation*, 22, 129-138.

- Staplin, L., Gish, K. W., Decina, L.E., Lococo, K. & McKnight, A. S. (1998). *Intersection Negotiation Problems of Older Drivers, Volume I: Final Technical Report*. USDOT/NHTSA Contract No. DTNH22-93-C-05237. Washington, DC.
- Staplin, L., Gish, K.W., & Joyce, J. (2008). “Low mileage bias” and related policy implications—A cautionary note. *Accident Analysis & Prevention*, 40, 1249-1252.
- Staplin, L., Gish, K., & Wagner, E. (2003). MaryPODS revisited: Updated crash analysis and implications for screening program implementation. *Journal of Safety Research*, 34(4), 389-397.
- Staplin, L., Lococo, K. H, Gish, K. W., & L. Decina, L. (2003). *Model Driver Screening and Evaluation Program Final Technical Report. Volume 2: Maryland Pilot Older Driver Study*. U.S. DOT/NHTSA Publication No. DOT HS 809 583, U.S. Department of Transportation, Washington, DC.
- Staplin, L., Lococo, K. H., McKnight, A. J., McKnight, A. S. & Odenheimer, G. L. (1998). *Intersection Negotiation Problems of Older Drivers, Volume II: Background Synthesis on Age and Intersection Driving Difficulties*. HS-808 850, Volume II,; Report No. 1446/FR,; Background Synthesis, National Technical Information Service.
- Staplin, L., Lococo, K. H., Stewart, J., & Decina, L. E. (1999). *Safe mobility for older people: Notebook*. Report No. DOT-HS-808-853. Washington, DC: National Highway Traffic Safety Administration.
- Strauss, S. H. (2005). *SPR 559 - New, Improved, Comprehensive, and Automated Driver's License Test and Vision Screening System*. Arizona Department of Transportation Report No. FHWA-AZ-04-559(1). Retrieved from

http://grandcanyonairport.info/TPD/ATRC/publications/project_reports/PDF/AZ559.pdf

- Stutts J., Martell, C., & Staplin, L. (2009). *Identifying Behaviors and Situations Associated With Increased Crash Risk for Older Drivers*. Report No. DOT HS 811 093. Office of Behavioral Safety Research, National Highway Traffic Safety Administration, U.S. Department of Transportation: Washington, DC.
- Subramanian, R., & Lombardo, L. (2007). *Analysis of Fatal Motor Vehicle Traffic Crashes and Fatalities at Intersections, 1997 to 2004*. Report No. DOT HS 810 682. National Center for Statistics and Analysis, National Highway Traffic Safety Administration, U.S. Department of Transportation: Washington, DC.
- Subzwari, S., Desapriya, E., Babul-Wellar, S., Pike, I., Turcotte, K., & Rajabali, F., et al. (2009). Vision screening of older drivers for preventing road traffic injuries and fatalities (Review). The Cochrane Collaboration, Issue 1. Art. No.: CD006252. doi:10.1002/14651858. CD006252. pub2.
- Summala, H., & Mikkola, T. (1994). Fatal accidents among car and truck drivers: Effects of fatigue, age, and alcohol consumption. *Human Factors*, 36, 315-326.
- Szlyk, J. P., Seiple, W., & Viana, M. (1995). Relative effects of age and compromised vision on driving performance. *Human Factors*, 37(2), 430-436.
- The National Transportation Safety Board (2010). *Forum on Safety, Mobility, and Aging Drivers* (Transcripts and Webcast of proceedings). Retrieved from <http://www.nts.gov/events/Aging-Drivers-2010/Aging-Drivers.html>
- Thorpe, J. D. (1964). Calculating relative involvement rates in accidents without determining exposure. *Australian Road Research*, 2, 25-36.

- Transportation Research Board (1988). *Proceedings of Transportation in an Aging Society: Improving Mobility and Safety for Older Drivers*. October, 1987. Washington, DC: National Research Council. Retrieved from http://www.trb.org/Publications/Blurbs/Transportation_in_an_Aging_Society_Improving_Mobil_159262.aspx
- Transportation Research Board (2004). *Proceedings of Transportation in an Aging Society: A Decade of Experience*. November 7-9, 1999, Bethesda, Maryland. Washington, D.C.: National Academy of Sciences. Retrieved from http://onlinepubs.trb.org/onlinepubs/conf/reports/cp_27.pdf
- Tsang, P. S. (1997). Age and pilot performance. In R.A. Telfer and P.J. Moore (Eds.), *Aviation Training: Learners, Instruction and Organization* (pp. 21-40). Brookfield, VT: Avebury.
- Tsang, P. S. (2003). Assessing cognitive aging in piloting. In P. S. Tsang and M. A. Vidulich (Eds.), *Principles and Practices of Aviation Psychology* (pp. 507-540).
- U.S. Census Bureau, Population Division (2008). Table 12. Projections of the Population by Age and Sex for the United States: 2010 to 2050 (NP2008-T12). Release Date: August 14, 2008. Retrieved from www.census.gov/population/www/projections/summarytables.html
- van Rijn, L. J., Wilhelm, H., Emesz, M., Kaper, R., Heine, S., Nitsch, S., Grabner, G., Volker-Dieben, H. J., (2002). Relation between perceived driving disability and scores of vision screening tests. *British Journal of Ophthalmology*, 86, 1262-1264.

- Verhaegen, P. K., Toebat, K. L., & Delbeke, L. L. (1988). Safety of older drivers: A study of their overinvolvement ratio. *Proceedings of the 32nd Conference of the Human Factors Society*, 185-188.
- Verschuur, W. L. G., & Hurts, K. (2008). Modeling safe and unsafe driving behaviour. *Accident Analysis & Prevention*, 40, 644–656.
- Viano, D. C., Culver, C. C., Evans, L., Frick, M., & Scott, R. (1990). Involvement of older drivers in multi-vehicle side impact crashes. *Accident Analysis & Prevention*, 22(2), 177-188.
- Williams, A. F., & Shabanova, V. I. (2003). Responsibility of drivers, by age and gender, for motor-vehicle crash deaths. *Journal of Safety Research*, 34, 527–531.
- Wood, J. M. & Owens, D. A. (2005). Standard measures of visual acuity do not predict drivers' recognition performance under day or night conditions. *Optometry and Vision Science*, 82, 698-705.
- Wood, J. M. & Troutbeck, R. (1995). Elderly drivers and simulated visual impairment. *Optometry and Vision Science*, 72, 115–24.
- Wood, J. M. (2002). Age and visual impairment decrease driving performance as measured on a closed-road circuit. *Human Factors*, 44, 482–494.
- Wood, J. M., & Bullimore, M. A. (1995). Changes in the lower displacement limit for motion with age. *Ophthalmic and Physiological Optics*, 15, 31-36.
- Wood, J. M., Anstey, K. J., Kerr, G. K., Lacherez, P. F., & Lord, S. (2008). A multidomain approach for predicting older driver safety under in-traffic conditions. *Journal of the American Geriatrics Society*, 56, 986–993.

Yan, X., Radwan, E. & Guo, D. (2007) Effects of major-road vehicle speed and driver age and gender on left-turn gap acceptance. *Accident Analysis & Prevention*, 39, 843–852.

Appendix A: Driver Perception Questionnaires

Confidential Driver Questionnaire

Name: _____ Telephone: _____

Mailing address: _____

- - - - -

Birth date (d/m/yr): _____ Sex (circle one): M F Do you own a car? _____

How many kilometres do you drive in an average month? _____ city _____ highway

For how many years have you been licensed to drive a car? _____ years

Have you received any tickets other than parking tickets within the last 2 years? _____
If yes, how many tickets? _____

Have you had any accidents within the last 2 years? _____
If yes, how many accidents? _____

Please estimate your own driving speed (kilometres/hour) compared to normal highway traffic.

self	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	self
faster	30kph	20kph	10kph	5kph	same	5kph	10kph	20kph	30kph	slower

Please estimate your own driving speed compared to normal city traffic.

self	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	self
faster	30kph	20kph	10kph	5kph	same	5kph	10kph	20kph	30kph	slower

Do you feel that highway traffic moves at a different speed now than it moved five years ago?

faster	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	slower
now	30kph	20kph	10kph	5kph	same	5kph	10kph	20kph	30kph	now

Do you feel that city traffic moves at a different speed now than it moved five years ago?

faster	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	slower
now	30kph	20kph	10kph	5kph	same	5kph	10kph	20kph	30kph	now

On the highway, do you drive at a different speed now than you drove five years ago?

faster	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	slower
now	30kph	20kph	10kph	5kph	same	5kph	10kph	20kph	30kph	now

On the highway, do you drive at a different speed than you did at 50 years of age?

faster	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	slower
now	30kph	20kph	10kph	5kph	same	5kph	10kph	20kph	30kph	now

In the city, do you drive at a different speed now than you drove five years ago?

faster	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	slower
now	30kph	20kph	10kph	5kph	same	5kph	10kph	20kph	30kph	now

In the city, do you drive at a different speed now than you did at 50 years of age?

faster	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	slower
now	30kph	20kph	10kph	5kph	same	5kph	10kph	20kph	30kph	now

☐ ☐ ☐ ☐ ☐ ☐ ☐

much better now same much better then

☐ self much better ☐ same ☐ average driver much better

self much better same average driver much better

never [] [] [] [] [] very often

never [] [] [] [] [] very often

never [] [] [] [] [] very often

never [] [] [] [] [] very often

very calm [] [] [] [] [] very anxious

If yes, please describe:

Do you feel that the Motor Vehicle Department deals fairly with senior drivers?

What changes, if any, would you like to see in their methods?

What transportation services would you like to see put in place for seniors who do not drive?

Please include any additional comments or suggestions about this questionnaire, this study, or about transportation issues in general. (What questions should I have asked that I did not?)

Confidential Passenger Questionnaire

For this questionnaire, you are the "passenger", and the "driver" is the person who asked you to fill it out. Please be as accurate as possible. To ensure that your answers remain completely confidential, please seal the completed questionnaire into the supplied envelope before returning it to the driver, who has been asked to return it, still sealed, to me. Your assessment will not be revealed to the driver, nor to anyone else. Thank you.

Driver's name: _____ Passenger's name: _____
Passenger birth date (d/m/yr): _____ Sex (circle one): M F
Relationship to driver (friend/relative): _____ Are you a licensed driver? _____

In an average month, how many kilometers do you ride with the driver? _____ city _____ highway.

Please estimate the driver's average city speed (kilometers/hour) compared to normal city traffic.

driver ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ driver
faster 20kph 15kph 10kph 5kph same 5kph 10kph 15kph 20kph slower

Please estimate the driver's average highway speed compared to normal highway traffic.

driver ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ driver
faster 20kph 15kph 10kph 5kph same 5kph 10kph 15kph 20kph slower

Please compare this driver's driving performance to that of an average driver of the same age.

this driver ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ average driver
much better same much better

Please compare this driver's driving performance to that of an average driver of 50 years of age.

this driver ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ average driver
much better same much better

Do you sometimes think you have seen a dangerous driving situation developing before the driver sees it?

never ☐ ☐ ☐ ☐ ☐ very often

Do you sometimes think you have seen an approaching or turning car before the driver has seen it?

never ☐ ☐ ☐ ☐ ☐ very often

Do you sometimes think you have seen an approaching or turning motorcycle before the driver has seen it?

never ☐ ☐ ☐ ☐ ☐ very often

Do you sometimes think you have seen a pedestrian in a crosswalk before the driver has seen him or her?

never ☐ ☐ ☐ ☐ ☐ very often

Do you sometimes think the driver has not seen a traffic sign?

never ☐ ☐ ☐ ☐ ☐ very often

What is your usual state of mind while riding with the driver?

very ☐ ☐ ☐ ☐ ☐ very
calm anxious

Please give your opinion about the safety of this driver.

very ☐ ☐ ☐ ☐ ☐ ☐ ☐ very
safe average unsafe

Please write any additional comments on the back of this page (optional). Thank you very much.

Appendix B: Driving Assessment 2007 Poster

Near Peripheral Motion Detection Threshold Predicts Detection Failure

Accident Risk in Younger and Older Drivers

Steven Henderson, Sylvain Gagnon, Alexandre Bélanger, Ricardo Tabone &
Charles Collin

Introduction

Collisions per mile increase after the age of 65, and more so after the age of 70. Age-related increases in both right of way (ROW) violations and accident responsibility may result in part from failure to detect other vehicles in the right-of-way. An age-related decline in visual motion detection may lead to some of these age-related attention or detection failure accidents. Motion contrast sensitivity in central vision declines after 65 or 70 years of age (Sekuler & Owsley, 1982). A similar decline in motion contrast sensitivity in the near periphery may degrade an older driver's visual orienting reflex toward encroaching objects. Henderson and Donderi (2005) reported that peripheral motion contrast sensitivity correlated significantly with their *Driver Perception Questionnaire* (DPQ), which gives a subjective measure of the effects of reduced detection distances and/or an increase in detection errors.

Research Objectives

The goal of this study was to determine if:

1. peripheral motion contrast threshold (PMCT) predicts detection failure accident risk at any age;
2. PMCT deteriorates with age;

3. the DPQ measures substantially the same driver competencies as a set of a priori selected questions from the well-validated and widely used *Manchester Driver Behaviour Questionnaire* (MDBQ) contained in the *Ageing Driver Questionnaire* (Rabbitt & Parker, 2002);
4. PMCT tests the visual function assessed by the *UFOV*® test battery (Ball et al, 2006), and by divided attention (UFOV2) in particular.

Method

Participants

- 9 men and 7 women, 24 - 42 years of age, ($M = 29.4$, $SD = 4.36$)
- 8 men and 7 women, 65 - 84 years of age, ($M = 73.1$, $SD = 5.36$)

All participants had at least 5 years of driving experience, good mental and physical health, and were tested with their normal visual correction.

Driving Questionnaires

Drivers answered fifteen questions (MDBQ15) relating to detection failures. The questions were selected *a priori* from the *Manchester Driver Behaviour Questionnaire*. Drivers answered five driver perception questions (DPQ5) from the *Driver Perception Questionnaire* about: unexpectedly seeing other cars, motorcycles, and pedestrians; missing signs; and driving anxiety. Response scores to each question were standardized across drivers within groups and averaged across questions for each participant.

Vision Measures

Peripheral motion contrast threshold. Gabor stimuli (vertical 0.4 cycles per degree sine wave gratings drifted centripetally at 13.75 degrees/sec within a Gaussian window) were presented at fifteen degrees eccentricity within a 1.5 second temporal

window, on either of two CRT monitors located 74 cm from the participant. The temporal two-alternative forced choice staircase procedure consisted of four randomly interleaved 2-down/1-up staircases. After each trial, the participant indicated whether the Gabor stimulus appeared “before or after the double beep” (i.e., in the first or the second temporal interval). The PMCT procedure required less than 20 minutes.

Useful field of view. All UFOV® subtests (speed of processing, divided attention, selective attention) were administered to all drivers.

Results

Younger driver PMCT ($M = -39.3$ dB, $SD = 3.00$ dB, $n = 16$) was significantly lower ($t(29) = 5.09$, $p < .00001$) than older driver PMCT ($M = -33.8$ dB, $SD = 3.05$ dB, $n = 15$).

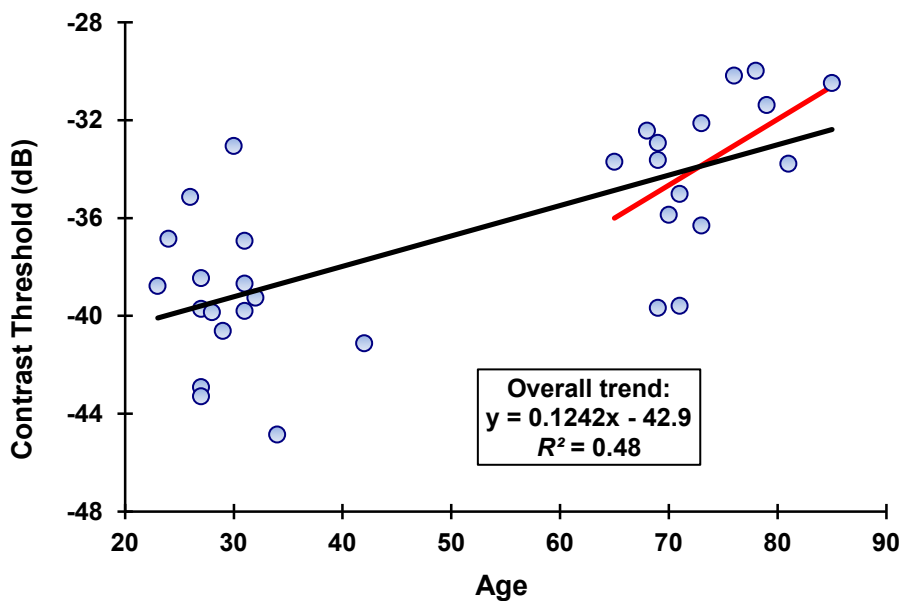


Figure B-1. Contrast threshold by age (overall and older)

Table B-1.

Pearson Product-Moment Correlations between Peripheral Motion Contrast Threshold, Age, and Questionnaire Scores

	Age	Driver Perception Questionnaire 5	Manchester Driver Behaviour Questionnaire 15
Contrast Threshold (PMCT)			
All ($n=31$)	.693****	.484**	.252
Younger ($n=16$)	-.262	.619**	.398
Older ($n=15$)	.491*	.492*	.395

* $p < .05$, ** $p < .01$, *** $p < .001$, **** $p < .0001$, all tests are directional (i.e., 1-tailed)

Table B-2.

Correlations across Questionnaires, Within Groups and Overall

	Man. Driver Behaviour Questionnaire 15
Driver Perception Questionnaire 5	
All ($n=31$)	.627****
Younger ($n=16$)	.589**
Older ($n=15$)	.726**

* $p < .05$, ** $p < .01$, *** $p < .001$, **** $p < .0001$

Table B-3.

Correlations Across Vision Measures, Age, and Questionnaire Scores for Younger and Older Drivers (n=31)

		Contrast	Manchester Driver	
		Threshold	Behaviour	Driver Perception
		(PMCT)	Questionnaire 15	Questionnaire 5
Age				
UFOV1				
(processing speed)	.303*	.136	.009	-.074
UFOV2				
(divided attention)	.671****	.561***	.095	.184
UFOV3				
(selective attention)	.796****	.577***	.002	.108
UFOV Category	.606***	.385*	.019	.087

* $p < .05$, ** $p < .01$, *** $p < .001$, **** $p < .0001$

Table B-4.

Partial Correlations for Peripheral Motion Contrast Threshold by Selected Variables,

Holding Age Constant (n=31)

	partial r (1-tailed, $n=31$)
Holding Age constant, Contrast Threshold by:	
Driver Perception Questionnaire 5	.549***
Man. Driver Beh. Questionnaire 15	.389*
UFOV Category	-.062
UFOV1	.02
UFOV2	.192
UFOV3	.058

* $p < .05$, ** $p < .01$, *** $p < .001$

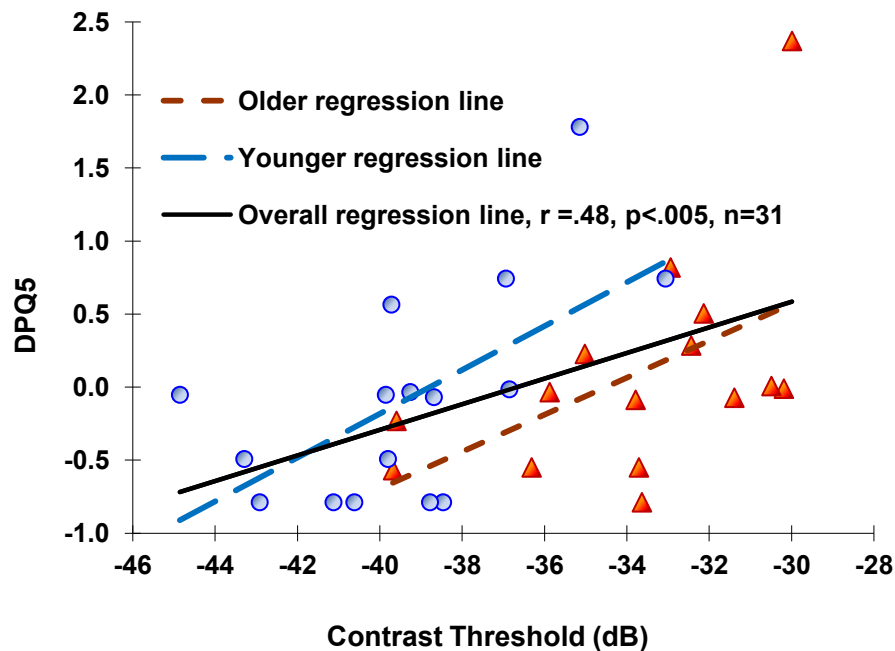


Figure B-2. DPQ5 by contrast threshold (overall and separate)

Discussion

Table B-1, Figure B-1. Age and PMCT were very strongly related overall, and strongly related for older drivers.

Table B-2. The Driver Perception Questionnaire was validated against the well-validated and widely used Manchester Driver Behaviour Questionnaire.

Table B-3. UFOV® measures are not related to questionnaire scores. UFOV® subtests involving peripheral stimuli are very strongly related to age, and less strongly to PMCT, while UFOV1 is significantly related only to age.

Tables B-3 & B-4. Age effects underlie the significant correlations between UFOV® and PMCT.

Figure B-2. A systematic effect of age group on DPQ5 vs. PMCT underlies some of the partialled out age effects.

Conclusion

If future research supports these findings, PMCT could be a demonstrably fair test for identifying drivers with relatively higher detection failure accident risk at any age, as it tests a visual function known to decline with age without being an age-based test. As well, the validated 5-question Driving Perception Questionnaire could offer a fast, confidential self-assessment, with PMCT assessment as a more rigorous follow-up if so indicated.

References

- Ball, K., Roenker, D.L., Wadley, V. G., Edwards, J. D., Roth, D. L., McGwin, Jr., G., ...Dube, T. (2006). Can High-Risk Older Drivers Be Identified Through Performance-Based Measures in a Department of Motor Vehicles Setting? *The American Geriatrics Society*, 54, 77-84.
- Henderson, A.S. & Donderi, D.C. (2005). Peripheral motion contrast sensitivity and older drivers' detection failure accident risk. In *Proceedings of the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, 41-50, Rockport, Maine 2005.
- Rabbitt, P., & Parker, D. (2002). *The Ageing Driver: A Program of Research*. Road Safety Research Report No. 29. Department for Transport: London.
- Sekuler, R., & Owsley, C. (1982). The spatial vision of older humans. In R. Sekuler, D. Kline, & K. Dismukes (Eds.), *Aging and Human Visual Function*, 185-202. New York: Alan R. Liss.

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Appendix C: Analysis of Older Driver Safety and PMCT Using TSB Methodology

The text below describes an analysis of older driver perception and accident risk within the context of my work at the TSB (where we identify safety deficiencies and inform the change agents about them so they can eliminate or mitigate them). By TSB definition, a safety deficiency is a systemic underlying factor (the unsafe condition at the deepest level of analysis) for which defenses are inadequate. Part of the art at the TSB is trying to describe unsafe conditions and safety deficiencies in a way that facilitates their further analysis. That process of analysis depends very simply on continuing to ask *why* an unsafe condition exists (which in general is answered by stating a deeper and more fundamental unsafe condition) until the scope has moved beyond the area of influence of any change agent that the TSB could reach. That deepest unsafe condition where the *why* stops (due generally to scope) is an underlying factor, and a single accident may have several of them. In general, though, the deeper the analysis goes, the wider the impact of TSB's safety actions (i.e., TSB communications to change agents about safety deficiencies).

In this case, one unsafe condition might be that tests do not exist to identify which older drivers are unable to detect and orient on important objects in the driving environment, increasing their chance of colliding with them.

Perhaps another unsafe condition is that nobody has been able until now to identify the visual function (see prior statement) that degrades with age in some older drivers, increasing their accident risk. That unsafe condition relates to the reason(s) that defenses are inadequate.

Perhaps the starting or first level of unsafe condition is that some older drivers tend to not adapt their immediate driving behaviour to potentially conflicting moving objects in their visual periphery, which lead to actual conflict. ("Moving" may refer to retinal motion, or motion relative to background.)

Why? Because they do not see/detect them.

Why? Because those older drivers are less likely to visually orient on moving objects in their visual periphery.

Why? Because their visual systems are relatively less sensitive to moving stimuli in the visual periphery.

If that is enough of a drill-down, the unsafe condition could be stated as:

Some older drivers tend to come into conflict and collision with other road users, pedestrians, or fixed objects, because their visual systems are relatively less sensitive to moving stimuli in the visual periphery.

Looking at that statement, I might think that something essential is missing, and restate the unsafe condition as:

Some older drivers tend to come into conflict with other road users, pedestrians, or fixed objects, because ***they are unaware that*** their visual systems ***have become*** relatively less sensitive to moving stimuli in the visual periphery.

That statement opens up a further cascade of whys, such as:

Why? 1. Because almost by definition, visual processing of peripheral information is carried out automatically and outside focal awareness (by the 50% of the visual cortex not devoted to the central 5 degrees of the visual field). That is why we don't notice what we don't notice. (I suspect that this level of unsafe condition has moved

outside the scope of any change agent, as it resides in the neural architecture of the brain, so we might keep it in hand as useful information but not treat it as the underlying factor, or go further with more whys).

Trying again: **Why?** 2. Because no test is available to determine that some older drivers have an age-related deficiency in a critical visual function for safe driving (i.e., stimulus-driven orientation on potentially conflicting peripheral objects).

Why? Because that critical function has not been identified until now.

The analysis seems to be moving into examining the "for which defenses are not adequate" component of the safety deficiency definition. I think that defenses are not adequate because no test is available, and that is because the critical visual function has not been identified until now. I would suggest that with the development of the PMCT test, and in particular, with the 2-minute version, two potentially adequate defenses can be proposed:

- 1) Older drivers can be tested and those with deficient PMCT can be
 - a) made aware of the need for compensatory strategies and trained in them to mitigate the deficit if possible, perhaps using the very effective scanning behavior retraining program developed and tested by Romoser and Fisher (2009), or
 - b) encouraged to make a well-informed decision to stop driving, as many older drivers do; and/or
- 2) DMVs can require a certain level of performance on a PMCT test, and restrict or revoke licenses below that level.