EFFECTS OF AGE-RELATED DECLINES IN VISUAL MOTION PROCESSING ON OLDER DRIVER SAFETY

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Abstract

This thesis reports three experiments investigating how age-related declines in visual motion processing affect older drivers' ability to drive safely. In particular, these experiments assess the efficacy of: 1) A test of motion sensitivity, the Peripheral Motion Contrast Threshold (PMCT) test, which evaluates ones' contrast threshold for detecting motion in the periphery, and 2) the 3D multiple-object tracking test (3D MOT), which evaluates the maximum stimulus speed at which one can maintain visual attention on several objects moving in three dimensions. Two versions of the PMCT test—the PMCT-10 and the shorter PMCT-2—were employed. Driving safety was measured via a high fidelity driving simulator, in addition to several self-report measures and archival data. Study 1 showed that PMCT-2 and PMCT-10 thresholds were associated with number of crashes in the simulator and other indices of unsafe driving. Study 2 examined whether the PMCT-2 could predict older driver performance during a different set of simulated driving scenarios, and whether it was associated retrospectively with real world crash rates. PMCT-2 results were significantly correlated with simulated crash risk. Moreover, Study 2 provided the first evidence that PMCT scores are associated with real-world crash, albeit in a small retrospective sample. Study 3 examined the relationship between results from both the PMCT-2 and 3D MOT tests and simulated driving. Multiple object tracking has previously been associated with older drivers' performance. Results showed a strong relationship in our sample between crash rates and 3D MOT results. However, we failed to replicate the results showing a relationship between PMCT and crash

occurrence. This may have been due to high rates of subject attrition due to simulator sickness, which resulted in a small final sample. Overall, findings from the three studies demonstrate that results from PMCT and 3D MOT are associated with older drivers' performance measures, such as crash rates, dangerous lane deviations, and speeding. These findings support visual motion processing measures as viable candidates for inclusion in a multi-domain assessment of older drivers' fitness to drive.

Preface

Acknowledgements

I would first like to acknowledge the love and support of my family and my partner Olivier, as they have always told me that I could achieve anything I put my mind to. Of course, a successful doctoral thesis is not possible without a great supervisor; Dr. Charles Collin has always been receptive and fostering toward all of my ideas, while at the same time helping to keep me on track. Thank you, Charles!

I have also greatly appreciated the role that my co-author, Dr. Sylvain Gagnon, has played in the successful completion of my studies. He has provided me with additional guidance and a wealth of expertise on the topic of driving and aging. Dr. Steven Henderson helped spark my curiosity on the topic of psychophysical measures and driving safety, and I thank him for introducing me to this area of research.

Contributions of Authors

Heather Woods-Fry was responsible for gathering the data for Study 1, as well as writing and submitting the published article describing it. Steven Henderson was responsible for the original development of the PMCT test, which was further developed with the aid of Charles Collin and Sylvain Gagnon. Steve Henderson was also responsible for much of the analysis of the data from Study 1, with assistance from Heather Woods-Fry.

Heather Woods-Fry was responsible for the design and implementation of Studies 2 and 3, with assistance from Charles Collin, Sylvain Gagnon, and Steve Henderson. She was also primarily responsible for gathering and analyzing the data from these

experiments. Heather Woods-Fry wrote the manuscripts describing these studies, with assistance from Charles Collin, Sylvain Gagnon and Steven Henderson. These manuscripts are due to be submitted for publication shortly.

Steven Henderson developed the initial research rationale for exploring whether motion sensitivity in the periphery, as measured by drifting sine wave gratings, could explain some of the variance in driving safety measures. This led him to develop the original forced-choice psychophysical method for assessing motion contrast thresholds in the periphery, the PMCT-10 and later on the PMCT-2.

The 3D-MOT test was originally developed by Jocelyn Faubert.

Charles Collin provided Heather Woods-Fry with supervisory guidance and support throughout the research program. He helped modify and perfect both the PMCT-10 and the PMCT-2. Dr. Collin advised Heather Woods-Fry regarding appropriate analyses and provided critiques and modifications to her manuscripts.

Dr. Sylvain Gagnon is a co-author and collaborator on all three studies, and has contributed guidance regarding the topic of driving and aging. He also provided expertise regarding driving simulator usage, and provided access to his high fidelity driving simulator.

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Introduction

Every year 1.25 million deaths occur from road traffic injuries (World Health Organization, 2015). The World Health Organization has reacted to this crisis of preventable deaths by endeavouring to cut the global number of traffic fatalities in half by 2020. To attain this road safety target, one important goal will be to address the overrepresentation of older adults in motor vehicle accidents. It is widely documented that crash involvement per kilometer driven begins to increase after the age of 65 (Chipman et al., 1993; Dellinger et al., 2002; Eberhard, 2008; Li et al., 2003, NHTSA, 2009) with the greatest rise in crash rates seen in drivers of 80 years and older. The current shift in population demographics will see the proportion of older adults increase from 14.4% of the Canadian population to 22.8% in 2031 (Statistics Canada, 2010). Trends suggest that driving will remain the most frequent mode of transportation for older individuals, as an increasing proportion of them remain active licensed drivers (Cheung & McCartt, 2011). In order to reduce older driver crashes, we must first understand the types of collisions they are most typically involved in. A review of many years of research shows that older drivers have a higher rate of involvement in merging, overtaking, and angle crashes, with an exceptionally high involvement in intersection crashes (Mayhew et al., 2006).

The work reported here investigates whether older drivers are at increased risk for such accidents due to a loss of visual motion sensitivity in peripheral vision. This reduction in peripheral motion sensitivity could degrade the visual orienting reflex towards moving peripheral hazards in the roadway, thus creating the potential for these

types of accidents to occur. To investigate the link between motion sensitivity and crash, we have created a test, called the *Peripheral Motion Contrast Threshold 10-minute Test* (PMCT-10 Test) that evaluates ones' contrast threshold for detecting moving stimuli in the periphery. This is based on an earlier test developed by Henderson and Donderi (2005), but uses different psychophysical methods. In addition to this, we have created an updated version of the PMCT-10 that produces the same threshold measurement in only two minutes (PMCT-2); this makes it appropriate for use in real-world assessment situations. Both of these measures have been employed in the studies reported here in order to gain a better understanding of the relationship between motion sensitivity and older driver safety.

Overall, the results of the studies reported herein indicate that both the PMCT-10 and PMCT-2 are predictive of certain simulated driving performance metrics (crash rate, minimum distance of approach to hazards, hazardous lane deviation) that are thought to be indicative of hazardous driving. In particular, Study 1 showed that the PMCT-2 and the PMCT-10 were similarly associated with number of crashes in the simulator, the minimum distance of approach to these hazards, and hazardous lane departures (colloquially known as "weaving"). Thus, it established that the PMCT-2 could be used in place of the PMCT-10 in future studies. Study 2 examined if the PMCT-2 was associated with older drivers' simulated driving performance, as well as with retrospective real world crash rates in our sample. It showed that PMCT-2 results were significantly correlated with simulated driving performance metrics and with real world crash rates (albeit in a very small sample of crashers).

The PMCT test is designed to assess a very low level aspect of motion perception. Indeed, it is designed to target the magnocellular pathway in isolation from any other visual cognitive functions. But driving involves much higher-order motion processing, including the attentional tracking of multiple moving objects. For this reason, in Study 3 we decided to study the relationship between results from a 3D multiple-object-tracking (3D MOT) task and older drivers' simulated and self-report driving ability. Study 3 also attempted to replicate the findings from studies 1 and 2 (i.e., a correlation between PMCT results and crash) but failed to do so, possibly due to the lack of power in our sample. However, the PMCT-2 was correlated with items from a self-report driving measure, called the Driving Behaviour Questionnaire (DBQ). Regarding multiple object tracking (MOT) ability, it was found that results from the 3D MOT task were strongly associated with older drivers' simulated crash rates and lane deviations in a highway setting. These findings are in line with other studies in the literature demonstrating the role of multiple object tracking in safe driving.

The PMCT and 3D MOT are complementary measures of visual motion processing, with the PMCT assessing very low-level contrast detection and the 3D MOT indexing higher-order attentional factors. Evidence of this is seen in the fact that outputs from the measures were not correlated. The PMCT2 is considered as a measure of first-order motion, and is likely measuring the basic functioning of the magnocellular pathway. The MOT is a measure of higher-order motion, and is more directly analogous of one of the more complex tasks done during driving.

Literature Review

In what follows, I first describe previous research regarding the types of accidents in which older drivers are typically involved. This is important in understanding the rationale for examining motion processing as a possible predictor of older driver safety. In this context I discuss the tendency of older drivers to be more involved in intersection crashes and right of way violations, as well as age-related changes to gap acceptance. This is followed by a description of previous work examining various vision measures and their relationship to older driver safety. Here I examine the inadequacy of visual acuity testing and various attempts to create more predictive visual tests, including the Useful Field of View (UFOV) instrument, visual motion perception assessments, and 3D Multiple Object Tracking tests. Finally, I discuss the measures of driving performance most commonly used by researchers in this field, which include driving simulators and the Manchester Driving Behaviour Questionnaire (DBQ) (Reason, Manstead, Stradling, Baxter & Campbell, 1990), a popular questionnaire based measure of driving behaviour. I also discuss the advantages and disadvantages of using retrospective crash data in assessing driving behaviour.

Older Driver Accidents

Intersection crashes. Older drivers are more than twice as likely to be involved in an intersection crash than are younger drivers (Abdel-Aty, Chen, & Schott, 1998). Specifically, up to 35% of older driver crashes are characterized by turning manoeuvres, particularly left turns at intersections. This is also the case in countries that drive on the left, where older drivers are overrepresented in right turn collisions (Baldock Mathias, Kloeden, & McLean, 2002). In line with these studies, Hakamies-Blomqvist (1993)

found that intersection crashes with a crossing vehicle were the most prevalent type of crash for older drivers (58% vs. 30.6% for younger drivers). With the increasing age of the driver, there is a systematic increase in the proportion of intersection crashes (Daigneault, Joly, and Frigon, 2002; Baker, Falb, Voas, & Lacey, 2003). Dissanayake and Perera (2009) conducted a characteristic analysis of younger, middle aged, and older drivers involved in police reported crashes from 2000-2006. When comparing across age groups, they found that older drivers were less likely to be involved in rear end crashes, but overrepresented in angle crashes (a crash where to vehicles impact at an angle). Left and right turns were problematic manoeuvres for older drivers, leading to more crashes than for their younger counterparts.

Oxley, Fildes, Corben, and Langford (2006) conducted a retrospective study of "black spots", which are sites in Australia that have the highest crash rates for older drivers. A total of 97% of the problem-sites were intersections. Of the 62 sites investigated, 65% were controlled with "stop" or "yield" signs. The remaining 35% were controlled by traffic lights. Similar studies have found that rural intersections are more risky than urban ones, and that non-signalized intersections are more problematic than signalized ones. However, at non-signalized intersections, a signed intersection has a higher crash risk than an unsigned intersection (Chandraratna et al., 2002; Griffin, 2004; Preusser, Williams, Ferguson, Ulmer & Weinstein, 1998).

Age and gap acceptance. Older drivers exhibit issues with the detection, perception and judgement of the safest gap in oncoming traffic (Laberge, Creaser, Rakauskas & Ward, 2006). That is, they have difficulty determining how much of a gap is necessary between two oncoming vehicles for one to merge one's own vehicle in

between them. Lerner Huey, McGee, & Sullivan (1995) conducted a field study examining the gap acceptance of different age groups. They tested 29 young (20-40 years old), 23 young-old (65-69) and 22 older (70 years and up) drivers seated in a stationary test vehicle parked perpendicularly to a four-lane roadway (with a speed limit of 30 mph or 48 km/h). They were asked to make yes/no judgements about the safety of making potential driving manoeuvres (proceeding straight through the intersection, turning left, or turning right). To indicate this, they pressed a button to signal that it was safe to initiate the potential manoeuver and released this button when they no longer deemed the situation safe. The test vehicle was equipped with sensors and video technology allowing for the calculation of the vehicle gap time that the participant indicated as safe versus unsafe. Results demonstrated a significant age effect, where the oldest participants required a gap interval that was 1-2 seconds longer in order to accept at least 50% of the gaps. It was concluded that the safe gap acceptance times of older driver are significantly longer than younger drivers.

A similar study by Skaar, Rizzo and Stierman (2003) tested the gap acceptance behaviours of 10 younger (25-57 years old) and 8 older (60-78 years old) licensed drivers using an instrumented car. For the ten experimental trials, the car was parked in a perpendicular driveway that faced a four-lane highway. Gap judgements were made from a stationary position, and participants were asked to press a button to indicate the last possible moment they would cross the road in front of a specific oncoming vehicle. The experimenter was located in the passengers seat and was using a radar device to measure the speed and distance of the specified oncoming vehicle. Results indicated that older drivers consistently made more conservative gap acceptance judgements in comparison to

younger drivers. However, gap distances for young versus older drivers were only compared at two velocity ranges (30-45 mph and 46-60 mph). A more in-depth analysis comparing how age impacts gap acceptance at various speeds might have revealed a difference in behaviour at lower versus higher velocity of approach.

A driving simulator study by Yan, Radwan and Guo (2007) examined the gap acceptance of younger, middle aged and older drivers at stop-controlled intersections. All participants were tested in two left turn gap acceptance scenarios: At lower speeds, where oncoming traffic was travelling at 25 mph (40.2 km/h; Scenario A) and at higher speeds where oncoming traffic was travelling at 55 mph (88.5 km/h; Scenario B). Results demonstrated that younger drivers chose similar gap distances regardless of the speed of the oncoming vehicle. However, older adults tended to select significantly larger gap distances in the lower speed condition of 40.2 km/h. When traffic speeds were higher, older drivers did not demonstrate the same conservative gap acceptance, reducing their gap distance significantly. Both Staplin et al. (1993) and Cicchino & McCartt (2014) proposed that older drivers accepted decreased gap size in high speed conditions because they attend more to the distance, not the speed of the oncoming vehicle. Spek et al. (2006) suggests that older drivers acceptance of smaller gaps at high speeds may make them more prone to collisions with speeding vehicles.

Another study by Hancock and Manser (1997) measured the gap estimation of younger (18-29 years old) and older drivers (55-83 years old) using a simulator. Participants were asked to estimate the approaching vehicles' time-to-contact (TTC) while waiting to conduct a left hand turn at an intersection. In experiment 1, the scenarios displayed three vehicle-approach-velocity conditions: 35, 40 or 45 mph. A second

experiment was also conducted to test a wider range of velocities, with speed of approach being 6, 9,15 and 44 mph. In both experiments, vehicles approached at a constant rate and participants had to indicate the TTC with a button press at the moment they estimated that the contact would have occurred. Results confirmed a general trend suggesting that younger drivers are more accurate than older drivers at estimating the TTC. Furthermore, they found that younger drivers as well as older drivers become more accurate at TTC estimations with increased vehicle approach velocity.

Accident responsibility and right–of-way (ROW) violations. Accident responsibility has been found to increase with age. Cooper (1990) analyzed the ratio of at fault to not at fault accidents by age, finding "an exponential-looking increase in accident responsibility from age sixty-five up" (p. 95). Williams and Shabanova (2003) also found an increase in accident responsibility with age when analyzing police reports of multi-vehicle collisions from 1997-2001. In this study, drivers 85 and older were found to be at fault in 83% of their accidents. A similar percentage was found by Clarke, Ward, Bartle and Truman (2010) in a study of accidents in the UK from 1994-2007. When analyzing crash records and police narratives, they calculated that accident responsibility increased monotonically after the age of 70. Drivers aged 85 and older were found responsible for 81% of their accidents.

A study by Hakamies-Blomqvist (1993) had a crash investigation team analyse 769 accident reports from 1984-1989 in Finland to determine the primary cause and contributing factors. Accidents of drivers aged 65+ were compared to those of drivers aged 26-40 years old (comparison group chosen on the basis that they are the most statistically safe age group of drivers). When comparing multi-vehicle accidents, older

drivers were found at fault for 87% of their accidents, whereas younger drivers were found at fault for 50% of their accidents.

A similar trend in right of way (ROW) violations is seen with increasing age, demonstrated by the rising proportion of ROW violations to total traffic convictions. (Cooper, 1990). Analysis of crash records by Clarke et al. (2010) found that 38% of at fault older drivers committed right of way violations. Of these ROW violations, the majority of accidents were a result of cross-traffic-flow turns. The cross flow turn crashes were assessed for the presence of one of five error categories (divided attention, visual search problems, poor contrast sensitivity, poor judgement of vehicle approaching speed or slow post turn manoeuvres). Over half of cross flow turn crashes were characterized by visual search errors.

Failure to perceive and detect a roadway hazard is often cited as a primary explanation for older driver crash. In the crash reports studied by Hakamies-Blomqvist (1993), it was concluded that the most common direct cause of older driver accidents was "observation error" (listed in 57.7% of older driver accidents vs. 30.8 % for younger drivers). Braitman, Kirley, Ferguson and Chaudhary (2007) also found that older drivers made significantly more errors of "search and detection" than their younger counterparts. Furthermore, inadequate search (looked but did not see) was the only type of search and detection error to increase with driver age. Summala and Mikola (1994) analyzed 1,357 multi vehicle accidents and found that only "failures of attention: failure to attend to one or more vehicles in the roadway", was attributable to increasing age.

Vision Measures and Driving

In order to drive safely, it is necessary to have adequate visual, cognitive and motor functions. It has been estimated that vision accounts for 85-95% of all sensing cues while driving (American Automobile Association, 1991). Due to the important role of visual functioning in safe driving, one would assume that proper assessment procedures are in place at licensing bureaus worldwide. However, vision screening for safe driving lacks consistency across North American licensing bureaus, and the general consensus among researchers is that the methodologies are insufficient and out-dated (Holder, 2005). The current vision assessment standards for licensing in the United States "stem from antiquated visual standards, a 1937 report approved by the American Medical Association, and widespread implementations and modifications of the Snellen Eye Chart of the 1860s" (Straus, 2005, p.57).

In 2010, the National Highway Traffic Safety Administration (NHTSA) issued the latest recommendations for physicians who assess older drivers' fitness-to-drive. This *Physicians Guide to Assessing and Counselling Older Drivers* provides a functional test battery called the Assessment of Driving Related Skills (ADReS). The ADReS only includes two visual assessment components, static visual acuity and visual field, even though the *Physicians Guide* acknowledges that there are visual functions associated with driving that are not assessed by the battery. These include: contrast sensitivity, angular movement sensitivity, dynamic visual acuity, depth perception, and colour vision. The importance of these capacities to safe driving is noted throughout the scientific literature (e.g., Cole, 2002; Crabb, Fitzke, Hitchings, Viswanathan, 2004).

Static visual acuity. Static visual acuity is described as the ability to resolve fine

details, and is typically assessed using high contrast stationary targets such as those found on the Snellen chart. The Snellen chart is the most common measure of visual acuity. It consists of eleven rows of letters that progressively decrease in size. Beginning at the top, one must cover one eye and read aloud each letter standing from 20 feet away. The size of the letters in the last row to be read accurately indicates the visual acuity in the given eye. Normal visual acuity is the ability to recognize a letter when it subtends 5 minutes of arc. This is represented numerically on a Snellen chart as either a ratio (e.g., 20/20 feet or 6/6 meters), or in terms of the log of the minimum angle of resolution in minutes of arc (i.e., 0.0 logMAR) (Millodot, 2000). Visual acuity has been shown to decrease monotonically with age. The visual acuity cut-off required for licensure varies by jurisdiction. In Canada, most provinces require acuity of at least 20/40 in the better eye. In the United States, acuity requirements range from 20/40 to 20/100 (American Association of Motor Vehicle Administrators, 2009). The lack of standardization and evidence-based recommendations for visual acuity in driving are obviously problematic, but it may be a moot issue in any case, as there is an abundance of research demonstrating that visual acuity is poor predictor of older driver safety (Decina & Staplin, 1993; Owsley, Stalvey, Wells, Sloan & McGwin, 2001; Rubin, Roche, Prasada-Rao, & Fried, 1994; Sivak, 1996).

Dynamic visual acuity. Dynamic visual acuity is the ability to resolve the details of a target in motion (Shinar & Schieber, 1991). Burg (1967) demonstrated that dynamic visual acuity was a better predictor of accident risk then static visual acuity. However, ten years later, Hills and Burg (1977) reanalyzed the accident data and performance on six visual acuity measures by breaking down the subjects (N=14,000) into four age groups.

The new conclusion demonstrated "a significant but very low correlation coefficient indicating that the accident prediction value of the visual acuity tests in question was very low" (p.13).

Static Contrast Sensitivity. Static contrast sensitivity is the ability to perceive slight differences in luminance between adjacent regions of the visual field. Humans are generally most sensitive to static contrast patterns at spatial frequencies of 4-6 cycles per degree. There is a significant decrease in contrast sensitivity that occurs around the age of 60. This age related decrease affects a broad range of middle and high spatial frequency stimuli in central vision (Owsley, Sekuler & Siemsen, 1983). Furthermore, the SF cutoff of the contrast sensitivity function (CSF)—that is, the point where sensitivity drops to zero—decreases significantly with age, paralleling and explaining the decrease in visual acuity (Bruce, 1996; Tessier-Lavigne, 2000).

Dynamic contrast sensitivity. Dynamic contrast sensitivity is the ability to perceive slight differences in luminance between adjacent parts of a moving stimulus. Young adults demonstrate an enhancement in contrast sensitivity when a spatial frequency grating is drifting at various speeds, relative to when it is static. For instance, incorporating a drift rate of 4.3 degrees per second to a spatial frequency grating makes it possible for them to detect the stimulus at 1/4 to 1/5 of the contrast of a stationary one. This motion enhancement in detection is not as strong for older participants, and it is observed that the amount of enhancement declines steadily with the age of the participant. It has been concluded from these findings that a significant portion of the decline in contrast sensitivity of the stationary middle and high spatial frequency gratings is due to a loss in retinal luminance of the aging eye; However, the motion enhancement

deficit is likely due to neural changes in the aging visual system, specifically in the motion-processing M pathway (Hutman, Sekuler & Owsley, 1980; Owsley et al., 1983; Owsley & Sloan, 1987).

Lower levels of contrast sensitivity have been associated with reports of prior accident involvement in older drivers (Ball, Owsley, Sloane, Roenker & Brunni, 1993). However, the role of contrast sensitivity in predicting crashes is unclear. Some prospective studies have found that it is not associated with *future* crash involvement (Cross et al., 2009, Rubin et al. 2007). In contrast, a study by Hennessy and Janke (2009) included contrast sensitivity as a screening tool in the license renewal process in California, and those who failed the contrast sensitivity screening were at a significantly higher risk of incurring future crashes in comparison to those who passed.

Wood and Owen (2005) tested the driving performance of 8 young drivers, 8 middle-aged drivers and 8 older drivers (N=24) on a 1.8 km closed road circuit during day and night conditions (1 daytime drive and four night-time drives at four different luminance levels). They were responsible for detecting targets that included road signs, low-contrast road hazards and pedestrians while maintaining a comfortable speed. Visual assessments included visual acuity and contrast sensitivity. Driving performance was defined as the number of targets detected while driving. Results demonstrated that target recognition was negatively impacted by night driving conditions, and this reduction in recognition ability was more severe for older drivers. Furthermore, standard visual acuity, as measured for licensing standards, did not predict driver target recognition under either day or night conditions. However, contrast sensitivity did predict recognition during night driving under the lowest luminance level. The authors noted that the strength of the

relationship between target recognition and contrast sensitivity may be underestimated in this study because of the individual differences in driving speed and how that could affect how many targets were detected.

Useful field of view (UFOV). The UFOV is an extensively researched measure that is currently the most widely used visual assessment measure of older driver accident risk. The UFOV comprises three subtests. The first is intended to measure speed of processing by requiring participants to indicate whether they see a car or a truck located in the centre of the display. The duration of the stimulus is manipulated across trials. The second subtest measures divided attention, requiring participants to locate a peripherally located car while simultaneously identifying if the central stimulus is a car or a truck. The third subtest is a measure of selective attention, requiring the participant to perform the same task as in the previous subtest, with the addition of visual distractors (triangles). Performance corresponds to the minimum duration (milliseconds) required for the participant to detect the correct target information.

The UFOV has been demonstrated to be a valid and reliable instrument for identifying older drivers with a history of prior accidents (Ball, Owsley, Sloane, Roenker, & Bruni, 1993), predicting future accident involvement (Clay et al., 2005), and predicting simulated driving performance (Roenker, Cissel, Ball, Wadley, & Edwards, 2003). Results on the UFOV have also correlated with self-report assessment of driving in unfamiliar settings (Van Rijn et al., 2002). The UFOV is presented as an assessment of higher-order cognitive abilities, taxing attentional capacities with components of visual sensory functioning. The set of capacities tested by the UFOV is an advantage, according to the developers, since driving is a complex task. However, this also means that it may

overlap with the scope of other assessment tools, and may not provide a predictive contribution above what is provided by more specific tools (see Wood, Anstey, Kerr, Lacherez & Lord, 2008)

Motion processing. Motion processing is a visual capacity that is known to decline with age (Trick & Silverman, 1991; Wood & Bullimore, 1995). Specifically, Snowden and Kavanaugh (2006) have demonstrated that older adults display a reduced sensitivity to visual motion across all spatial frequencies, as well as a decline in their ability to discriminate motion at various speeds. Decrements in motion sensitivity have been shown to influence older driver safety (Henderson, Gagnon, Belanger, Tabone, & Collin, 2010; Raghuram & Lakshminarayanan, 2006; Wood, 2002; Wood, Anstey, Kerr, Lacherez & Lord, 2008; Lacherez, Au & Wood, 2012), which is not surprising given that the driving environment is per force dynamic. Adequate perception of objects in motion and one's position relative to the environment are extremely important components of safe driving.

Some of the best evidence for the importance of visual motion processing in predicting older driver safety comes from Wood (2002). In this study, a variety of visual functions—including static acuity, dynamic acuity, contrast sensitivity, glare score, UFOV, central motion sensitivity, and static and kinetic visual fields—was assessed for 139 drivers with ages ranging from 25-80. Participants were then tested on a closed circuit road, which involved complex tasks requiring recognition, divided attention, perception, maneuvering and reversing. An overall driving score was derived by summing the sub-scores on six driving tasks, which was then compared to the average score for one's age group. The relationships between the overall driving score and the

various visual function scores were explored, with the highest correlation being with central motion sensitivity and contrast sensitivity. Furthermore, the best model for predicting driving performance included: central motion sensitivity, UFOV, contrast sensitivity and dynamic visual acuity. This model could account for 50% of the variance in driving scores. It was concluded that motion sensitivity, being the strongest predictor, demonstrated the greatest promise for predicting older driver safety and therefore should be explored in more depth (Wood, 2002).

Raghuram and Lakshminarayanan (2006) measured motion sensitivity in 15 older adults (*M*: 71 years) using speed discrimination (radial and lamellar motion), motion prediction (time to collision), and direction of heading. A motion sensitivity index score was derived from performance on these tasks. Scores on the UFOV were also collected. Driving performance and accident rates were measured with a self-report questionnaire exploring common driving difficulties. Results demonstrated that drivers reporting at least one accident had a higher motion sensitivity index score (> 40%), but were still classified as having a low accident risk by the UFOV. The authors recognized that their sample was too small to determine quantitative significance, however, a qualitative trend was identified and, based on this, they suggested that motion sensitivity should be explored in future studies with a larger sample size.

Wood et al. (2008) provided further support for the role of motion sensitivity in driving when they demonstrated that measuring this function was an essential part of a test battery that best predicted older driver safety. Out of a group of five visual measures, motion sensitivity was the strongest predictor of driving performance in a model that included a large array of visual, motor, and cognitive tests.

More recently, several studies have tested motion sensitivity with the use of a drifting Gabor patch. Henderson, Gagnon, Belanger, Tabone and Collin (2010), assessed the sensitivity of older drivers to moving targets in the near visual periphery by using a drifting Gabor stimulus (low spatial / high temporal frequency sine wave grating). The stimulus was designed to optimally stimulate the visual pathway responsible for motion processing (i.e., the magnocellular pathway). Findings indicated that thresholds for motion sensitivity decline with age, and that results on their task were significantly correlated with older adults' scores on self-report driving measures. Lacherez, Au and Wood (2012) used a similarly designed, but centrally presented, stimulus and found that thresholds for motion sensitivity as measured by the drifting Gabor patch were significantly correlated with older drivers' scores on the hazard perception test (HPT). The HPT measures one's ability to detect and respond to hazardous events in the roadway environment. A series of short video clips of everyday driving situations are shown to the participant in first person perspective, and they must identify each potential traffic conflict as quickly possible. The overall score is derived from the mean response time and accuracy.

To gain a deeper understanding of the relationship between motion processing and safe driving, Lacherez, Turner, Lester, Burns and Wood (2014) measured first-order and second-order motion processing changes in 61 drivers aged 21-84 years old. First-order motion processing is defined by changes in luminance across the image, and was measured via a random dot kinetogram (RDK) and a drifting gabor patch. Second–order motion is defined by changes in texture, colour or contrast and was measured with a contrast-modulated patch of dynamic noise. Driving performance was measured using the

HPT and a Direction of Heading (DOH) test. In the DOH test, participants were shown short videos from the drivers' perspective and had to report any deviations in lane keeping. As expected, older drivers demonstrated significant performance decrements on all motion sensitivity measures in this study. There were significant correlations between all first order motion processing tests and results on the HPT. However, the strongest predictor of HPT response time and accuracy was the first order motion processing measure using the drifting Gabor stimulus similar to the one from Lacherez et al. (2012). Of particular interest was that the test of second order motion processing was not related to results on the HPT or DOH. The authors suggest that there is a specific and unique contribution of first order motion processing to driving-related judgments such as those illustrated in the HPT. Furthermore, the relationship between motion processing and the HPT was significantly mediated by DOH. The authors believe that this is likely due to the role that optic flow plays in proper lane keeping judgments. Optic flow information gives one the ability to estimate the angle of approach to a hazard, which is essential to determining if one is on a collision course with it.

Multiple object tracking is another aspect of visual processing that is regarded as important to safe driving. However, there has not been much applied research conducted on this topic. The MOT is a measure that assesses ones' ability to track multiple moving objects (Pylyshyn & Storm, 1988). The task of multiple object tracking was originally developed by Pylyshyn and Storm (1988) to measure visual attention, where a small number of moving visual objects (i.e. targets) are independently tracked among other featurally identical objects (i.e. distractors). The underlying mechanism implicated during multiple object tracking was hypothesized to be an essential part of visual-motor

coordination, because motor reactions would require the selection of potentially important target items and a directed focus to these items even when moving throughout the visual field (Pylyshyn, 2009). Research shows that on average, a young adult can track around 4 targets, but that accuracy is speed dependent (Feria, 2013). Older adults' tracking ability is lower than younger adults, likely around 3 objects (Trick, Perl & Sethi, 2005). Tracking performance is also affected by other factors, such as object spacing and speed (Drew, Horowitz & Vogel, 2013). Tracking is influenced by which visual hemifield the target objects are located, suggesting that there is an independent resource allocation that is hemisphere-specific (Chen, Howe & Holocombe, 2013).

As previously mentioned, there are only a handful of studies that have examined multiple object tracking in the context of driving. And although it is generally stated that the MOT task captures the demands of real-world challenges, the lack of applied research may be a result of certain obvious differences between a classic laboratory multiple object tracking task and the actions that take place during driving. First, multiple object tracking tasks allow for objects to change their direction randomly, whereas road users have a limited number of manoeuvres, rate of travel speed and direction of heading that they can exhibit. Secondly, multiple object tracking tasks involve objects that are abstract to the participant, and they have no pre-conceived knowledge about these objects. However, drivers have a lifetime of knowledge about the way certain road users may act or move. Another difference between the MOT task and real-world driving is that driving is a complex task with multiple ongoing sub-tasks. The laboratory MOT task would typically take place alone, with no secondary task to split ones' attention. Finally, MOT

tasks usually involve tracking 2-dimensional objects, whereas a realistic task like driving would involve 3-dimensional stimuli (Lochner & Trick, 2014).

Despite these dissimilarities between the task of multiple object tracking and driving, Bowers et al. (2013) explored the relationship between older driver safety and MOT and found that tracking ability was predictive of road test performance. The drivers that had better speed thresholds on the MOT task were scored as being safer drivers on a standardized road test. Another study, by Lochner and Trick (2014), asked the vital question of whether multiple object tracking could even be performed while driving. Therefore, they formulated several experiments that investigated multiple object tracking in the context of a driving task. The first experiment consisted of an MOT task that was adapted to be performed in a simulated driving environment. While completing a driving scenario, the participants had to keep track of a set of moving vehicles in an array of other vehicles on the road. They found that as the participants had to track more objects (1, 3 or 4), their ability to maintain a consistent headway while driving was compromised. Average deviation in headway maintenance was significantly larger when tracking four targets in comparison to one or three targets. Deviations in lateral positioning also followed the same trend. A second experiment examined whether tracking while driving would enhance the drivers' ability to respond to changes in the tracked vehicles. They found that participants were more successful at detecting featural changes in tracked versus untracked vehicles, in addition to making faster detections when a tracked vehicle swapped properties with another vehicle. Most importantly, they found that drivers were 14% more accurate at detecting when a target vehicle braked as opposed to a distractor vehicle.

Driving Performance Measures

A variety of measures are used to assess driving ability in the literature. For instance, driving simulators are often used to assess performance in a variety of virtual driving situations designed to mimic real-world driving. Researchers also commonly use questionnaires to assess driving performance. The most commonly used one is the Manchester Driving Behaviour Questionnaire (DBQ) (Reason, Manstead, Stradling, Baxter & Campbell, 1990). Additional measures of driving include on-road testing and archival examination of driving history, including crash history. Each of these measures is discussed below.

Driving simulators. Driving researchers often use a simulator as tool to assess a drivers' capability. There are many advantages to using a driving simulator in place of on-road testing. For instance, simulators offer a safe alternative to on-road testing, which always carries the potential risk of accidents. Also, on-road testing does not allow for the precise control of environmental stimuli, whereas simulators are able to produce objective and repeatable conditions. However, the validity of driving simulators has been questioned. That is, it is not a given that performance in simulated driving is an appropriate measure of real world driving. To address this issue, Lee, Cameron and Lee (2003) compared on-road driving performance to simulator performance in 129 older adults. Participants completed 45 minutes on the driving simulator and then went out for a 40 minute on-road driving assessment. The simulated drive included various scenarios, testing one's knowledge of traffic rules and other perceptual and cognitive skills known to be associated with safe driving. Driving performance in the simulator was measured with 10 assessment criteria (Road skills: rule compliance, traffic sign compliance, driving

speed, use of indicator, road use obligation; Cognitive/Perceptual: decision & judgement, working memory, multi-tasks, confidence on high speed, attention task). On-road driving was tested for a prescribed route, and participants were assessed during the drive at predetermined points. The on-road assessment criteria consisted of 11 items (road use obligation, traffic sign compliance, traffic light, T-junction, general driving skill, normal driving, error detection, error recovery, use of indicator, driving speed, working memory). To compare results of simulator driving and on-road driving, principal components analysis was conducted to create an overall Simulated Driving Index and a Road Assessment Index. The index was essentially a weighted average score of the assessment criteria, and a higher index score indicated better performance. The Simulated Driving Index was highly correlated with the Road Assessment Index (r=.716). These results suggest a high degree of transferability between simulated and on-road assessments, and that driving simulators can be used in place of on-road testing as a safe and practical alternative.

Self-report questionnaires. Self-reported driving ability can be measured through a questionnaire, as a way to assess driving performance. The most widely implemented measure is the Manchester Driving Behavior Questionnaire (DBQ). The DBQ was developed by Reason, Manstead, Stradling, Baxter and Campbell (1990). To begin, they sampled a total of 520 drivers across the entire age range and administered a 50-item DBQ. With these responses, they conducted a Principal Components Analysis (PCA) and thus identified three factors that underlie self-reported driving behaviour. The first factor that was found related to violations, that is, deliberate deviations from rules and safe practices. The second factor identified was labelled *errors*, intentional actions

with unintended consequences. The third factor was *slips and lapses*: unintentional actions and failures of memory with inconsequential results. Parker, Reason, Manstead, and Stradling (1995) replicated these results by collecting self report driving data from the entire age range with an abbreviated 24-item DBQ, and using a PCA to confirm the presence of the three factors mentioned above. Interestingly, Parker et al. (1995) identified that older drivers tended to commit more errors or lapses, whereas younger drivers committed more intentional violations. The DBQ offers a valid and reliable way to effectively measure driving behaviour on a larger scale. As a result, the DBQ is a widely used way to measure driving behaviour in traffic research. Recently, De Winter and Dodou (2010) conducted a meta-analysis of 174 studies that used the DBQ, finding that the number of DBQ violations and errors was predictive of self-report accidents.

Accident history. Accident data is another way of assessing driving ability. This involves examining a subject's record of reported crashes, usually via a government database. The advantage of this method is that it provides an easy means to assess real-world driving behaviour without any physical danger to the participant or experimenter. The disadvantage is that it is, by definition, a retrospective measure, and may not necessarily reflect the prospective driving performance of participants. Also, retrospective database reports may be non uniform or incomplete (O'Day, 1993).

On-road testing. On-road driving is the most direct way of measuring actual driving performance, and testing protocols have been developed to ensure a safe, valid and reliable test. Typically, a set of specific assessment criteria (i.e. traffic sign compliance, general driving skill, error detection and recovery, driving speed) is used to score the drivers' overall performance. However, the predictive value of on-road testing

is debated since there are ethical barriers to obtaining the most desirable prospective information (violations, crashes), since a driver who was clearly impaired would not be permitted to finish the test (Brown & Ott, 2004).

Summary of Introduction

In summary, older drivers have a higher rate of involvement in merging, overtaking, and angle crashes, with an exceptionally high involvement in intersection crashes (Mayhew et al., 2006). Older driver accidents can most often be characterized as right of way (ROW) violations, with the common causal factor being detection failures (Summala & Mikkola, 1994). There exists no standard assessment to measure older driver safety, but researchers advocate for a multi-domain (cognitive, visual, motor) assessment battery to measure older drivers' fitness to drive (Staplin, Lococo, Gish, & Decina, 2003). The only established measures for visual function include the assessment of traditional visual acuity, as well as the Useful Field of View (UFOV). However, neither of these measures addresses visual motion sensitivity, a visual capacity that has shown much promise in predicting older driver performance (Wood et al. 2008; Lacherez et al., 2012). Therefore, the purpose of this research was to explore the relationship between visual motion sensitivity and older drivers' simulated driving performance. Through the use of two in-house measures (PMCT-10 & PMCT-2) we have assessed the motion sensitivity of our older driver participants to see if results on these tests are associated with simulated driving performance measures such as crash and dangerous lane deviations. We have also assessed how a related aspect of visual motion perception, the ability to track multiple moving objects at once, is associated with driving performance in older drivers. This was measured by the 3D-Multiple Object Tracking

(3D-MOT) task (Legault, Allard & Faubert, 2013), a task of multifocal attentional pursuit that assesses the ability to track moving targets amongst other featurally identical distractor objects. Finally, we have assessed the accident history of our drivers and how the PMCT score may differ for drivers with one or more crashes. Self-reported driving behaviours were also collected with the use of the DBQ to see if certain pre-selected items related to hazard detection and avoidance behaviours are associated with PMCT-2 thresholds.

Chapter I: A Brief Peripheral Motion Contrast Threshold Test Predicts Older Drivers' Hazardous Behaviours in Simulated Driving

The aim of this study was to determine if a newly developed test of motion sensitivity could predict older drivers' simulated driving performance as effectively as a previously developed version, called the Peripheral Motion Contrast Threshold (PMCT) test. The PMCT was previously established as a significant predictor of older adults' self-reported driving ability and simulated driving performance (Henderson et al 2010; Henderson et al. 2013). However, the PMCT takes 10 minutes to complete and is therefore not ideal for use in licensing bureaus, where it is recommended that tests of functional capacity should take no more than two minutes to administer as part of an overall 20 minute screening battery for older drivers (Staplin, Locco, Gish & Decina, 2003). Therefore, the PMCT-2 minute was developed as a quicker version of the previous test. In order to determine if results on this new test were also associated with older driver performance, we implemented both versions of the peripheral motion sensitivity test (PMCT-10 & PMCT-2) to see if results from them could predict older driver performance in the simulator.

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A Brief Peripheral Motion Contrast Threshold Test Predicts Older Drivers' Hazardous Behaviours in Simulated Driving

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Abstract

Our research group has previously demonstrated that the peripheral motion contrast threshold (PMCT) test predicts older drivers' self-report accident risk, as well as simulated driving performance. However, the PMCT is too lengthy to be a part of a battery of tests to assess fitness to drive. Therefore, we have developed a new version of this test, which takes under two minutes to administer. We assessed the motion contrast thresholds of 24 younger drivers (19-32) and 25 older drivers (65-83) with both the PMCT-10 minute and the PMCT-2 minute test and investigated if thresholds were associated with measures of simulated driving performance. Younger participants had significantly lower motion contrast thresholds than older participants and there were no significant correlations between younger participants' thresholds and any measures of driving performance. The PMCT-10 minute and the PMCT-2 minute thresholds of older drivers' predicted simulated crash risk, as well as the minimum distance of approach to all hazards. This suggests that our tests of motion processing can help predict the risk of collision or near collision in older drivers. Thresholds were also correlated with the total lane deviation time, suggesting a deficiency in processing of peripheral flow and delayed detection of adjacent cars. The PMCT-2 minute is an improved version of a previously validated test, and it has the potential to help assess older drivers' fitness to drive.

Keywords: older drivers, simulated driving, peripheral motion, contrast thresholds

Introduction

It is expected that the U.S. population aged 65 and older will more than double in the next fifty years (U.S. Census Bureau, 2012), and that a growing proportion of older individuals will continue to be active drivers (Cheung & McCartt, 2011). With these shifts in demographics, the issue of older driver safety continues to increase in importance. It is widely documented that crash involvement per kilometer driven begins to increase after the age of 65 (Chipman et al., 1993; Dellinger et al., 2002; Eberhard, 2008; Li et al., 2003, NHTSA, 2009) with the greatest rise in crash rates seen in drivers of 80 years and older. Drivers of that age group have one of the highest degrees of crash risk and are the most likely to be found at fault (NHTSA 2009).

Research on the accident characteristics of older drivers indicate that collisions most commonly occur at intersections and are often a result of failures to yield the right of way (Bao & Boyle, 2009; Braitman et al., 2007; Daigneault et al., 2002; Edwards et al., 2003; Hakamies-Blomqvist, 1993; Langford & Koppel 2006; Levin et al., 2009; Oxley et al., 2006; Rakotonirainy et al., 2012; Retting et al., 2003; Schlag 1993; Stamatiadis & Deacon, 1995; Staplin, Gish et al., 1998: Staplin, Lococo et al.,1998; Subramanian & Lombardo, 2007). The highest crash risk is associated with navigating turns across oncoming traffic (i.e. left hand turns for countries that drive on the right. This data would be reversed in countries that drive on the left) (Chandraratna et al., 2002; Chandraratna & Stamatiadis, 2003; Mayhew et al., 2006), and angle crashes are the most common manner in which a collision occurs (Dissanayake & Perera, 2009; Mayhew, 2006). In addition, older drivers require a longer critical gap when performing turns, as they often exhibit difficulty with estimating the distance between oncoming vehicles

(Chandraratna et al., 2002). The occurrence of such incidents may also be associated with the presence of certain physical impairments of older drivers (reduction in neck range of motion, poor balance, slower reaction time, limb weakness and reduced peripheral sensation) (Lacherez, Wood, Anstey & Lord, 2014)

Several research groups have conducted large-scale analyses of multi-vehicle accidents where the driver was at fault. These have found that failure to detect an oncoming car is most frequently reported as the primary causal factor in older drivers' accidents. For instance, Hakamies-Blomqvist (1993) examined factors that were specifically related to at fault collisions and found that over half of older driver accidents resulted from an observation error where the other vehicle was never detected or was detected too late to avoid collision. Similarly, Braitman et al. (2007) examined crashes that involved right of way violations at intersections and found that inadequate search was to blame for more than 50% of the accidents of drivers aged 65 and older. In line with previous findings from Summala and Mikola (1994), they also found that search and detection errors were the sole causal factor to increase significantly with age.

Henderson et al. (2010) suggest that these patterns of crash characteristics in older drivers arise from a failure to detect the vehicle in the right-of-way. The detection failure hypothesis posits that a reduction in peripheral motion sensitivity degrades the visual orienting reflex towards a moving object outside of central fixation. This capacity plays an essential role in detecting vehicles in the right-of-way.

In support of Henderson et al's hypothesis, declines in motion sensitivity have been repeatedly linked to an increase in collisions with age. For instance, Wood (2002) found that motion sensitivity was a strong predictor of driving performance in older

drivers during an on-road assessment. Her later work showed that, of a group of five visual measures, only motion sensitivity was significantly predictive of crash rates (Wood, 2008). Compatible with this are the results of De Raedt and Ponjaert (2000) who tested 84 older drivers on the Ergovision motion perception test (a commercial visual assessment device), which presents participants with moving arrow structures and asks them to indicate the direction of their movement. Their data showed that motion perception significantly predicted participants' on-road assessment score.

In another related study, Gaubade and Ficout (2005) examined the driving behaviours of two groups of older drivers. The experimental group consisted of 20 participants who had been involved in three or more accidents occurring in the last 3 years. The control group consisted of 20 participants who had no accidents during the same time period. Participants completed an on-road assessment in traffic and were also tested on three visual measures (Ergovision movement perception, visual acuity, and contrast sensitivity). Of these measures, only movement perception was predictive of on-road driving performance during the assessment.

More recently, Lacherez, Au, and Wood (2012) have demonstrated the importance of motion perception in the detection of hazardous driving events. Motion sensitivity was assessed in their experiment via two measures: 1) participants' minimum coherence threshold for detecting motion direction in a random dot kinematogram and, 2) their minimum contrast thresholds to detect a centrally-presented drifting sine wave grating stimulus. Hazard detection was assessed via a modified version of the Hazard Perception Test (HPT) by Horswill, Anstey, Hatherly, Wood and Pachana (2011). In the HPT, participants are presented with video clips filmed from a driver's point of view and

are required to indicate any potential traffic hazards they see (e.g. a pedestrian walking out into traffic). Participants were asked to press the area on the touch screen where they detected a potential incident. Results showed a significant correlation between both measures of motion sensitivity and participants' HPT response times.

Most recently, Poulter and Wann (2013) measured motion processing at different eccentricities in drivers aged 21-83 years old. The stimuli used were photo-realistic images of cars that moved at varying speeds. During the central sensitivity task, participants were asked to make a judgment as to which of two cars was approaching faster. The peripheral sensitivity task required participants to fixate centrally and detect which peripherally located car had approached towards them. Results showed that older drivers were less sensitive than young- and middle-aged drivers to motion across the entire visual field. Furthermore, peripheral motion sensitivity was negatively associated with age. Drivers aged 75+ detected fewer than 30% of the stimuli located at 30° eccentricity, whereas young drivers detected more than 90% of such stimuli.

A possible explanation for why older drivers show deficits in motion detection in the periphery is that they experience a degradation of the magnocellular pathway. This is a processing channel in the mammalian visual system that primarily responds to low spatial frequency and high temporal frequency inputs in peripheral vision. Several lines of evidence indicate a deficit in this pathway in older individuals. For instance, previous research has demonstrated that older adults have a higher peripheral contrast threshold when presented with a stationary low spatial frequency sine wave grating (Schefrin, Tregear, Harvey & Werner, 1999). Additionally, an age related deficit in central motion contrast sensitivity is observed with the presentation of a dynamic low spatial frequency

sine wave grating (Owsley, Sekuler & Siemsen, 1983; Sekuler, Hutman & Owsley, 1980). Raghuram, Lakshminarayanan and Khanna (2005) found that older adults also had higher speed discrimination thresholds for dynamic high contrast gratings. These deficits in processing low spatial frequency high temporal frequency stimuli are likely due to an age related degeneration of the magnocellular pathway (Conlon & Herkes, 2008; Schefrin et al., 1999).

In order to investigate the relationship between magnocellular decline and hazardous driving in older individuals, our group has developed a motion test based on the known characteristics of the magnocellular pathway. The Peripheral Motion Contrast Threshold (PMCT) test is designed to specifically assess the magnocellular channel's sensitivity, with a low spatial frequency and high temporal frequency sine wave grating presented in the near visual periphery. Our previous work has demonstrated that peripheral motion contrast thresholds increase with age and that results from this test correlate with self-report accident risk questionnaires and crash rates during simulated driving (Henderson & Donderi, 2005; Henderson, Gagnon, Bélanger, Tabone, & Collin, 2010; Henderson, Gagnon, Collin, Tabone, and Stinchcombe, 2013).

The PMCT uses the method of descending limits to reach an accurate measure of peripheral motion thresholds. However, the 10-minute duration of this test does not make it easily field deployable as part of a battery of tests to assess driver performance. For this reason, we have developed a new 2-minute version of the PMCT that uses an increasing contrast two-alternative forced choice variation on Békésy's (1947) *threshold tracking* method to assess peripheral motion contrast threshold. The current study will assess the ability of both the 10-minute and 2-minute PMCT tests to predict various measures of

driving performance (i.e., crash rate, distance of approach to hazards, and lane deviation time). We hypothesize that PMCT results will be directly associated with crash rate. This prediction is based on our past work (Henderson & Donderi, 2005; Henderson, Gagnon, Bélanger, Tabone, & Collin, 2010; Henderson, Gagnon, Collin, Tabone, and Stinchcombe, 2013) showing that the PMCT seems to capture an age-related deficit in the ability to orient towards and detect other vehicles and hazards. For the same reasons, we hypothesize that PMCT scores will be inversely related to the minimum distance of approach to hazards. We will also examine whether PMCT results are associated with other driving behaviours such as lane deviation. The tendency towards lane deviations may be related to a decline in the processing of peripheral visual flow as well as the late detection of adjacent vehicles. Finally, we aim to validate the new 2-minute version of the PMCT by comparing the results from the 2-minute test against those of the 10-minute test. We hypothesize that the shorter test will yield very similar results to the longer one and that both will capture an age-related deficit in the drivers' ability to respond to challenging driving situations.

Method

Participants

Younger drivers (N=24; 16 males & 8 females; 19-32 years, $M = 25.4$, $SD = 8.6$) and older drivers (N=25; 17 males & 8 females; 65-83 years, $M = 69.7$, $SD = 4.7$) participated in the study. Younger drivers were recruited through the University of Ottawa's undergraduate subject pool and received course credit for their participation. Older drivers were recruited from advertisements in the community and from a previous study on simulated driving; compensation of 20 dollars was given to them for

participation. Five older participants did not complete the experiment due to symptoms of simulator sickness; No younger drivers dropped out for this reason. Previous research by Mullen, Weaver, Riendeau, Morrison and Bédard, (2010) has demonstrated that participants who drop out due to simulator sickness do not differ from those who complete the task on most measures, mitigating concerns that differential drop-out rates might affect the current results. Outlier analysis ($\pm$ 2.5 SD) resulted in one older and one younger participant being excluded from PMCT-10 data analysis due to extreme contrast threshold scores.

Participants read a summary of the experimental procedure and consented to participation before testing commenced. The testing session lasted approximately 60-75 minutes.

Vision Measures

Drivers were tested on three different versions of the PMCT test. The order of administration was counterbalanced across participants.

PMCT 2-minute test. All participants were run on two implementations of this test with the only difference between them being the operating system used to run the experiment (*PMCT 2-minute PC* and *PMCT 2-Minute iMac*). Both implementations used the same procedure to determine thresholds. The 2-minute PMCT tests were respectively conducted on a PC (Quad Core i5 at 2.9 Ghz, with a 17" ASUS 10-bit monitor, using custom software programmed in C++) and on an Apple computer (28" iMac 3.2 Ghz i3 processor with OSX 10.6.8, using Matlab version 2010b, running PsychToolbox and custom software). The PC was viewed from 72 cm, and the iMac from 57.3 cm, but

stimuli were scaled to make them equal in terms of visual angle on both platforms (see below).

We used a gabor stimuli, which is a sinusoidal gratings of 0.4 cycles/degree spatial frequency, drifting centripetally at 13.75°/second within a Gaussian contrast window whose standard deviation was 10°. The stimulus was located at 15° horizontal eccentricity, directly to the left or right of a fixation cross. Stimulus contrast was recorded in decibel units (dB) (i.e., 20*log(M), where M is Michealson Contrast). On each trial, contrast of the grating started at -48 dB and increased at a rate of 2 dB/second. Participants were instructed to indicate which side the stimulus was presented on as soon possible. This method is similar to Bekesy's (1947) *threshold tracking* method, except that only an ascending direction was presented. There were a total of ten trials, five on each side, presented in random order. Participants received detailed instructions and two practice trials prior to testing.

PMCT-10 minute test. Using a 2-alternative forced choice method of descending limits, thresholds were determined using a sinusoidal grating with the same characteristics as mentioned above (i.e., sinewave gratings of 0.4 cycles/° spatial frequency phase shifting centripetally at 13.75°/sec). The stimulus was presented at four locations: 5° above or below a point on the visual horizon that was 15° to the right or left of fixation. The stimulus was presented within a half-sine temporal window of 1.5 s duration, providing a smooth stimulus onset and offset. The stimulus was preceded and followed by a 0.5 s blank interval. Stimuli were presented using two 17" CRT monitors that were located at a 65 cm distance from the head fixation point. Mean background luminance was 53.9 cd/m^2. The stimuli were generated using MATLAB software on an

IBM PC running Windows XP. Stimulus contrast was recorded in decibel units (dB).

The test consisted of two sets of 4 blocks of trials. The psychophysical method of descending limits was employed in all blocks. In the first set of 4 blocks, the contrast of the grating started at -18 dB and descended by steps of 2 dB per trial. In the second set of 4 blocks, contrast started 4 dB above the threshold measured in the first four blocks, and descended by steps of 1 dB per trial. Thus, the first set of blocks provided a relatively coarse estimate of threshold that served as a starting point for the more finely grained assessment of the second 4 blocks. In both sets of 4 blocks, 2 of them measured contrast threshold to the right of fixation and 2 measured contrast to the left of fixation. These were presented in a randomly interleaved fashion.

On each trial, the stimulus appeared at one of the four possible locations. That is, for a trial from a left-side block, the stimulus would appear on the left monitor, either above or below the visual horizon; For a right-side trial, the stimulus would appear either above or below the visual horizon on the right monitor. Recall that left-side and right-side blocks were randomly interleaved, so a participant could not predict which monitor the gabor would appear on. After the stimulus was presented, a horizontal line appeared on the monitor where it had been shown. Participants were instructed to indicate whether the stimulus had appeared above or below the line's location. Thus, despite there being 4 possible stimulus locations, the task in fact involved a 2 alternative forced choice procedure.

Throughout the trials, participants were instructed to fixate a red LED light positioned at 11" on a mast installed between the two monitors. Their gaze was monitored by the experimenter, who sat facing the participant with the fixation point

between them. If a participant directed their gaze away from the fixation point, the experimenter hit a button to discard the trial. Peripheral motion contrast thresholds (dB) were averaged across all trial blocks for each participant. No participant took more than 10 minutes to complete this task.

Driving Performance Measures

A high fidelity STISIM 3.0 driving simulator by Systems Technology Inc. (systemstech.com; Hawthorne, CA) was used to generate the virtual driving environment. Simulations were projected onto three screens (side panels 123cm x 91cm; center panel 138cm x 91cm) that were located 160 cm away from the driver's seat, providing a 180 degree forward field of view. A modified Logitech G25 steering wheel was used along with pedals from Extreme Competition Controls Inc (ECCI). The virtual environment was coordinated with realistic audio effects allowing for acceleration cues. The STISIM 3.02.13 Drive software collects several variables, including vehicle position and motion, as well as the status of the various driving controls, at a rate of 10 Hz. The software was run on a Windows XP operating system with four Dell Dimension 9200 computers (2.4 GHz Intel Core 2 Duo processor, 3 GB RAM per computer).

Participants completed three simulator scenarios: A familiarization scenario, a highway merging scenario, and a city driving scenario. In the familiarization scenario, participants drove on a two lane road for 5.7 km where they learned how to maintain their speed, perform a complete stop and navigate left and right turns. The highway merging scenario was a 10.7 km drive that required participants to enter and exit a highway numerous times. Participants were verbally prompted by the simulator to perform lane changes to the left-most or right-most lane. As they advanced in the scenario, traffic

levels increased, thus making it more difficult to perform the instructed lane changes. The city driving scenario was 7.8 km long. The setting began in a downtown environment, where participants drove through a small town, followed by a rural road and then a city environment. A total of 5 unexpected events were presented during this scenario: 1) on a 6-lane road, a car merged onto the road from a gas station on the right; 2) on a 6-lane road, a car ran a red light from the left just as the participant was crossing an intersection; 3) on a 2-lane road, a car merged onto the road from the shoulder; 4) on a 2-lane road, a moose ran across the road from the right; and 5) on a 4-lane road, a car merged onto the road from a right-side merging lane.

During the driving scenarios, our three variables of interest were recorded automatically by the simulator (crash rate, minimum distance of approach to all hazards, and lane deviation time). Crash rate was determined by the total number of crashes with objects in the simulated environment. These included, but were not limited to, the objects involved in the 5 unexpected events. The minimum distance of approach to all hazards was recorded as the closest distance a participant's vehicle came to each of the objects involved in the 5 unexpected events. This measure only included near collisions and did not consider the events where full contact was made with the object. Finally, we also examined participants' total lane deviation time. This was recorded for the duration of the simulation and was considered as the unforced time spent outside of a prescribed lane. Lane deviations in response to a hazard were not considered as incorrect.

Results

To test the hypothesis that there are age-related differences in PMCT scores, we ran a between-groups *t*-test for each of the three variants of the test. There were highly

significant differences between the mean scores of older and younger participants on each version: PMCT-10, t = -4.661, p<.0001, PMCT-2(PC), t = -4.877, p<.0001; PMCT-2(iMac): t=-4.998, p<.0001. Older participants' mean PMCT thresholds were higher than the younger participants in all three versions of the test. Older participants also demonstrated a wider range of PMCT scores (see Figure 1.1). These results are consistent with the assumption that PMCT thresholds rise with age. Thresholds can rise more so in one individual than another, therefore producing a greater spread of scores.

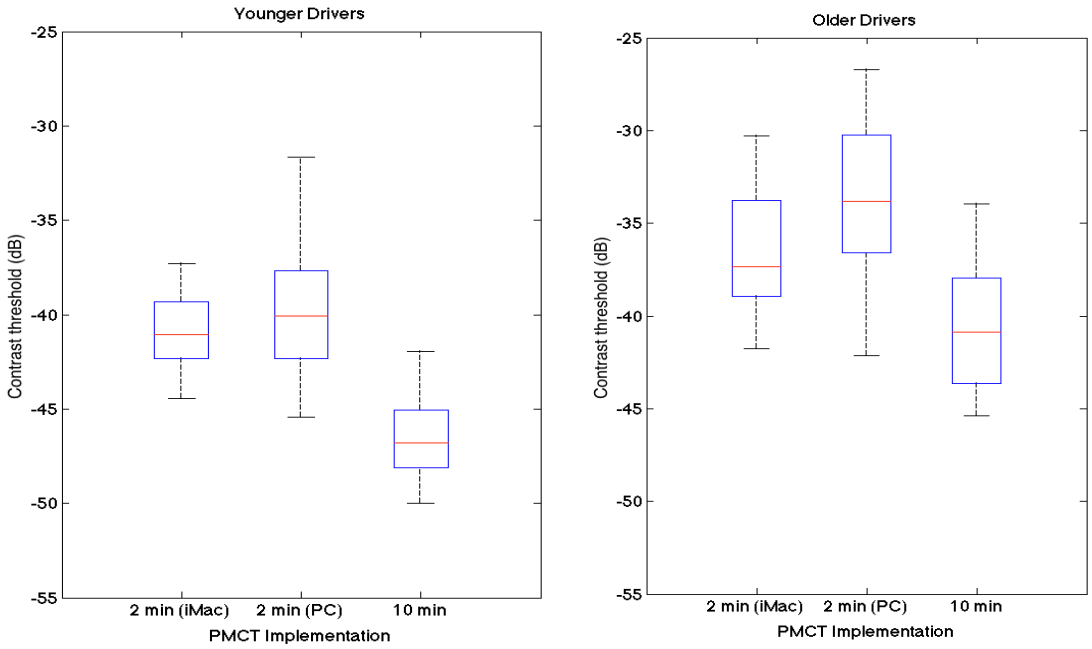

Figure 1.1 Box plots of contrast thresholds for younger and older drivers from three versions of the PMCT

In order to compare the longer and shorter version of the PMCT test, we calculated the correlation between older adults' contrast thresholds measured with the PMCT 10 and those measured by the PMCT 2 (PC; r = .78, p < .00001) (iMac; r = .84, p < .00001). These results demonstrate that the shorter implementations of the test are in substantial agreement with the longer version despite differences in psychophysical methods. The older adults' thresholds from the two implementations of the 2-minute test

were very highly correlated (r = .89, $p < .000001$) suggesting that they provide equivalent results regardless of the difference in computing platform and programming language. In the younger participants, test results from both versions of the 2-minute test were also correlated ($r = 0.52$, $p <. 01$). The smaller correlation here is likely due to range restriction, as younger participants had a very small range of threshold scores (-37.06 to -42.7 dB) as compared to older drivers (-30.3 to -41.78 dB).

Scores of the 10 minute version of the PMCT were significantly higher than those of the 2 minute versions of the PMCT (2-min iMac & 2-min PC). This was the case for both young drivers (iMac vs. 10 minute: M= .92, M= .50 t(22)= 8.75, p <.0001. 2min PC vs. 10 minute: M= 1.04 M= .50, t(22)= 8.33 p <.0001) and older drivers (iMac vs. 10 minute: M= 1.57 M=.99, t(19)= 7.62, p < .0001. 2min PC vs. 10 minute: M= 2.31 M= .99, t(19)= 7.24, p <.0001). These differences are as expected, because the 10 minute version of the PMCT uses a descending method of limits that produces a downward bias in threshold estimate, whereas the 2 minute version uses an ascending tracking method that produces an upward bias.

To determine whether PMCT scores predict simulated driving performance, we calculated the correlation between contrast thresholds and simulator measures associated with driving errors. As previously mentioned, crash rate was calculated as the total number of crashes with objects in the simulated environment (including but not limited to, the objects from the 5 unexpected events). The minimum distance of approach to hazards was calculated as the mean of the z-score of the closest distance any part of a participant's vehicle came to each of the objects involved in the 5 unexpected events. Distances were converted into z-scores relative to all drivers' approach distances to each

given hazard in order to normalize scores relative to one another across the widely different events. We also calculated a separate measure of minimum distance of approach to *lateral* hazards. This was calculated as the mean of the z-score of the closest distance any part of a participant's vehicle came to the unexpected events that were most lateral in nature. Three out of the five unexpected events were considered as lateral hazards: 1) a car that merged from the right onto the road from a gas station, 2) a car that merged onto a 2-lane road from the shoulder, and 3) a car that merged onto a 4-lane road from a right-side merging lane. Again, we converted all distances to z-scores in order to normalize the various events relative to one another, as they had very different mean distances of approach. Minimum distance of approach to hazards and minimum distance of approach to lateral hazards included only near collisions and did not consider the events where full contact was made with the object. Total lane deviation time was calculated as the overall unforced time spent outside of a prescribed lane. Deviations in response to one of the five hazards were not considered as incorrect.

We compared the average crash rate across the entire simulation for both younger and older drivers. Older drivers had slightly more crashes on average than younger drivers, 2.4 vs. 2.21. However, this difference was not statistically significant, $t(41) = -0.3425$, $p = 0.3669$ (SD= 1.7441).

There were no significant correlations between younger participants' thresholds and any measures of driving performance. However, the contrast thresholds of older adults were predictive of their driving performance during simulated driving. Correlations (one-tailed) between PMCT scores and driving performance measures are shown in Table 1.1. Results from all versions of the PMCT were significantly correlated with crash rate

and minimum distance of approach to hazards. PMCT scores were also significantly correlated with minimum distance of approach to lateral hazards. Taken together, these results suggest that PMCT can help predict the risk of collision or near collision. A positive correlation between PMCT scores and total hazardous lane deviation time was found (though this did not reach significance for the 2-minute PC version of the test), suggesting deficient peripheral processing of self-position and adjacent objects.

Table 1.1

Correlations between PMCT scores and hazardous driving measures in older drivers

	2-min iMac	2-min PC	10-min PC
Crash rate	+.66, *p*=.0008	+.45, *p*=.024	+.55, *p*=.006
Min distance of approach to hazards	-.47, *p*=.019	-.39, *p*=.047	-.55 , *p*=.006
Min distance of approach to lateral	-.61, *p*=.002	-.48, *p*=.016	-.64, *p*=.001
Total hazardous lane deviation time	+.41, *p*=.036	+.24, (ns)	+.41 , *p*=.036

Discussion

Our findings suggest that our test of peripheral motion detection can be useful in predicting crash risk in older drivers. In this study, we demonstrated that higher scores on the PMCT were directly related to crash during simulated driving. The significant correlation between PMCT scores and crash rate supports our hypothesis that the tests capture an age-related deficit in the ability to orient towards and detect other vehicles and hazards. In addition, all measures of PMCT significantly predicted the minimum distance of approach to hazards, which is consistent with the hypothesis that a decline in sensitivity of the magnocellular pathway is associated with late detection of hazards. These results are in agreement with previous studies that have linked driving performance

and motion sensitivity. For instance, Wood et al. (2008) found motion processing to be the sole visual measure predictive of driving performance in older adults. Furthermore, Gabaude and Ficout (2005) examined a group of accident-prone older drivers (3+ accidents in a span of 3 years) and a control group (no accidents during the same time period) and found that motion perception (measured with the Ergovision assessment device from De Raedt & Ponjaert-Kristoffersen, 2000) was significantly related to on-road test results.

Our results are compatible with a number of previous studies showing that various aspects of motion processing decline with age. For instance, it is well documented that there are declines in motion coherence thresholds and minimum motion thresholds during normal aging (Gilmore, Wenk, Naylor, & Stuve, 1992; Snowden & Kavanagh, 2006; Trick & Silverman, 1991). Also, older adults have difficulty detecting and discriminating between differences in speed of motion (Norman, Ross, Hawkes & Long, 2003; Raghuram, Lakshminarayanan & Khanna, 2005). Older adult's ability to discriminate the speed of motion is further impaired when eye movements are made to pursue a moving random dot pattern stimulus in comparison to fixating upon a stationary version of the stimulus (O'connor, Margrain & Freeman (2010)

Evidence for the role of motion processing in safe driving is further demonstrated by our findings that total lane deviation time was also correlated with both PMCT 2 min (iMac version) and PMCT 10 min. That is, as PMCT scores of older drivers increased, they became more prone to making lane deviations during simulated driving. The capacity for lane keeping was especially challenged in the highway merging scenario, which required a number of successive lane changes and thus a carful monitoring of

adjacent traffic. The tendency towards lane deviations may be related to a decline in the processing of peripheral visual flow as well as the late detection of adjacent vehicles. Li and Chen (2010) demonstrated that optic flow information was a key determinant in proper lane keeping, and that additional optic flow information improved lane-keeping control. Impairments in the magnocellular pathway would necessarily create impairments in this higher order motion processing task.

The current research highlights the reliability of PMCT measurements, in that we obtained similar results on both 2-minute implementations of the test, as well as the 10-minute version. Furthermore, we have strengthened the evidence for the effectiveness of the PMCT 10 minute that was originally validated in our previous studies (Henderson et al. 2010, Henderson et al. 2013). Finally, we presented an alternative version that is more concise while maintaining the ability to predict simulated driving performance in older adults. The PMCT measures are highly focused on the most fundamental aspects of motion processing and use a stimulus that is designed to narrowly target the functioning of the magnocellular pathway, which underlies all forms of visual motion processing. The latest version of our test has several advantages over previous methods. First, it is fast, taking just 2 minutes to run. The duration of the new version is in accordance with guidelines proposed by Staplin et al. (2003), who suggest that a test of functional capacity should take no more than two minutes to administer as part of an overall 20 minute licensing bureau screening battery for older drivers. Our test is simple to run and easy for participants to complete, making it an excellent candidate for a field deployable driving assessment tool. Additionally, the PMCT 2-minute is compatible with research advocating a multifactor approach, which suggests that older drivers undergo a battery of

tests evaluating their visual, cognitive and motor performance in order to assess their fitness to drive (Wood et al., 2008)

We are currently planning a large multi-center study focused on validating the new 2-minute PMCT test relative to older drivers' on-road driving performance. In the current study, no retrospective driving data was collected from our participants. However, we are currently undertaking further studies, which includes this information. These studies should allow us to establish a critical cut off score on the PMCT test, which would indicate an at risk driver in need of additional training.

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Chapter II: An Updated Version of the Peripheral Motion Contrast Threshold Test Predicts Older Drivers' Simulator Performance

The purpose of this study was to further validate the PMCT- 2 test as a predictor of older driver accident risk and simulated driving performance. The simulator scenarios used in this study were different from those tested in study 1. The simulator scenarios are described in greater detail below. In addition, unlike in Experiment 1, accident history was collected for this sample of older drivers. The accident history was extracted from both police-reported and self-reported incidents. Accidents were assessed for their relatedness to failures of motion processing and those participants with relevant accidents (e.g., intersection crashes, angle crashes) were compared to those who had had no accidents to see if PMCT scores differed between crashers and non-crashers.

An Updated Version of the Peripheral Motion Contrast Threshold Test Predicts Older Drivers' Simulator Performance

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Abstract

A deficit in the visual motion processing of older drivers has been associated with measures of driving performance in a variety of studies. In the current study, peripheral motion processing, as measured by the PMCT-2 minute test, was assessed in 58 older drivers aged 72-89 years old. We investigated if results on the PMCT-2 minute were correlated with measures of driving performance in older drivers. Driving performance was measured using a driving simulator and on-road accident history data was also collected. Participants also completed the subtest 1 & 2 of the UFOV. Results showed that the PMCT-2 minute thresholds were predictive of simulated crash risk, as well as lane deviations. The UFOV subtest 1 & 2 results were not correlated with the PMCT results, nor were they correlated with simulated crash risk. Accident history data showed that participants who had crashes that could be categorized as being due to late hazard detection had significantly worse motion sensitivity in the periphery. Our findings support the idea that the PMCT-2 minute test should be included as part of a battery of tests for assessing older adults' fitness to drive.

Introduction

Older driver accidents per kilometer driven begin to increase at the age of 65, and demonstrate a substantial acceleration after the age of 70 (Chipman et al., 1993; Dellinger et al., 2002; Eberhard, 2008; Li et al., 2003). Such mileage-based estimates of risk may be inflated due to the reduction in miles driven with age. To address this, a study by the National Highway and Traffic Safety Administration (NHTSA, 2009) controlled for the low mileage bias by comparing not-at-fault to at-fault drivers within each age group, by various crash types. They conducted what is called an "induced exposure" analysis of two-vehicle crashes collected from the National Automotive Sampling System (NASS)/ General Estimates System (GES). The analysis was conducted to measure older drivers' exposure level by age group to certain crash situations. To measure this, a Crash Involvement Ratio (CIR) was calculated by comparing the ratio of at fault to not at fault drivers within each age group for a particular driving situation. A CIR greater than 1.00 indicates over-involvement in a particular situation, whereas a CIR less than 1.00 indicates under-involvement. The 60-69 year old group did not show an elevated crash risk in comparison to middle-aged drivers, only demonstrating a slight increase in their CIR ratio for intersection navigation. However, drivers' aged 70-79 displayed increased CIRs for complex driving environments such as intersections, multiple lane highways, and higher speed areas. Drivers aged 80 and over demonstrated substantially higher CIRs across many different driving situations, translating into a higher proportion of at fault crashes (NHSTA, 2009).

The aforementioned study effectively illustrates which factors are most problematic for older drivers of different age groups. For instance, it is clear from its

results that intersections pose the greatest problem for older drivers. This group of drivers is greatly overrepresented in intersection crash statistics, with some studies reporting up to three quarters of older driver accidents characterized by intersection crashes (Schlagg, 1993). The prominence of this finding necessitates "*a better understanding of the pre-crash circumstances of older driver intersection crashes*" (Mayhew et al. 2006, pg. 118).

Braitman et al. (2007) examined at fault older drivers involved in intersection crashes, and found that the predominant error for over half of the crashes was most often described as a detection failure. The majority of the detection failures by older drivers could be accounted for by inadequate search. Summala and Mikkola (1994) found similar results when investigating 1357 multi-vehicle accidents. They categorized the data into five groups of primary causal factors; Failures of attention was the only causal factor that became more prevalent with age

Based on these and similar studies, Henderson and Donderi (2005) presented the *detection failure hypothesis*, suggesting that some of the incidents of older drivers may result from a failure to notice the other vehicle in the right-of-way (ROW), and that the increased accident risk of older drivers is partly a result of detection failures. Furthermore, they hypothesized that these age-related detection failures may be associated with an age-related decline in motion sensitivity. They proposed that a decline in motion detection occurs in the near visual periphery and may be responsible for degrading an older driver's visual orienting reflex towards moving peripheral hazards.

In support of this hypothesis, it has been documented that motion contrast sensitivity declines with age in central vision (Owsley, Sekuler & Siemsen, 1983; Sekuler & Owsley, 1982). There have also been numerous studies demonstrating that motion

sensitivity is predictive of driving performance measures (Wood, 2002; Wood, 2008; De Raedt & Ponjaert, 2000; Gaubade and Ficout, 2005; Lacherez, Au, & Wood, 2012; Poulter & Wann, 2013). It is possible that older drivers show deficits of motion detection in the periphery as a result of degradation in the magnocellular pathway. This pathway is a processing channel in the mammalian visual system that primarily responds to low spatial frequency and high temporal frequency inputs in peripheral vision, and which is thought to subserve all motion processing.

Evidence for an age-related decline in the magnocellular pathway includes data showing that older adults have a poorer peripheral contrast threshold when presented with a stationary low spatial frequency sine wave grating (Schefrin, Tregear, Harvey & Werner, 1999). Although the stimulus is stationary in this case, this deficit is thought to be indicative of a magnocellular decline because the peripheral retina primarily feeds information into this pathway. In addition, an age-related deficit in central motion contrast sensitivity is observed with the presentation of a dynamic low spatial frequency sine wave grating (Owsley, Sekuler & Siemsen, 1983; Sekuler, Hutman & Owsley, 1980). Raghuram, Lakshminarayanan and Khanna (2005) also found that older adults had higher speed discrimination thresholds for dynamic high contrast gratings. These aforementioned deficits in processing low spatial frequency and high temporal frequency stimuli are likely due to an age related degeneration of the magnocellular pathway (Conlon & Herkes, 2008; Schefrin et al., 1999).

In order to investigate how peripheral motion processing is related to safe driving and hazard avoidance, Henderson and Donderi (2005) developed the Peripheral Motion Contrast Threshold (PMCT) test based on the known characteristics of the magnocellular

pathway. Previous results have demonstrated that the PMCT is correlated with older drivers' self- report accident risk (Henderson, Gagnon, Bélanger, Tabone, & Collin, 2010), as well as driving performance in a simulator (Henderson, Gagnon, Collin, Tabone, and Stinchcombe, 2013). An updated version of this test, called the PMCT-2, is a quicker version of the original test and can be completed in under 2 minutes. The PMCT-2 has also demonstrated an association with older drivers' performance in the simulator (Henderson et al., 2015).

The aim of the current study is to assess the ability of the PMCT-2 to predict various measures of driving performance in the simulator (i.e., crash rate, lane deviation) as well as self-reported driving ability and accident history. We hypothesize that PMCT-2 results will be directly associated with crash rate. This prediction is based on our past work (Henderson et al. 2005; Henderson, et al., 2010; Henderson et al., 2013, Henderson et. Al 2015) demonstrating that the PMCT seems to capture an age-related deficit in the ability to orient towards and detect other vehicles and hazards. For the same reasons, we hypothesize that PMCT-2 scores will be related to self-report accident history.

Method

Participants

Older adults were recruited from a longitudinal Canada-wide initiative on safe driving called "Candrive". Participants were 58 volunteers with ages ranging from 72-87 years old (*M*= 76.8, *SD*: 3.6). Since they were a part of Candrive, they were assessed yearly with the Montreal Cognitive Assessment (MoCA) (Nasreddine et al. 2005) for good mental health (M: > 26) and had no history of neurological, psychiatric or substance

abuse problems. All participants were tested with their normal visual correction. Recruitment and testing for this study took place during the 3rd year of the longitudinal Candrive study. There were 20 participants that dropped out after the first experimental driving scenario due to symptoms of simulator sickness. Outlier analysis (± 2.5 SD) resulted in three participants being excluded from the data analysis due to extreme scores. Seven cases were excluded from the analysis due to not having complete PMCT-2 data.

Procedure

Participants read a summary of the experimental procedure and consented to participation before testing commenced. They understood that their participation in the current study did not affect their status within the main Candrive study. The testing session lasted approximately 120 minutes. Upon coming in to the lab, we asked our participants to fill out the Simulator Sickness Questionnaire (SSQ) (Appendix A) to gather a baseline to compare to any changes in symptoms due to simulator sickness produced by the simulated drives. After this, the SSQ was filled out following every simulator scenario in order to monitor any changes in symptoms.

Vision Measures

PMCT-2 minute test. All participants were run on the PMCT-2. The 2-minute PMCT test was conducted on an Apple computer (28" iMac 3.2 Ghz i3 processor with OSX 10.6.8, using Matlab version 2010b, running PsychToolbox and custom software). The iMac was viewed from 57.3 cm, using a chin rest to secure the viewing distance.

We used a Gabor stimulus, which is a sinusoidal luminance grating of 0.4 cycles/degree spatial frequency, drifting centripetally at 13.75°/second within a Gaussian contrast window whose standard deviation was 10°. The stimulus was located at 15°

horizontal eccentricity, directly to the left or right of a fixation cross. Stimulus contrast was recorded in decibel units (dB) (i.e., 20 × log(M), where M is Michealson Contrast). On each trial, contrast of the grating started at -48 dB (.09% Michaelson contrast) and increased at a rate of 2 dB/second (i.e., contrast increased in relative terms by 10.5% per second). Participants were instructed to indicate which side the stimulus was presented on as soon possible. This method is similar to Bekésy's (1947) *threshold tracking* method, except that only an ascending direction was presented. There were a total of ten trials, five on each side, presented in random order. Participants received detailed instructions and two practice trials prior to testing.

Useful field of view (UFOV). Subtests 1 & 2 were administered to participants (processing speed & divided attention). The UFOV has been demonstrated as a valid and reliable predictor of older drivers' vehicle collisions (Ball et al., 2006; Clay et al., 2005). In the processing speed subtest, participants must accurately indicate whether they saw 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 accurately indicate the location of a car presented eccentrically while identifying whether the central stimulus was a car or a truck. Performance (milliseconds) corresponds to the threshold at which a participant is able to accurately detect the target information.

Pelli-Robson contrast sensitivity. The contrast sensitivity of our participants was determined at a distance of 1m for the left and right eye, as well as binocularly. Participants were tested using the Pelli-Robson contrast sensitivity chart that measures contrast sensitivity using large letters (equivalent to 20/60 acuity). Letters are grouped into sets of three, and contrast decreases from left to right with each grouping of letters.

The lowest contrast at which 2 or 3 of the letters in a group can be read determines the subject's log contrast sensitivity score. A score of 2.0 indicates normal contrast sensitivity, while a score below 1.5 suggests a reduced sensitivity. Normal binocular contrast sensitivity for the age group of 60-75 is 1.90 (+/- 0.11) (Mäntyjärvi & Laitinen, 2001).

Driving Assessment

A high fidelity STISIM 3.0 driving simulator by Systems Technology Inc. (systemstech.com; Hawthorne, CA) was used to generate the virtual driving environment. Simulations were projected onto three screens (side panels 123cm x 91cm; center panel 138cm x 91cm) that were located 160 cm away from the driver's seat, providing a 180-degree forward field of view. A modified Logitech G25 steering wheel was used along with pedals from Extreme Competition Controls Inc. (ECCI). The virtual environment was coordinated with realistic audio effects allowing for acceleration cues. The STISIM 3.02.13 Drive software collects several variables, including vehicle position and motion, as well as the status of the various driving controls, at a rate of 10 Hz. The software was run on a Windows XP operating system with four Dell Dimension 9200 computers (2.4 GHz Intel Core 2 Duo processor, 3 GB RAM per computer).

Participants drove four simulated driving scenarios: a familiarization scenario, a construction site navigation scenario, a second familiarization scenario, and a left turn navigation scenario. In the first familiarization scenario, participants drove straight on a two-lane road where they learned how to use the simulator controls to maintain proper speed and lane positioning. The construction site navigation scenario required participants to maintain a speed of 30 km/h while driving through the construction zones.

There were a total of three construction sites separated by stretches of clear roads. Participants had to properly follow the signage in each construction site, and the sites became increasingly difficult to navigate. Potential hazards such as construction workers and lane markers were placed throughout the scenario. During the second familiarization scenario, participants drove on a two-lane roadway where they encountered 4 intersections (two stop sign controlled & two signalized). They learned how to perform a complete stop and navigate left and right turns. Finally, the left turn navigation scenario included ten signalized intersections, where participants had to perform a left turn into oncoming traffic. In doing so, they had to choose the appropriate gap in the oncoming traffic. The gaps between the oncoming traffic became smaller with each intersection turn.

During the driving scenarios, all variables of interest were recorded automatically by the simulator (crash rate and lane deviation time). Crash rate was determined by the total number of crashes with objects in the simulated environment, regardless of type (i.e, other cars, buildings, and pedestrian collisions were all included). Participants' total lane deviation time was recorded for the duration of each simulation and was considered as the unforced time spent outside of a prescribed lane. Lane deviations in response to a hazard were not considered as incorrect.

Results

Simulated Driving Data

To determine whether PMCT-2 scores predict simulated driving performance, we calculated the correlation between contrast thresholds and simulator measures associated

with driving errors. As previously mentioned, crash rate was calculated as the total number of crashes with objects in the simulated environment. Total lane deviation time was calculated as the overall unforced time spent outside of a prescribed lane. Correlations (one-tailed) between contrast thresholds and driving performance measures are shown in Table 2.1. Although some sample sizes were reduced due to simulator sickness drop out rates, this did not affect the power for the aforementioned analyses. Results from the PMCT-2 were significantly correlated with overall crash rate, suggesting that the PMCT-2 can help predict the risk of collision. Furthermore, we found a positive correlation between PMCT-2 scores and total lane deviation time. This may be indicative of a deficiency in peripheral processing of self-position and adjacent objects. We also examined the relationship between scores on the UFOV subtest 1 & 2 and our older drivers' simulated crash rates. Neither the processing speed nor the divided attention subtest of the UFOV was correlated with crash rates in the simulator.

Table 2.1

Correlations between PMCT-2 scores and simulated driving measures in older drivers

	PMCT-2	Power
Scenario 1 crash rate	.34 $p<.01$	.78
Total crash rate	.44 $p<.01$	.78
Total lane deviation	.41 $p< .01$	.72

Note. Scenario 1 crash rate indicates the correlation between the crash rate from the construction scenario and PMCT-2 thresholds (N= 48). *Total crash rate* indicates the correlation between the overall crashes rate from both scenarios and the PMCT-2 thresholds (N=28). Total lane deviation indicates the correlation between overall lane deviation from both scenarios and the PMCT-2 thresholds (N=28).

On-Road Accident Data

We conducted an independent samples t-test to examine if PMCT-2 results were significantly worse for older drivers with an accident history of one or more crashes, as compared to those with no crashes. In our sample, we had 9 participants who experienced one or more on-road crashes in the past 3 years, for a total of 10 crashes. Retrospective accident data from Ministry of Transportation – Ontario (MTO) was collected for all Candrive participants prior to the commencement of the Candrive longitudinal study. During the longitudinal study, MTO and self report accident data was collected for each year of participation in the Candrive study. Therefore, because our sample of Candrive participants was tested at the end of year three of the longitudinal study, we had access to retrospective MTO accident data two years prior to the beginning of the Candrive study, in addition to MTO and self report accident data for years one to three of the Candrive longitudinal study (Appendix B). The information available from these 10 accidents was analyzed and categorized according to the nature of the accident. Accidents that occurred at intersections, or that involved turning left or right were categorized as being potentially due to a late detection of a roadway hazard. Accidents such as rear-end collisions or single vehicle collisions in private lots or driveways were not considered as a detection failure. Ultimately, six out of ten accidents were deemed as involving potential late detection of hazards. In order to determine if the PMCT-2 scores of participants with accidents involving possible hazard detection failures (N= 6) were significantly different from those of participants with no such accidents (N= 42), an independent samples t-test was conducted. Levene's test for equality of variances was found to be violated for the present analysis, $F(1, 55) = 4.67$, $p = .035$. Accounting for this violated assumption, a *t*

test not assuming homogeneity of variance was calculated. The results of this test indicated that there was a significant difference in the PMCT-2 scores observed between the groups, $t(10.71)= -2.589$, $p < .01$. These results indicate that the individuals with a history of crash had significantly worse PMCT-2 thresholds (M= -33. 83, SD= 1.33) than individuals with no detection failure crashes (M= -35.51, SD= 2.57). The post hoc power for this analysis was .05. Although the analysis was underpowered, and the data come from a very small retrospective sample, they nonetheless provide the first evidence to date suggesting that PMCT scores are related to real-world crash risk.

PMCT-2 and Other Visual Measures

The PMCT-2 scores of our older drivers' were negatively correlated with their binocular contrast sensitivity values, as measured by the Pelli-Robson contrast sensitivity chart (r= -.327, p= .01). This relationship is in the expected direction, such that participants with higher contrast sensitivity had lower PMCT-2 thresholds.

PMCT-2 results were not associated with either processing speed or divided attention as measured by the UFOV. This is likely because the UFOV measures higher-order attentional and cognitive factors, whereas the PMCT assesses a lower-level perceptual capacity. That is, the two tests appear to measure complementary abilities.

Discussion

Our findings suggest that the PMCT-2 can be useful in predicting some aspects of hazardous driving in older drivers. Specifically, results from the current study demonstrate that scores on the PMCT-2 were directly related to crash during simulated driving. These findings are in support of our hypothesis that the PMCT-2 captures an

age-related deficit in the ability to orient towards and detect other vehicles and hazards. Furthermore, the PMCT-2 significantly predicted older drivers' total lane deviations. These results are compatible with the idea that the PMCT-2 is measuring a deficiency in peripheral processing of visual flow information. In comparison to our results from our previous work (Henderson et al., 2015), the current study has slightly weaker correlations between the PMCT-2 and our two variables of interest (i.e., number of crashes and lane deviation time). This may be due to the nature of the simulator scenarios used in the current study. These scenarios were not directly focused on assessing driving skills that involve the peripheral processing of motion. They were, however, more focused on assessing fine handling maneuvers of a simulated vehicle, as well as the ability to make appropriate decisions under pressure.

We did not find that the UFOV subtests were predictive of older driver simulated crash rate. It has been previously demonstrated that the UFOV is predictive of driving performance on a closed (Wood, 2002; Wood & Troutbeck, 1995) and open road circuit (DeRaedt & Ponjaert-Kristoffersen, 2000). However, the UFOV is a measure of visual attention that only assesses drivers using static stimuli. Since driving occurs in a dynamic environment, where both self-motion and relative motion occur, we believe that it is imperative to include a measure that assesses the visual motion sensitivity component of safe driving.

We also hypothesized that PMCT-2 scores would be worse for older drivers' with a self-reported history of one or more detection failure crash. This hypothesis was supported by results indicating that participants who experienced this type of crash had significantly poorer PMCT-2 scores than participant who had no history of such a type of

crash. Although we only had a small group of individuals who had crashed, these results are a preliminary real world example of the importance of peripheral motion sensitivity to the detection and avoidance of roadway hazards. This reduced sensitivity in peripheral motion could be contributing to certain types of older driver crash and this should be explored in future studies with a larger sample size.

Our present results support previous studies that have demonstrated that the motion processing capacities of the visual system decline with age and that this decline has implications regarding ones' ability to drive safely. Conlon, Brown, Power and Bradbury (2014) found that older adults have poorer motion coherence thresholds than younger adults, and that their motion coherence threshold is further impacted by reducing the contrast of the stimuli. They also found that older adults' motion coherence threshold was predictive of self-reported driving difficulties, such as trouble seeing cars and other objects in the roadway. In further support of the current findings, Gabaude and Ficout (2005) studied a group of accident-prone older drivers (3+ accidents in a span of 3 years) and a control group (no accidents during the same time period) and found that motion perception, as measured by a test of moving arrow structures, was significantly related to number of errors during a road test. Based on these findings, it is perhaps not surprising that Wood (2008) found that motion sensitivity was the only visual measure that was predictive of on-road driving performance.

Results from studies solely examining the extent of the age-related decline in motion processing are in line with the findings from the current study. Poorer motion coherence thresholds and minimum motion thresholds are observed with normal aging (Gilmore, Wenk, Naylor, & Stuve, 1992; Snowden & Kavanagh, 2006; Trick &

Silverman, 1991). Also, motion processing thresholds are further impacted when perceiving a second-order stimulus (defined by contrast, texture or depth) (Habak & Faubert, 2000). Older adults have difficulty detecting and discriminating between differences in speed of motion (Norman, Ross, Hawkes & Long, 2003; Raghuram, Lakshminarayanan & Khanna, 2005). Most importantly, their ability to discriminate the speed of motion is further impaired when eye movements are made to pursue the stimulus (O'connor, Margrain & Freeman, 2010). Older adults also have a reduced sensitivity to optic flow, which is important visual information about the apparent motion of objects, surfaces, edges etc. caused by the relative motion between the observer and the visual scene (Lich & Bremmer, 2014).

The documented decline in various aspects of visual motion processing helps explain why our motion sensitivity test is related to important elements of safe driving. For instance, our results demonstrating that the PMCT-2 was able to predict lane deviations may be related to the age related decline in the processing of optic flow (Lich & Bremmer, 2014). The decline in optic flow processing may also be related to late detection of adjacent vehicles. Li and Chen (2010) demonstrated that optic flow information was a key determinant in proper lane keeping, and that additional optic flow information improved lane-keeping control. Impairments in the magnocellular pathway would almost certainly create impairments in this higher order motion processing task.

In conclusion, the PMCT-2 is highly focused on the most fundamental aspects of motion processing and uses a stimulus that is designed to narrowly target the functioning of the magnocellular pathway, which underlies all forms of visual motion processing. The PMCT-2 has many advantages. First, we have demonstrated its effectiveness at

predicting important metrics of safe driving in the simulator, as well as providing preliminary data indicating that it may predict real-world crash rates. It is fast and easy to administer, taking just 2 minutes to run. Notably, the duration of the PMCT-2 is in accordance with guidelines proposed by Staplin et al. (2003), who suggest that a test of functional capacity should take no more than two minutes to administer as part of an overall 20 minute licensing bureau screening battery for older drivers. Finally, the PMCT 2 also fits well within a multifactor approach, which suggests that older drivers undergo a battery of tests evaluating their visual, cognitive and motor performance in order to assess their fitness to drive (Wood et al., 2008).

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Appendix A

Post-exposure Simulator Sickness Questionnaire

SYMPTOM CHECKLIST (Post-exposure)

Post-exposure instruction: please fill in this questionnaire. Circle below if any of the symptoms apply to you now.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eyestrain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increase	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. "Fullness of the head"		No	Yes (Slight	Moderate Severe)
11. Blurred vision	No	Yes (Slight	Moderate	Severe)
12. Dizziness eyes open		No	Yes (Slight	Moderate Severe)
13 Dizziness eyes close		No	Yes (Slight	Moderate Severe)
14. Vertigo		No	Yes (Slight	Moderate Severe)
15. Stomach awareness		No	Yes (Slight	Moderate Severe)
16. Burping		No	Yes (Slight	Moderate Severe)

Appendix B

Self-Report Accident data from Year 1-3

Table B1

Summary of accident data from entire sample

Participant ID	Source	Type/Location	Included in analysis?	PMCT2 Score (% contrast)
01-1012	Self-Report	Single vehicle collision-Parking lot (no pedestrian/obstacle)	No	-36.42 (1.51)
01-1051	Self-Report	Left turn-Intersection	Yes	-34.45 (1.89)
01-1120	Self-Report	Right turn-Intersection	Yes	-35.06 (1.77)
01-1506	Self-Report	Left turn-Parking lot	Yes	-31.26 (2.74)
01-1511	Self-Report	Stationary-Received rear end collision	No	-36.50 (1.50)
01-1525	MTO	Intersection	Yes	-33.92 (2.01)
01-1571	Self-Report	Reversing-Committed rear end collision	Yes	-34.44 (1.90)
01-1557	Self-Report	Stationary-Received rear end collision	No	-37.47 (1.34)
01-1614	MTO	Intersection	Yes	-33.82 (2.04)
01-1614	MTO	Private Driveway	No	-33.82 (2.04)

Note. The information provided in this table summarizes all the accident data available (self- report and police reported-Ministry of Transport Ontario (MTO) accidents) for our sample, ranging from two years prior to the start of the Candrive study up until and including the third year of the study (which is the year that the current study took place in).

Table B2

Self-report Accident Data in Year 1 of Candrive Study

Participant ID	01-1051	01-1012	01-1557
Included in analysis	Yes	No	No
PMCT-2 threshold	-34.45	-36.42	-37.47
Where did collision take place?	Urban	Urban	Urban
Lighting conditions	Full daylight	Full daylight	Full daylight
Weather conditions	Clear-No precipitation	Clear-No precipitation	Clear-No precipitation
Road type	City street	Parking lot	Two-lane highway
Characteristics of collision	Two-vehicle collision	Single vehicle collision	Rear-end collision
Type of vehicle involved	Car	Car	Car
Where did collision take place	On open road	Parking lot	Other-At red light on a bridge. Traffic was bumper to bumper
At the time of collision, you were:	Making a left turn	Proceeding at normal speed	Stopped
Driving speed prior to collision	Low speed (<60 km/hr)	Parking lot speed	Fully stopped

Note. The information provided includes all the self-report accident data for those participants in our sample who experienced a crash in year 1 of the Candrive study, however, at fault status is not reported.

Table B3

Self-report Accident Data in Year 2 of Candrive Study

Participant ID	01-1120	01-1571
Included in analysis	Yes	Yes
PMCT-2 threshold	-35.06	-34.44
Where did collision take place?	Urban	Urban
Lighting conditions	Full daylight	Full daylight
Weather conditions	Clear-No precipitation	Clear-No precipitation
Road typ e	City street	Other-Laneway
Characteristics of collision	Two-vehicle collision	Two-vehicle collision
Type of vehicle involved	Car	Car
Where did collision take place	At an intersection with a yield sign	On open road
At the time of the collision, you were:	Making a right turn	Backing up slowly
Driving speed prior to collision	Low speed (<60 km/hr)	Reversing

Note. The information provided includes all the self-report accident data for those participants in our sample who experienced a crash in year 2 of the Candrive study, however, at fault status is not reported.

Table B4

Self-report Accident Data in Year 3 of Candrive Study

Participant ID	01-1506	01-1511
Included in analysis	Yes	No
PMCT-2 threshold	-31.26	-36.50
Where did collision take place?	Urban	Urban
Lighting conditions	Full daylight	Full daylight
Weather conditions	Clear-No precipitation	Clear-No precipitation
Road type	Parking lot	City street
Characteristics of collision	Two-vehicle collision	Rear-end
Type of vehicle involved	Truck	SUV
Where did collision take place	Parking lot	At a traffic light
At the time of the collision, you were:	Making a left turn	Stopped
Driving speed prior to collision	Slow speed	Fully stopped

Note. The information provided includes all the self-report accident data for those participants in our sample who experienced a crash in year 3 of the Candrive study, however, at fault status is not reported.

Table B5

Ministry of Transport Ontario (MTO) Accident Data 2 Years Retrospective to Candrive Study

Participant ID	Included in analysis	PMCT-2 threshold	Accident location
01-1525	Yes	-33.92	Intersection
01-1614	Yes	-33.82	Intersection
01-1614	No	-33.82	Private driveway

Note. The MTO accident data is not recorded in detail. The above information includes the participants who experienced a crash during the 2 years prior to the start of the Candrive study. At fault status is not reported.

Table B6

Ministry of Transport Ontario (MTO) Accident Data During Candrive Study (Year 1-3)

Year of Study	Participant ID	Included in analysis	PMCT-2 threshold	Accident location
Year 1	01-1051	Yes	-34.45	Intersection
Year 2	N/A	N/A	N/A	N/A
Year 3	N/A	N/A	N/A	N/A

Note. The MTO accident data is not recorded in detail. The above information includes the participants who experienced an MTO recorded accident during year 1 to 3 of the Candrive study. At fault status is not reported. The accident involving participant 01-1051 is the same as the one recoded above in year 1 of the self-report accident data. There were no MTO recorded accidents during year 2 or 3 in our sample of participants.

Chapter III: Multiple Object Tracking in Three Dimensions Predicts Older Drivers' Hazardous Driving Behaviours

The purpose of this study was to determine whether a measure of multiple object tracking in three dimensions (the 3D-MOT task) (Legault, Allard & Faubert, 2013) would be significantly related to older drivers' performance in a simulator. In addition, we aimed to further validate the PMCT-2 as a predictor of older driver accident risk. To do this, we measured the simulated driving performance of 30 older drivers in scenarios that were more tailored to assessing driving skills related to peripheral motion processing and detection of hazards. We also collected data using a subset of items from the Driving Behaviour Questionnaire (Reason, Manstead, Stradling, Baxter & Campbell, 1990) that were predetermined to be associated with hazard detection and avoidance.

Multiple Object Tracking in Three Dimensions Predicts Older Drivers' Hazardous Driving Behaviours

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Abstract

We assessed the relationship between three-dimensional multiple-object-tracking (3D-MOT) ability and older driver simulated driving performance. In addition, we investigated the relationship between results on the PMCT-2 minute test and older drivers' performance during simulated driving. The aim of this secondary aspect of the study was to replicate the findings from Henderson et al. (2015) and Woods-Fry et al. (forthcoming), by using the simulator scenario from the former study that incorporated materialized hazards in the roadway environment. Participants included 30 older drivers from the local community who completed a simulated drive, as well as the 3D-MOT task and our test of motion sensitivity (PMCT-2). We also collected self-report driving data using items from the Driving Behavior Questionnaire (DBQ) previously determined to be associated with hazard detection ability. The speed thresholds on the 3D-MOT task were strongly negatively associated with lane deviation and crash rates during a simulated highway drive. However, the current PMCT-2 results failed to replicate previous findings, possibly due to the lack of power in our final sample. The implications of these findings are discussed below.

Introduction

Although there has been a reduction in older driver crash involvement within the last decade (Cicchino & Mcartt, 2014), drivers aged 70 and up are still over-represented in certain types of accidents, such as failure to yield to right of way, and angle crashes (especially at non signalized intersections). Age-related cognitive, visual and physical declines can impact an older driver's ability to navigate difficult driving situations and perform the required actions (Anstey, Wood, Lord & Walker, 2005). More specifically, it has been well documented that adequate visual processing is necessary for safe driving. Indeed, it is thought that 90% of the information used in driving is gathered by the visual system (Rockwell, 1972). Current vision screening by licensing authorities typically involves only a simple test of acuity, despite evidence demonstrating that visual acuity tests do not assess the visual skills necessary for safe driving (Sivak, 1996). Therefore, new evidence-based visual screening measures are required to help establish a standard to include as part of the assessment of older drivers' fitness to drive.

When examining the type of visual information that we encounter in our daily lives, a large amount of what we perceive is in motion. Not only must we be able to effectively process the visual motion in our environment, but we must also be able to accurately track the moving objects of relevance so that we can know their current location in relation to us and anticipate their subsequent movements. A task known as multiple object tracking (MOT), introduced by Pylyshyn and Storm (1988), is assumed to be widely applicable to such every day tracking tasks, and is considered to be a laboratory-based analogue for real world tracking. The traditional MOT task assesses the ability to track the position of a number of target items as they move among featurally

identical distractors. Many researchers assert that multiple object tracking is vital to driving (Fencsik, Klieger & Horowitz, 2007; Feria, 2008; Horowitz et al. 2007), however only a couple of studies have directly examined the relationship between MOT and driving (Bowers et al., 2013; Lochner & Trick, 2014). Bowers et al. (2013) found that MOT results are predictive of the on-road driving performance of older drivers, such that older drivers with poorer results on the MOT task were at risk of committing highway, observation, planning, speed control, and indication errors. Lochner and Trick (2014) asked the vital question of whether multiple object tracking could even be performed while driving. Therefore, they formulated several experiments that investigated if there was any interference from performing multiple object tracking in the context of a driving task. Their experiments consisted of a multiple object tracking task that was adapted to be performed in a simulated driving environment. In the first experiment, the participants completed a driving scenario while having to keep track of a set of moving vehicles in an array of other vehicles on the road. They found that as the participants had to track more objects (1, 3 or 4), their ability to maintain a consistent headway while driving was compromised. Average deviation in headway maintenance was significantly larger when tracking four targets in comparison to one or three targets. Deviations in lateral positioning also followed the same trend. A second experiment examined whether tracking while driving would enhance the drivers' ability to respond to changes in the tracked vehicles. They found that participants were more successful at detecting featural changes in tracked versus untracked vehicles, in addition to making faster detections when a tracked vehicle swapped properties with another vehicle. Most importantly, they

found that drivers were 14% more accurate at detecting when a target vehicle braked as opposed to a distractor vehicle.

Both aforementioned studies examined important aspects of driving performance in relation to multiple object tracking ability. The current study was designed to expand upon the small amount of research in this area by examining how a measure of multiple object tracking, called the three dimensional multiple object tracking (3D-MOT) task, is related to the driving ability of older adults. The latter was measured via a driving simulator and a commonly-used questionnaire, called the *Manchester Driving Behaviour Questionnaire* (DBQ). Using a driving simulator allowed us to expose our drivers to simulated hazardous events that would not be ethical to test during an on-road assessment and thus assess the relationship between our vision measures and crash rates. The DBQ is a 47-item commonly used to measure driving behaviour in traffic research, and has been demonstrated as a predictive of self-report accidents (De Winter & Dodou, 2010).

The 3D-MOT was created by Legault, Allard and Faubert, (2013). Instead of assessing number of items successfully tracked, as is common in other MOT tasks, it uses object speed as the dependent variable. Legault et al. (2013) chose this dependent variable because it can vary on a continuous ratio scale and is not affected by the number of objects that can be tracked at once. Because older adults can usually track around 3 objects (Trick, Perl & Sethi, 2005), this is the number we used in our version of the 3D MOT task. That is, instead of focusing on the number of items successfully tracked, this version of the MOT uses three targets at all times and instead assesses the individual differences in one's capabilities to track the prescribed number of targets in terms of threshold speed of motion (Faubert & Sidebottom, 2012).

The 3D MOT task used here also varies from the traditional task in that it is presented three dimensionally. It has been demonstrated in the literature that three dimensional multiple object tracking differs from the 2D variety. For instance, it produces better speed threshold performance, likely due to the higher ecological validity (Tinjust, Allard, and Faubert, 2008). Tinjust et al., (2008) demonstrated that multiple object tracking speed thresholds were significantly better when the task was presented in stereoscopic versus a non-stereoscopic conditions. Another study found that occlusion cues and binocular disparity enhanced the number of items successfully tracked (Viswanathan & Mingolla, 2002).

Multiple object tracking can be classified as a measure that involves higher order motion, which is made evident by the activation of the human motion integration area MT+ during MOT tasks (Culham et al., 1998; Culham, Cavanagh & Kanwisher, 2001; Jovich et al., 2001). Therefore, as a complement to our use of the 3D MOT task, we also included a measure of low-level motion processing, the Peripheral Motion Contrast Threshold (PMCT-2) test. The PMCT-2 is designed to assess a very basic aspect of motion processing. Indeed, it is designed to target the sensitivity of the early magnocellular pathway, a brain structure that underlies the processing of visual motion, in isolation from any other visual cognitive functions (Henderson et al., 2015). Our previous studies have demonstrated that this test of visual motion sensitivity is associated with measures of driving performance in older drivers (Henderson et al., 2010; Henderson, Gagnon, Collin, Tabone & Stinchcombe, 2013; Henderson et al., 2015). These findings are in line with studies showing that visual motion processing declines with age, and that it is a strong predictor of older drivers' on-road performance (Wood,

Anstey, Kerr, Lacherez & Lord, 2008). Therefore, the current study incorporated both the 3D-MOT and PMCT-2 as complementary measures, with the PMCT-2 assessing the perception of very low-level motion cues and the 3D-MOT indexing higher-order factors.

One reason for including the PMCT-2 in the current study was to simply replicate previous findings from Henderson et al. (2015) and Woods-Fry et al. (forthcoming). We chose replicate the methods of the former, because we felt that the simulator scenarios used in Henderson et al. (2015) were more representative of driving skills that require motion sensitivity in the periphery. In particular, we believe that the presence of materialized hazards (visible hazards that require evasive action) in a driving scenario are necessary in order to test a drivers' sensitivity to motion in the periphery. In addition, we also wished to examine the relationship between our participants' PMCT-2 scores and self-reported driving behaviours as measured by the DBQ. Our previous results have shown a correlation between self-report driving measures and PMCT scores (Henderson, Gagnon, Bélanger, Tabone, & Collin, 2010).

We hypothesized that results on both the 3D MOT and PMCT-2 tasks would be related to measures of unsafe driving, such as number of crashes and lane deviations. However, we expect that the results from the PMCT-2 and the 3D-MOT would not be correlated; This is predicted because the PMCT-2 is designed to be a low level psychophysical measure of ones' ability to detect motion at different levels of contrast in the periphery, where as the 3D-MOT is measuring more complex capacities of visuo-spatial attention to multiple stimuli. We also hypothesized that both the 3D MOT and PMCT-2 thresholds would be correlated with the DBQ-index of hazard detection related items from the DBQ, as they both measure some aspect of avoidance of hazards in the

roadway.

Method

Participants

Older drivers were recruited using advertisements in the community. Participants were 30 volunteers with ages ranging from 65-85 years old (*M*= 72.5, *SD*: 5.7). The participants were screened for good mental health (*M*: 25.3, *SD*: 2.44) with the Montreal Cognitive Assessment (MoCA) (Nasreddine et al. 2005). Participants had no existing eye disease. They were required to possess a G2 license for a minimum of 5 years prior to testing. The participants received 30$ compensation for their time. Upon coming in to the lab, we asked our participants to fill out the Simulator Sickness Questionnaire (SSQ) (Appendix A) to gather a baseline to compare to any changes in symptoms due to simulator sickness produced by the simulated drives. After this, the SSQ was filled out following every simulator scenario in order to monitor any changes in symptoms. Out of 30 participants, only 11 were able to complete all simulator scenarios due to simulator sickness. The individual scenarios had a higher completion rate. There were 15 participants who completed the city driving experimental scenario and 16 participants who completed the highway merging experimental scenario. All incompletions were due to symptoms of simulator sickness.

Vision Measures

Drivers were tested on three different vision measures.

3-Dimensional multiple object tracking test (3D-MOT). The 3D MOT task is a technique that is used to study how the visual system tracks moving targets in three

dimensions. Participants were asked to track three spherical targets moving amongst four featurally identical distractors. That is, a total of seven yellow spheres were presented. At the start of each trial these were static. After 2 seconds, the three target spheres turned red with a surrounding white halo. This highlighting remained for 2 seconds, after which the targets turned back to yellow. The spheres then started to move for 8 seconds along a linear path within the constraints of the screen (i.e., they bounced off the walls of the virtual space they were in). They moved through one another and at times occluded one another. After this, all spheres stopped moving and were labeled with numbers 1-7. Subjects used the mouse to click on the three spheres they believed to be the targets. Once their response was locked in, the correct target spheres were revealed and feedback was given. After each trial, the speed of the sphere movement for the next trial was increased if the subjects' answer was correct, or else it was reduced.

The dependent measure was the speed threshold for tracking three targets. The test consisted of 20 trials and the threshold was estimated using the staircase method. The duration of the test was approximately 10 minutes (Legault et al., 2013).

PMCT-2 minute test. All participants completed the 2-minute PMCT test on an Apple computer (28" iMac 3.2 Ghz i3 processor with OSX 10.6.8, using Matlab version 2010b, running PsychToolbox and custom software).

The PMCT-2 used a gabor stimulus, which is a sinusoidal grating of 0.4 cycles/degree spatial frequency, drifting centripetally at 13.75°/second within a Gaussian contrast window whose standard deviation was 10°. The stimulus was located at 15° horizontal eccentricity, directly to the left or right of a fixation cross. Stimulus contrast was recorded in decibel units (dB) (i.e., 20*log(M), where M is Michealson Contrast). On

each trial, the contrast of the grating started at -48 dB and increased at a rate of 2 dB/second. Participants were asked to indicate which side the stimulus was presented on as soon possible. A total of ten trials, five on each side, were presented in random order. Participants received detailed instructions and two practice trials prior to testing.

Freiburg acuity test (FrACT). The FrACT is a widely used online visual test battery (www.michaelbach.de/fract/index.html) that employs optimized psychophysical methods to provide an automated and self-paced measurement of visual acuity (Bach, 1996). Participants were tested on the FrACT at a distance of 195 cm using the "tumbling E" acuity test. Participants were presented with the letter "E" on each trial in one of four different orientations (i.e. pointing right, left, up or down). Participants had to identify which direction the "E" was pointing by responding with the 4 arrows on the keypad provided. The FrACT uses a standard psychophysical procedure called "best PEST" (Lieberman & Pentland, 1982) to estimate the smallest size of stimulus that the participant can reliably identify correctly. The test estimates the participant's size threshold and provides the experimenter with an estimate of the participant's visual acuity in terms of logMAR (log of minimum angle of resolution).

Driving Performance Measures

Driving simulator. A high fidelity STISIM 3.0 driving simulator by Systems Technology Inc. (systemstech.com; Hawthorne, CA) was used to generate and present the virtual driving environment. Simulations were projected onto three screens (side panels 123cm x 91cm; center panel 138cm x 91cm) that were located 160 cm away from the driver's seat, providing a 180° forward field of view. A modified Logitech G25 steering wheel was used along with pedals from Extreme Competition Controls Inc (ECCI). The

virtual environment was coordinated with realistic audio effects allowing for acceleration cues. The STISIM 3.02.13 Drive software collects several variables, including vehicle position and motion, as well as the status of the various driving controls, at a rate of 10 Hz. The software was run on a Windows XP operating system with four Dell Dimension 9200 computers (2.4 GHz Intel Core 2 Duo processor, 3 GB RAM per computer).

Participants completed three simulator scenarios. To begin, all participants completed a familiarization scenario. Two experimental driving scenarios were then completed: a city driving scenario and a highway merging scenario. The order of the experimental driving scenarios was counterbalanced.

In the familiarization scenario, participants drove on a two-lane road for 5.7 km where they learned how to maintain their speed, perform a complete stop and navigate left and right turns. The city driving scenario was 7.8 km long. The setting began in a downtown environment, where participants drove through a small town, followed by a rural road and then a city environment. A total of 5 unexpected events were presented during this scenario: 1) on a 6-lane road, a car merged onto the road from a gas station on the right; 2) on a 6-lane road, a car ran a red light from the left just as the participant was crossing an intersection; 3) on a 2-lane road, a car merged onto the road from the shoulder; 4) on a 2-lane road, a moose ran across the road from the right; and 5) on a 4-lane road, a car merged onto the road from a right-side merging lane. The highway merging scenario was a 10.7 km drive that required participants to enter and exit a highway numerous times. Participants were verbally prompted by the simulator to perform lane changes to the left-most or right-most lane. As they advanced in the scenario, traffic levels increased, thus making it more difficult to perform the instructed

lane changes.

During the driving scenarios, our variables of interest were recorded automatically by the simulator (i.e., crash rate and lane deviation). Crash rate was determined by the total number of collisions with objects in the simulated environment. These included, but were not limited to, the objects involved in the 5 unexpected events. We also examined participants' lane deviation time. This was recorded for the duration of the simulation and was considered as the unforced percentage of time spent outside of a prescribed lane. Lane deviations in response to a hazard were not considered as incorrect.

Driving behaviour questionnaire (DBQ). All participants answered 11 questions from the DBQ that were previously selected based on their relation to hazard detection and avoidance behaviours during driving. The items can be found in Appendix B. The Cronbach alpha for this index of hazard detection and avoidance related items was .89.

Results

3D-MOT & Simulated Driving

To determine whether 3D-MOT threshold scores predict simulated driving performance, we calculated the correlation between tracking speed thresholds and simulator measures associated with driving errors (crash rate, lane deviation) for both scenarios and each scenario individually. The correlations (one-tailed) can be found in Table 3.1. A post hoc power analysis was completed for the smallest sample (N=11), and it was determined that the analysis was likely underpowered, with a value of .50, indicating that there was a high likelihood of a type II error. Despite this, we find highly

significant correlations between 3D MOT thresholds and both crash rate and lane deviation in the highway driving scenarios. This is not the case with the City Driving scenarios. Putting all scenarios together yields moderate correlations that approach significance.

Table 3.1

Correlations between the 3D-MOT and simulated driving measures in older drivers

	Total (N= 11)	City Driving (N= 15)	Highway Merging (N= 16)
Crash rate	-.499 p= .059	-.226 p= .209	-.581 p= .009
Lane deviation	-.518 p= .051	-.040 p= .44	-.555 p= .02

3D-MOT & DBQ Hazard Detection Related Items

There was no significant correlation between 3D-MOT threshold results and the DBQ index of hazard detection related items (r= .054, p= .389).

PMCT-2 & Simulated Driving

To determine whether PMCT-2 scores predict simulated driving performance, we calculated the correlation between contrast thresholds and simulator measures associated with driving errors (crash rate, lane deviation) for both scenarios and each scenario individually. The correlations (one-tailed) can be found in Table 3.2. A post hoc power analysis was conducted and it was determined that there was likely not enough power in our sample to find an effect of the PMCT scores on driving measures. The smallest N=11 was used to determine that the analysis was underpowered, with a value of .067, indicating that there was a high likelihood of a type II error.

Table 3.2

Correlations between the PMCT-2 and simulated driving measures in older drivers

	Total (N= 11)	City Driving (N= 13)	Highway Merging (N= 16)
Crash rate	-.052 p= .440	.024 p= .469	-.064 p= .407
Lane deviation	-.142 p= .347	.206 p= .250	-.217 p= .228

PMCT-2 & DBQ Hazard Detection Related Items

PMCT-2 thresholds were significantly correlated with a DBQ index of hazard detection and avoidance related items r= .426 p= .013 (See appendix A for complete list of pre-selected DBQ items).

Visual Acuity and Driving Measures

Visual acuity was not associated with total crash rate (r= .029, p= .467) or total lane deviation (r= -.051, p= .428). These results confirm the consensus in the literature that visual acuity is not predictive of driving performance.

3D-MOT and PMCT-2

The 3D-MOT and the PMCT 2 were not associated (r= -.089 p= .439).

Discussion

We hypothesized that 3D-MOT tracking speed thresholds would be negatively associated with crash rates during simulated driving. That is, we expected that the worse a person's performance at the 3D MOT, the more often they would engage in hazardous driving behaviours. Our results showed that overall, the association between 3D-MOT and total crash rate was trending, but did not quite reach significance, possibly due to

high subject attrition and a resultant small sample. However, the individual scenarios differed markedly, demonstrating that 3D-MOT was significantly negatively associated with crash in the highway merging scenario but not in the city driving scenario.

We further hypothesized that the 3D-MOT tracking speed thresholds would be negatively associated with lane deviation during simulated driving. Our results showed that the relationship between the 3D-MOT and total lane deviation almost reached significance. As with crash rates, the results from the two scenarios were quite different. 3D-MOT was highly negatively associated with lane deviation in the highway merging scenario but not the city driving scenario. Thus, our results showed a trend towards individuals with higher tracking speed thresholds being less likely to crash. Furthermore, a similar trend appeared where higher tracking speed thresholds indicated better overall lane maintenance.

An explanation for the differences in outcome between the scenarios may come from work by Wickens (2002). He states that driving can be divided into ambient and focal attentional tasks. Ambient attention is used for sensing direction and orientation; it is a more broad and unfocused general sense of one's position relative to one's surroundings. Focal attention is used for detailed tasks, such as reading, pattern recognition, or obstacle detection, essentially anything that requires foveation. Wickens describes lane keeping and general positioning as tasks that rely on the ambient attentional stream, whereas obstacle avoidance is mainly a task of focal attention. It is important to note that the ambient and focal channels are linked, such that the ambient channel provides positional information to the focal channel and thus acts as the foundation for focal attention (Previc, 1998; Oksama & Hyona 2016).

Both ambient and focal attentional channels are thought to be involved in object tracking, depending on the nature of the tracking task. Specifically, the multiple object tracking (MOT) task, where one must know the location of the tracked objects, calls primarily upon the ambient stream; Conversely, the task of multiple identity tracking (MIT) calls upon both the ambient and the focal streams (Oksama & Hyona, 2016). Multiple identity tracking is similar to MOT, except that the identities of the tracked objects are also relevant information, not just the positions of the objects (Oksama & Hyona, 2004). The additional information gathered about the identity of the tracked objects implicates the focal attention stream, because the objects must be foveated in order to be identified (Oksama & Hyona, 2016). The real world task of driving is arguably most similar to MIT, since the driver is aware of their position relative to the surrounding road environment, but also aware of the identities of the different types of road users that are nearby. We had our participants complete a tracking task that is thought to implicate primarily the ambient attentional channel; this is likely why we see a relationship between results on this task and lane keeping (i.e., both are primarily tasks of ambient attention).

The relationship between MOT—which is primarily a task of ambient attention—and crash –which is thought to be a failure of focal attention—is more difficult to explain in the context of Wicken's (2002) model. However, it might be explained based on the idea that the ambient attentional stream acts as the foundation of focal attention. That is, ambient attention gathers general position and directional heading information, which subsequently informs the focal attention mechanism used to identify possible obstacles.

We hypothesized that older drivers' PMCT-2 results would be associated with driving performance during simulated driving. The current study did not show any significant correlations between these variables and we were thus unsuccessful at replicating the results from our previous studies. We remain confident, based on our previous work, that peripheral motion contrast thresholds are predictive of certain measures of older driver performance (Henderson et al., 2010; Henderson, Gagnon, Collin, Tabone & Stinchcombe, 2013; Henderson et al., 2015).

Finally, we hypothesized that there would be a significant correlation between PMCT thresholds and a DBQ index of hazard detection related items. This hypothesis was supported. We found that poorer scores on the PMCT-2 were associated with a higher average response to an index composed of DBQ items measuring the frequency of hazardous driving behaviours. This finding complements our previous findings of a relationship between driving performance (simulated and on-road accident data) and motion processing thresholds. We did not, however, find a relationship between 3D-MOT results and the DBQ index. Given that the PMCT and 3D MOT were not correlated with one another, this result may be seen as further evidence that these two tests measure different aspects of motion processing.

Overall, the current study has highlighted the importance of including a test that incorporates visual motion processing as part of a battery to assess older adults' fitness to drive. Furthermore, we have helped to expand the existing knowledge regarding multiple object tracking and driving, as it is commonly assumed that some aspects of safe driving include the ability to track the movement of many objects. Our findings will help further

elucidate the relationship that motion processing has with driving performance in the older driver population.

Appendix A

Post-exposure Simulator Sickness Questionnaire

SYMPTOM CHECKLIST (Post-exposure)

Post-exposure instruction: please fill in this questionnaire. Circle below if any of the symptoms apply to you now.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eyestrain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increase	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. "Fullness of the head"		No	Yes (Slight	Moderate Severe)
11. Blurred vision	No	Yes (Slight	Moderate	Severe)
12. Dizziness eyes open		No	Yes (Slight	Moderate Severe)
13 Dizziness eyes close		No	Yes (Slight	Moderate Severe)
14. Vertigo		No	Yes (Slight	Moderate Severe)
15. Stomach awareness		No	Yes (Slight	Moderate Severe)
16. Burping		No	Yes (Slight	Moderate Severe)

Appendix B

List of Driving Behaviour Questionnaire items used in DBQ-hazard detection and avoidance index

How often do you do each of the following?

(1 = Never, 2 = Hardly ever, 3 = Occasionally , 4 = Quite often, 5 = Frequently, 6 = Nearly all the time)

- Attempt to overtake someone that you hadn't noticed to be signalling a right turn
- Fail to notice that pedestrians are crossing when turning into a side street from a main road
- On turning left, nearly hit a cyclist who has come up on your side
- Queuing to turn left onto a main road, you pay such close attention to the main stream of traffic that you nearly hit the car in front.
- Underestimate the speed of an oncoming vehicle when overtaking.
- Hit something when reversing that you had not previously seen.
- Get into the wrong lane approaching a roundabout or junction.
- Miss 'Give way' signs, and narrowly avoid colliding with traffic having right of way
- Find that the distance you have allowed for stopping is too short
- 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.

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General Discussion

Many research groups have explored the relationship between visual motion sensitivity and older driver safety in efforts to better define how declines in this visual capacity can affect certain aspects of driving performance (Raghuram & Lakshminarayanan, 2006; Wood, 2002; Wood, Anstey, Kerr, Lacherez & Lord, 2008; Lacherez, Au & Wood, 2012). In the experiments described above, we have tested two measures of motion perception. One is a measure of peripheral motion sensitivity called the Peripheral Motion Contrast Threshold (PMCT) task. Using first-order motion cues, the PMCT is a test designed to specifically assess the magnocellular channel's sensitivity, which is a pathway in the brain that is responsible for processing visual motion. The other measure is the 3D MOT test, an attentional tracking task that incorporates higher-level motion, and which is designed to test the ability to track the position of a number of target items as they move among featurally identical distractors.

The PMCT test uses a stimulus designed to maximally engage the magnocellular pathway, a low spatial frequency and high temporal frequency drifting sine wave grating that is presented in the near visual periphery. In previous studies, thresholds measured via the PMCT were found to correlate with older drivers' self-report accident risk (Henderson et al. 2010), and scores from a simulated driving test (Henderson et al. 2013). After this, the PMCT was further refined into a shorter version called the PMCT-2, which only takes two minutes to complete (as opposed to earlier versions, which took 10 or 20 minutes). The PMCT and PMCT-2 measure the same capacity; both correlate with crash rates in simulated driving, and results on them are strongly and directly correlated (Henderson et al., 2015).

The aim of the first study in this thesis was to compare the effectiveness of the original PMCT-10 to the PMCT-2, in order to ensure that the new test was as strong a predictor of older driver performance measures in a simulator (i.e., crash, dangerous lane deviations, minimum distance of approach to hazards, and speeding) as the older one. It was determined that the new test–the PMCT-2—was an even stronger predictor of simulated driving performance than our original test, the PMCT-10. Therefore, the aim of study 2 was to evaluate how well the PMCT-2 could predict performance in a differing set of simulated driving scenarios. The driving scenarios used in study 2 did not include materialized hazards, but did require the driver to navigate technically difficult driving environments. We found that PMCT-2 results were associated with simulator measures of driving performance, such as crash and lane deviation, as well as real world accident data. Essentially, participants who required more contrast to detect the PMCT-2 stimulus were more likely to have crashed or deviated from their lane during a simulated drive. Furthermore, participants with a history one or more real-world crashes, where they failed to detect and avoid a real world road hazard, had significantly worse PMCT-2 thresholds.

The third study was designed to examine the relationship between 3D-MOT results and older driver performance in order to explore how the ability to track multiple moving objects relates to driving safety. In addition, we aimed to replicate the findings between PMCT-2 and older driver performance from studies 1 and 2. The predictive ability of the PMCT-2 is thought to be strongest when examining its relationship with older drivers' ability to detect and avoid materialized hazards in the driving environment. Therefore, study 3 used the same simulator scenarios as in study 1, which incorporates

materialized hazards into the scenarios. We also measured if the 3D-MOT and PMCT-2 scores were associated with items from the DBQ deemed to be indicative of hazard detection ability.

Our findings showed that results of the 3D-MOT speed thresholds and simulated driving measures (i.e., total crashes, total lane deviation time) were highly correlated in a highway setting. We suggest that the 3D-MOT is related to our highway scenario driving measures because both the MOT task and the simulated driving task call upon the ambient attentional channel. This theory is compatible with the findings of a study by Lochner and Trick (2014), where they had participants complete a tracking task while driving in a simulator. If MOT and driving performance call upon the same ambient attention mechanism, then one would expect to see interference between these two tasks if done simultaneously, and indeed this is what was found. Specifically Lochner and Trick (2014) demonstrated that tracking while driving interfered with the drivers' ability to maintain both headway and lateral lane positioning. The correlation between 3D-MOT and total driving measures (total crash, total lane deviation) from both scenarios were trending towards significance.

Regarding the relationship between PMCT and hazardous driving, findings from the third study failed to replicate those from studies 1 and 2. The PMCT-2 results were not correlated with simulator performance in older drivers. However, the PMCT-2 was related to a group of DBQ items that were previously selected due to their association with hazard detection and avoidance. These DBQ items assessed how often respondents find themselves encountering dangerous driving situations due to late detection of hazards. The 3D-MOT was not associated with the DBQ-index of hazard detection

related items, possibly because the 3D-MOT is measuring a global form of attention, which would be most important for heading and lane keeping. Conversely, the PMCT-2 is measuring low level motion, which may be more related to individual object detection and thus crash avoidance. This may also explain why the PMCT-2 and the 3D-MOT results were not correlated; The PMCT-2 may be more related to the detection of potential hazards in the roadway, whereas MOT results may instead measure ones' ability to globally track the ensemble of moving objects in the visual environment and thus be related to self-motion assessment.

In summary, our findings support the notion that motion processing is an important aspect of safe driving, and that the PMCT-2 and 3D-MOT may be useful measures that tap into different aspect of visual motion found in the driving environment. In study 1, we introduced a new shorter version of our motion processing test, the PMCT-2, demonstrating that it was able to predict simulated driving performance just as well as a previous longer version. Our motivation for implementing the new version of our test was based on the study by Staplin et al. (2003), who suggest that a test of functional capacity should take no more than two minutes to administer as part of an overall 20 minute licensing bureau screening battery for older drivers.

In study 2, we examined how PMCT-2 scores were related to simulated and on road driving by using real world accident reports. Similar to the findings in study 1, this study also demonstrated the ability of the PMCT-2 to predict simulated driving performance, however, the association between driving performance measures and PMCT scores was weaker, likely due to the nature of the scenarios used. The scenarios in study 2 were more focused on assessing general handling and driving ability in

environments that are less representative of what older drivers may typically encounter. However, the real world accident data showed that the participants who had a history of one or more crash involving late hazard detection, had significantly worse PMCT-2 thresholds than those who did not have such type of crash nor any crash at all.

In study 3, we helped to expand what little is known about multiple object tracking and driving. Although many researchers state that the ability to track multiple objects is an important aspect of safe driving (Fencsik, Klieger & Horowitz, 2007; Feria, 2008; Horowitz et al. 2007) there is a relative lack of applied studies that have addressed this statement. In the current study, we found similar results to Bowers et al. (2013) who previously demonstrated that multiple object tracking speed thresholds were predictive of an older drivers' performance. Our results indicate that older drivers with better speed thresholds on the MOT task were less likely to experience crash or deviate from their lane. Although these results do not address the question of whether drivers are actually performing some type of multiple object tracking while driving, they do help to understanding that there is a common underlying visual and attentional capacity between the two tasks. Finally, study 3 failed to replicate our previous findings, in that we did not see an association between PMCT-2 thresholds and older driver simulator performance. This was likely due to not having enough power in our sample and a lack of variability in our samples' PMCT scores. However, the PMCT-2 scores were associated with a DBQ-hazard detection index, composed of a group of 11 DBQ items were pre selected based on their relation to hazard detection in the roadway environment.

Limitations

The current studies had a few limitations that must be acknowledged in interpreting the findings. First, large reductions in sample size were present in study 2 and 3 due to the occurrence of simulator sickness symptoms in our participants. Mitigating concerns that differential drop-out rates might affect the current results, Mullen, Weaver, Riendeau, Morrison and Bédard, (2010) have demonstrated that participants who drop out due to simulator sickness do not differ from those who complete the task on most measures. The reductions in sample size do however affect the power of the studies. The greatest loss in participants was in study 3, leading to some of the analyses being underpowered.

Study 1 only had minor losses in participants likely because the older adults were selected from a previous driving simulator study based on their insensitivity to simulator sickness. This may have also in turn affected the results from study 1, since these participants were previously experienced with a driving simulator.

Another limitation that deserves mentioning is that the average MoCA score in study 2 was lower than the established cut off for mild cognitive impairment. The sample had an average value of 25.3, which is very slightly below the cut off (<26) for mild cognitive impairment. Although it is not uncommon for a sample of community recruited older adults to have an average MoCA score below the cut off, it may be said that our sample was not representative of healthy older adults. However, in our analyses, the MoCA scores were not predictive of any driving performance measures.

Future Directions

A possible next step in this research program would be to collect a large database of older adults' police-reported as well as self-reported crash, which would include at-fault status as well as a detailed description of the accident. We could then develop and implement an algorithm that would select the crashes that were considered as failures in hazard detection and avoidance. We could compare this crash data to the older drivers' PMCT-2 scores and determine whether these types of accidents in older drivers were associated with reductions in sensitivity to visual motion.

The relationship between the multiple object tracking task and driving in the third study was a promising finding, warranting more attention in the driving literature. Future studies should continue to elucidate the relationships between multiple object tracking capacity and safe driving. We know that performance on both are correlated; However, we do not yet know if some form of multiple object tracking is regularly conducted during the task of driving as a means to keep track of the various road users. Furthermore, additional research should be conducted to expand our knowledge about how age-related declines in tracking ability impact a wider variety of driving tasks.

Ultimately, the effectiveness of both these tests, as well as any proposed battery of which they might be part, can only be established via a prospective large-scale multi-centre study. That is, we must test individuals first and then follow them for a period of years to see if those with poorer performance on PMCT and/or 3D MOT show higher crash rates. Clinical cut-off scores would then have to be established.

Final Word

As our population ages, we have to ensure that older drivers remain safe on the roads. Improvements in technology have helped reduce the rates of injury and death, but reducing them further will require a multi-pronged approach. One part of this approach will be superior testing to determine who is and is not fit to drive. In this context, the sensitivity and specificity of the tests take on great urgency, for a test with a high false positive rate will needlessly reduce the independence of individuals, while one with a high false negative rate will lead to increases in traffic-related injuries and deaths. The current work is part of an attempt to develop a test battery with low levels of both types of errors. Likely this battery will involve measures of cognitive and motor function, as well as visual and auditory perceptual capacities.

The three studies reported here have highlighted the importance of how declines in visual motion processing can impact the ability to drive safely. The PMCT is associated with older drivers' crash risk, as well as lane deviations during a simulated drive. There is initial evidence that the PMCT is also correlated with older drivers' self-report accidents involving a detection failure. These promising results are in addition to findings on a visual attention test that incorporates higher-level motion, the 3D-MOT, which was found to be highly indicative of older drivers' performance in a highway setting. We believe that the PMCT-2 and the 3D-MOT are complementary visual tests, with the former measuring the ability to detect and orient towards a potential hazard and the latter indicating one's ability to keep a broad focus on elements of the driving environment.

The development of a battery of tests, one that incorporates motion processing into an assessment on fitness to drive, will become increasingly important as older drivers

continue to remain active drivers later into their lives (Cheung & McCartt, 2011). The present work helps to solidify the relationship between visual motion processing and driving safety, and will hopefully motivate the continuation of research in this area. We believe that the PMCT-2 and 3D MOT are strong candidates for the inclusion in such an assessment battery.

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