The impact of blur, illumination and distracters on tests related to driving performance

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Abstract

Uncorrected refractive error is a leading cause of visual impairment. A decrease in visual acuity due to uncorrected refractive error affects activities of daily living, including driving. Driving involves the integration of continuous visual information derived from the constantly changing driving environment. Studies have shown a significant effect of blur on driving performance under both day and night-time conditions, especially for targets that are dynamic and may often be viewed briefly while driving, such as road signs and hazards (Higgins & Wood, 2005, Higgins, et al., 1998, Wood, et al., 2011). In order to better understand the impact of blur on the resolution of such dynamic and briefly presented targets, this research aimed to investigate the effect of blur under controlled laboratory conditions for different light levels, on tests that are potentially related to driving performance.

The presence of blur is known to reduce visual acuity. However, adaptation to blur over time results in an improvement in visual acuity compared to that measured immediately after imposing blur. Thus the level of adaptation to blur is an important factor to consider in experimental designs such as these, in order to control for the effect of short-term changes in visual acuity due to blur adaptation. In addition, since individuals with uncorrected refractive error are likely to be adapted to the resultant blur, it is important to determine the effect of blur on tests related to driving performance following adaptation to induced blur.

The first experiment investigated the short term changes in visual acuity for +1.00 D blur, under photopic illumination; +2.00 D blur, under photopic illumination; and +2.00 D blur, under mesopic illumination conditions. Fourteen young visually normal participants (mean age 29.5 ± 2.7 years) were tested. Visual acuity was tested

using a computer-generated tumbling-E target (where participants were allowed unlimited time to make a response). Testing involved three different sessions (session 1: baseline observation without blur; session 2: blur adaptation, and; session 3: recovery session without blur). The experiment also measured the persistence of blur adaptation during session 3 by reintroducing blur for two single measures of visual acuity (approx 2 min each in duration) at 14 min and 28 min post-adaptation. Comparison of blur adaptation in the +1.00 D photopic and +2.00 D photopic conditions showed that the improvement in visual acuity following adaptation was significantly greater for +2.00 D blur compared to +1.00 D blur ($p < 0.01$).

Pairwise comparison of adaptation times showed that blur adaptation peaked at about 14 min and was maintained over the remainder of the adaptation period. However, there was no significant difference in adaptation to the +2.00 D blur condition under either photopic and mesopic illumination conditions, with the greatest adaptation to blur occurring at about 14 min following imposition of blur for both conditions. Importantly, reintroducing blur for a single visual acuity measurement following 28 min of recovery from blur, resulted in a reduction in visual acuity, but this was significantly less than for when blur was first introduced in session 2 for both +2.00 D blur under photopic and mesopic conditions ($p < 0.05$). This demonstrates that the participants' capacity to adapt to blur carries over to subsequent exposures to the same levels of blur. The findings of the time course and persistence of blur adaptation were used as the basis for the design of Experiments 2 and 3.

The visual information available while driving is dynamic and important cues may only appear briefly when driving at high speeds. Thus the effect of blur on the ability to resolve briefly presented targets may be important in understanding the impact of

blurred vision on driving. The second experiment investigated the effect of blur on visual acuity for briefly presented targets in comparison to untimed target presentations (in which the stimulus remained visible until the participant responded) under photopic and mesopic testing conditions. Twenty visually normal, young participants (mean age 29.4 ± 3.1 year) were recruited. Visual acuity was measured using a tumbling-E presentation for four different visual conditions (0.00 D (baseline), +0.50 D, +1.00 D and +2.00 D). Each condition was measured for brief, timed (100 ms) and untimed tumbling-E presentations following 14 min of adaptation to blur, in the order of lower to higher dioptric levels (based on the findings from Experiment 1). The visual acuity for all conditions was measured under photopic and mesopic illumination conditions on two separate days. As expected, the results showed that increasing blur resulted in a significantly greater decrease in visual acuity. The effect of blur on visual acuity was greater for the 100 ms presentation compared to the untimed target presentation ($p < 0.01$). A decrease in illumination to mesopic levels exacerbated the effect of blur on visual acuity for both target presentations. However, the brief (100 ms) presentation showed a much greater decrease in visual acuity in the mesopic condition compared to the untimed condition. These findings suggest that the effect of even a small amount of blur (+0.50 D) may be greater for briefly presented targets compared to targets presented for an unlimited exposure time under mesopic conditions. This information is important in real-world driving conditions, where small amounts of uncorrected refractive errors may significantly affect ability to detect briefly presented events. This effect of blur on briefly presented events may be worse under low lighting conditions, such as night-time driving.

The third experiment investigated the effect of blur and a secondary auditory distracter task on reaction times to potential hazards under controlled laboratory conditions using the Hazard Perception Test. Twenty young participants (mean age of 29.4±3.2) who had prior driving experience and a current driving license participated in the study. Participants were required to view video recordings of traffic scenes in the Hazard Perception Test and to respond to the potential hazards within the traffic scene. The reaction times for responding to potential hazards within the video clip were recorded. The reaction times to hazards were tested twice, once without audio instructions and the second time with an auditory distracter (satellite navigation audio instructions). Each participant was tested for four visual conditions (0.00 D (baseline), +0.50 D, +1.00 D and +2.00 D), following a period of blur adaptation and the order of testing was from lower to higher levels of blur. Reaction times to hazards increased significantly with increasing blur, where participants were significantly slower in reacting to hazards for the +1.00 D and +2.00 D blur conditions compared to the no blur condition. There was also a significant increase in reaction times to hazards in the presence of the additional secondary task (auditory distracter). However there was no significant interaction between blur and distracter conditions on reaction times.

Collectively, these findings suggest that blur due to uncorrected or under-corrected refractive errors may show a greater effect on the resolution of briefly presented targets (such as road signs and hazards) while driving, particularly under low light conditions. Blur, in combination with audio distracters, may also increase mental workload and slow a driver's reaction to potential hazards on the road, thus reducing safe driving ability. Thus the findings highlight the importance of eye care practitioners correcting even small refractive errors (0.50 D) and also drivers using an appropriate refractive correction while driving, particularly at night.

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List of Abbreviations

min: Minutes

D: Dioptres

ms: Milliseconds

MAR: Minimum Angle of Resolution

SE: Standard Error

Statement of original authorship

The work contained in this thesis has not been previously submitted to meet the requirements for an award at this or any higher education institution. To the best of my knowledge and belief the thesis contains no material previously published or written by another person except where due reference is made.

Signature: QUT Verified Signature

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Chapter 1: Introduction

1.1 Background

Uncorrected refractive error is the leading cause of visual impairment, affecting about 153 million people around the world (Vision2020, 2011). The decrease in visual acuity resulting from uncorrected refractive error has a negative impact on quality of life and vision-related activities of daily living, including driving (Coleman, et al., 2006, Lamoureux, et al., 2009, Nirmalan, et al., 2005, Rahi, et al., 2008, West, et al., 2002). There is increased interest in the safety of drivers with uncorrected refractive errors, given that a number of studies have reported that individuals continue driving without appropriate refractive correction (Adeoye, et al., 2007, Erdogan, et al., 2011, Keeffe, et al., 2002).

Studies have investigated the impact of different levels of simulated blur on driving performance under both day and night-time conditions. Increasing blur was reported to affect both day and night-time driving performance, with the effect of blur being greater in these studies taken at night compared to those under daytime conditions (Higgins & Wood, 2005, Higgins, et al., 1998, Wood, et al., 2011). The experiments in this thesis sought to investigate the effect of blur on laboratory tests related to driving performance under both photopic and mesopic light levels, in order to better understand some of the potential factors underlying the impact of blur on driving performance.

The main effect of optical blur is to reduce the ability to see fine detail (or in spatial frequency terms, to selectively reduce the ability to resolve high spatial frequencies), resulting in a decrease in visual acuity. In clinical settings the decrease in visual acuity with blur (or uncorrected refractive error) is measured using a standard letter chart where individuals are given as long as they require to correctly recognise letters. The standard visual acuity measurement is also the most common test used to determine driving eligibility. However, visual information available while driving is dynamic and can be fixated only briefly at the fovea while driving on high speed roads. Thus visual acuity measurement for briefly presented stimulus may be important in understanding the variation in vision while driving. Studies of on-road driving performance particularly noted that the effect of blur was greater for events that may be presented briefly, such as road signs and hazards (Higgins & Wood, 2005, Higgins, et al., 1998, Wood, et al., 2011). Thus it may be important to further investigate the effect of blur on visual acuity for briefly presented targets.

Studies measuring the effect of simulated blur and cataracts on driving performance reported that simulated cataracts showed a greater effect on driving performance compared to simulated blur under both day and night-time conditions (Wood, et al., 2010, Wood, et al., 2009). The authors speculated that adaptation to blur under every day conditions may have resulted in the effects of blur on driving being less than that of simulated cataracts. This speculation is supported by the findings of an improvement in visual resolution following adaptation to blur in laboratory-based experiments (Cufflin, et al., 2007, Mon-Williams, et al., 1998, Pesudovs & Brennan, 1993, Rosenfield, et al., 2004). Thus in laboratory-based studies that seek to measure the effect of blur on visual acuity, the level of adaptation to blur may be an important factor to consider.

Visual information while driving is continuously presented, including environmental information that allows identification of hazards on the road. Thus perception and timely reaction to hazards is important for driving safety. Hazard perception is the ability of the driver to anticipate dangerous events on the road. A decrease in the ability to perceive and react to hazards can put drivers at risk. Studies of on-road driving performance have noted that blur resulted in a reduction in the ability to detect and avoid large low contrast hazards on the road (Higgins & Wood, 2005, Higgins, et al., 1998, Wood, et al., 2011). However, the effect of blur on the reaction time to other types of hazards is poorly understood.

Interest in the impact of in-vehicle devices on driving performance is increasing as they may act as a distracter task while driving, requiring the driver to divide their attention between driving and the secondary task, causing distraction (Poysti, et al., 2005). Studies have reported that visual and auditory distraction caused by a secondary task (adjusting the radio, dialling numbers on a phone, talking on a mobile phone) while driving may affect driving performance by slowing down the reaction time to hazards on the road and putting drivers at risk of crashing (Haigney & Westerman, 2001, Hoedemaeker & Neerincx, 2007, Horrey, et al., 2008, Klauer, et al., 2006). Thus it is important to investigate the effect of blur and secondary tasks on reaction times to hazards, in order to understand the interaction between blur and secondary tasks on driving reaction times.

1.2 Aims of the study

The overall aim of the experiments described in this thesis was to investigate the effects of refractive blur, reduced illumination and the impact of secondary tasks on laboratory tests that are potentially linked to driving performance. Three studies were conducted to address these aims. The aim of Experiment 1 was to determine the time of peak adaptation following the introduction of blur, measured for different levels of blur and under different illumination conditions. The study also aimed to determine if blur adaptation persisted even after removing blur, which would provide important insight into decisions regarding the testing order for different blur levels in Experiments 2 and 3. Experiment 2 aimed to investigate the effect of different levels of blur as well as the influence of different illumination conditions on visual acuity measured for different exposure times. Experiment 3 aimed to determine whether the reaction time for the identification of potential hazards in road scenes increased with the introduction of blur and also aimed to investigate whether the effect of blur on reaction times was exacerbated in the presence of a secondary task.

Chapter 2: Literature review

2.1 Prevalence of refractive error in the population

A refractive error describes the condition where parallel rays of light are not focused on the retina when accommodation is relaxed, resulting in blurred vision. The main categories of refractive error include myopia, hyperopia and astigmatism which affect people of all ages and ethnic groups. Uncorrected refractive error has been identified as a major cause of visual impairment worldwide and it is estimated that approximately 153 million people are visually impaired due to uncorrected refractive errors (Vision2020, 2011). This estimate of visual impairment was based on a presenting visual acuity of less than 6/18 (i.e. visual acuity with the currently available refractive correction, if any) that could be improved with appropriate refractive correction (Vision2020, 2011). The prevalence of uncorrected refractive error results in loss of education and employment opportunities, lower productivity and impaired quality of life (Chia, et al., 2006, Coleman, et al., 2006, Jaggernath & Naidoo, 2012, Lamoureux, et al., 2009, Nirmalan, et al., 2005, Rahi, et al., 2008, Smith, et al., 2009, West, et al., 2002). The worldwide prevalence of uncorrected refractive error, excluding presbyopia, is estimated to be 13 million for those aged 5-15 years, 47 million for those aged 16 to 49 years and for ages greater than 50 years this number rises to more than 95 million (Vision2020, 2011).

The prevalence of uncorrected refractive error has been increasing dramatically, particularly among Asian populations (Dandona, et al., 2002a, Dandona, et al., 2002b, Murthy, et al., 2002, Raju, et al., 2004, Saw, et al., 2002, Shimizu, et al., 2003, Vitale, et al., 2008, Wu, et al., 2001). This increase in prevalence is likely to be due to the ageing population (Raju, et al., 2004, Shrestha, et al., 2010), growing poverty (Holden, 2007) and the increase in the rate of myopia development due to more indoor living and intense education (Ip, et al., 2008, Seet, et al., 2001). Interventions to correct refractive error, such as spectacles, are cost effective and generally easily accessible. However the accessibility of these refractive corrections in some situations is limited, as only 20% of the population in developing countries have access to spectacle corrections (Dandona & Dandona, 2001). Importantly refractive errors are also often not diagnosed, which makes this a major public health concern (Resnikoff, et al., 2008).

Driving is considered to be an important activity of daily living, as it is the main mode of transport in many countries and helps to fulfil the essential needs of daily living, including driving to shops, accessing medical services, participating in social activities and visiting friends (Horgas, et al., 1998). Interest in the driving safety of drivers with uncorrected or under-corrected refractive errors is increasing given that a significant proportion of individuals continue driving with their reduced vision due to uncorrected refractive errors (Guest & Jennings, 1983, Saw, et al., 2004, Thiagalingam, et al., 2002). Keeffe, et al., (2002) reported from a large sample of Australian drivers, that uncorrected refractive error was the main cause of decreased visual acuity in 80% of drivers, whose visual acuity levels were below the legal limit for driving of 6/12. A study conducted on commercial drivers in Nigeria indicated that among 215 drivers, most had not had an eye examination prior to obtaining their driving license. Among drivers who had received an eye examination, 8% of the drivers had a refractive error, however, none were wearing a refractive correction (Adeoye, et al., 2007). Another cross-sectional study of 200 heavy vehicle drivers indicated that uncorrected myopia was most prevalent among drivers (Erdogan, et al., 2011). Similarly, van Rijn, et al., (2011) measured visual function among a sample of 2422 European drivers and noted that 5.3% of drivers had visual acuity lower than that required for driving and visual acuity improved with appropriate refractive correction to meet the licensing standards.

The increase in the number of drivers with uncorrected refractive errors on our roads poses a potential risk for road safety, as the resulting poor vision may affect the abilities required for safe driving. Sagberg, (2006) investigated the relative crash involvement risk for 4448 drivers with and without diagnosed medical conditions, including refractive errors, using self-reported questionniares. The study noted that along with other medical conditons, drivers who were myopic were at increased risk of crash involvement (odds ratio of 1.22) compared to drivers with no refractive error.

2.2 Visual acuity and driving

Optimal visual acuity is widely considered to be important for safe driving performance, given that 90% of the information available while driving is considered to be visual (Hills, 1980). A limited number of studies have shown a positive, but weak association between visual acuity and crash involvement (Davison, 1985, Hofstetter, 1976, Humphriss, 1987, Ivers, et al, 1999, Marottoli, et al., 1998). Burg, (1968) were the first to report a significant but small association between visual acuity and driving safety in a large sample of 17,500 California drivers. Davison, (1985) analysed 1,000 drivers' accident history and visual function, and found that monocular and binocular visual acuity were significantly correlated with crash rates. Similarly, Humphriss (1987) reported three different South African studies, which showed that for 666 drivers who had visual acuity less than 6/12 (which is the vision standard required for a South African driving licence), 632 (94%) drivers had reduced visual acuity due to uncorrected refractive errors. The study also noted that a randomly selected group of drivers who were involved in a high number of accidents had visual acuity less than that required for licensure. Ivers, et al, (1999) conducted a cross-sectional study on 2379 Australian drivers aged 49 years and older who had been involved in crashes; each subject had a detailed eye examination and were interviewed. The comparison of retrospective data for crash involvement and visual acuity indicated that a two line decrease in visual acuity was associated with a significantly increased risk of accidents. Hofstetter, (1976) reported that poor visual acuity (defined as visual acuity lower than the lower quartile) had a 50% greater chance of crashing than drivers with good visual acuity.

Conversely, Hills & Burg, (1978) examined the association between visual acuity and driving safety among a larger sample of young and middle aged California drivers, and demonstrated no relationship between poor visual acuity and motor vehicle collision involvement, however, they found a significant but weak association in older drivers. Decina & Staplin, (1993) also performed an examination of visual function for 12,400 drivers in Pennsylvania at the time of license renewal and correlated this with self-reported crashes over 3.7 years. The study reported that visual acuity was not correlated with crash involvement. Similarly other studies have failed to report a significant association between visual acuity and crash involvement (Ball, et al., 1993, McCloskey, et al., 1994, Owsley, et al., 1998). Two recent cohort studies involving 1801 participants (Rubin, et al., 2007) and 3158 participants (Cross, et al., 2009) failed to find a significant relationship between visual acuity and motor vehicle collision rates. Hunt, et al., (1993) also failed to find an association between visual acuity and on-road driving performance.

Although standard visual acuity measured for an unlimited target exposure, as is the case for assessment with standard letter charts, has been shown to be only weakly associated with driving performance, it is the most common visual function considered for driving eligibility. However, the visual information available while driving is dynamic and often presented for a brief period of time only, thus the ability to process briefly presented events while driving may be important for driving safety (Baldock, et al., 2007, Richardson & Marottoli, 2003), especially while reading road signs and identifying hazards on high speed roads. Given that the minimum fixation time for viewing a road sign while driving has been reported to be of the order of 100 ms (Ho, et al., 2001), measurement of visual acuity for brief (100 ms) stimulus presentations under laboratory conditions may be useful in understanding the variation in vision for such briefly presented events on the road.

Studies measuring visual acuity as a function of stimulus exposure duration have reported that a stimulus presentation time of 100 ms is the minimum exposure time needed for optimal resolution of briefly presented targets (i.e. visual acuity measured for brief letter presentations) under photopic luminance conditions (Barlow, 1958, Baron & Westheimer, 1973, Niwa & Tokoro, 1997, Saunders, 1975). Under reduced luminance conditions the critical duration time at which the processing is largely complete may be longer than 100 ms (Brown & Black, 1976). The effect of uncorrected refractive error or simulated optical blur on visual processing time for short presentation of targets, especially under reduced illumination conditions is poorly understood. This information may further assist our understanding of the impact of blur on brief presentations of events while driving, especially for road sign recognition and hazards identification, and for night compared to daytime driving.

2.3 Effect of blur and illumination on visual functions

Visual acuity is a primary visual function that is defined as the ability to discriminate fine details. Introducing blur (defocus) reduces both visual acuity and contrast sensitivity (Rabin, 1994). The loss in contrast sensitivity with optical blur is spatial frequency dependent, affecting high spatial frequencies more than low spatial frequencies (Charman, 1979, Green & Campbell, 1965) and increased levels of blur have a greater effect on high and mid spatial frequencies (Campbell & Green, 1965). Accordingly, studies have also shown that increasing blur results in an increasing reduction in visual acuity (Johnson & Casson, 1995, Plainis, et al., 2011, Radhakrishnan, et al., 2004, Schmidt, 1994).

The other important factor that can impact on resolution ability are illumination levels. As illumination levels decrease, many properties of the visual system change in order to maintain optimal levels of visual performance, involving a shift in the spatial, temporal and adaptive properties of the visual system. As light levels change from photopic (above 3 cd/m^2) through mesopic (0.001-3 cd/m^2) to scotopic conditions (<0.001 cd/m^2), the system becomes more sensitive to light but shows relatively poorer spatial and temporal resolution (Stockman & Sharpe, 2006). Visual acuity under photopic illumination is normally 6/6 or better, where cone function is primarily responsible for resolving fine details and perceiving colours. A decrease in illumination to very dim levels (scotopic illumination), results in reduced resolution ability given that rods are primarily responsible for visual function at these light levels. There is a transition zone between photopic and scotopic levels, known as mesopic illumination, where vision is mediated by both rods and cones. The majority of visual tasks at night involve mesopic vision where both rod and cone pathways are active and interacting (Charman, 1996, Gruber, et al., 2012, Stockman & Sharpe, 2006). However, the vast differences between rods and cones, including spectral sensitivities, spatial distributions across the retina, temporal properties and post-receptoral pathways have provided challenges for research that has aimed to better understand mesopic vision (Stockman & Sharpe, 2006). Decreasing illumination to mesopic levels reduces a range of visual functions, including visual acuity (Glover, et al., 1999, Rabin, 1994, Simpson, et al., 1986), contrast sensitivity to mid and high spatial frequencies (Peli, et al., 1996, Sloane, et al., 1988), depth perception (Legge, et al., 1987, Tucker & Charman, 1986, Wang & Ciuffreda, 2004) and colour vision (Knight & Knight, 2009, Schneider & von Campenhausen, 1998, Shin, et al., 2004). These effects on visual function are likely to occur because of a shift from cone mediation of vision under photopic illumination conditions to incomplete rod and cone mediation under mesopic illumination conditions (Cao, et al., 2010, Cao & Pokorny, 2010, Cao, et al., 2011, Zele, et al., 2013). In addition, under mesopic illumination conditions pupil size is increased relative to that measured under photopic conditions, which leads to a larger retinal blur circle (Green, et al., 1980, Ogle & Schwartz, 1959).

In terms of geometrical optics, the correlation between acuity and defocus can be defined using blur circle diameters. Smith, (1991) defined the relationship as $X = D \times \Delta L$, where X = angular blur disc diameter (in radians), D = diameter of the entrance pupil (in meters), and ΔL = defocus (in dioptres). Further, Smith and colleagues also reported a linear relationship between MAR acuity and defocus that holds over a wide range of defocus errors (0–10 D) accounting for 98% of the variance in acuity.

However, they suggested that higher order aberrations may confound this relationship for low dioptric values of defocus below about 0.25 D (Smith, 1991, Smith, et al., 1989).

2.4 Effect of blur on day and night-time driving performance

The effect of different levels of visual acuity degradation (20/20, 20/40, 20/100, 20/200) resulting from different levels of optical blur on daytime driving performance has been previously investigated (Higgins & Wood, 2005, Higgins, et al., 1998). Increased acuity degradation had a linear relationship with reduced road sign recognition and road hazard avoidance, and resulted in a significant increase in total driving time.

A decrease in illumination to mesopic levels, as for night-time driving conditions (Plainis, et al., 2005), results in a decrease in driver's visual acuity and contrast sensitivity, making driving performance potentially more challenging (Andre, 1996, Sturgis & Osgood, 1982). Driving at night is considered to be more dangerous than driving in the daytime and has been shown to be associated with high fatal crash rates (Owens & Sivak, 1996, Sullivan & Flannagan, 2002), and injuries as a result of crashes (Rice, et al., 2003). The severity of fatal collisions has been shown to be doubled during the night compared to the day and injury severity was almost three times higher in the absence of street lighting in night-time driving for different road types (Plainis, et al., 2006). Objective assessments of driving performance using driving simulators with induced blur and simulated night driving (using neutral density filters) have shown an increased effect of blur on steering performance under reduced illumination conditions (Brooks, et al., 2005, Owens & Tyrrell, 1999).

Studies of driving performance on closed road circuits have also demonstrated that driving ability is impaired under reduced illumination conditions (Owens, et al., 2007, Wood & Owens, 2005). Wood, et al. (2011) investigated the impact of optical blur (+0.50 D, +1.00 D, +2.00 D) compared to optimal refraction on real world driving performance and eye movements under day and night-time conditions. Results showed that even a small amount of blur (+0.50 D) had a significant effect on driving at night compared to daytime conditions where the same level of blur had minimal effect.

Studies have also been conducted to compare the effect of simulated blur and simulated cataracts on driving performance. Wood, et al., (2009) measured these effects on daytime driving performance and reported that simulated cataracts resulted in a greater degradation in performance for road sign recognition and hazard avoidance compared to blur. Similarly, Wood, et al, (2010) compared the impact of simulated cataract and blur for night-time driving performance and reported results similar to those for daytime driving, where the cataract simulation had a greater effect on driving performance compared to blur conditions and the number of road signs correctly recognised were halved in the cataract condition compared to the blur condition under the reduced illumination conditions.

The lesser effect of optical blur on driving performance compared to cataracts in these studies by Wood and colleagues may be the result of two processes, as speculated by the authors. Firstly, the greater loss of contrast sensitivity in the simulated cataract condition may have had a greater impact on driving performance, and secondly, improvement in visual resolution following adaptation to blur conditions may have resulted in a reduced effect of blur on driving. Thus blur adaptation may be an important consideration in understanding the impact of uncorrected refractive errors on driving performance and in driving experiments which explore these factors in the laboratory.

2.5 Blur adaptation

Individuals often encounter blur in everyday activities by failing to wear their refractive correction or by wearing a refractive correction that is not optimal for their refractive status. However, it has been suggested that they can adapt to such small levels of blur, such as when myopes do not wear their spectacles (Pesudovs, 2005, Pesudovs & Brennan, 1993). Pesudovs & Brennan (1993) were the first to report this visual acuity improvement in myopic participants, demonstrating a small but significant two letter improvement in visual acuity following fixation of a distant object for 90 minutes without wearing a myopic spectacle correction. Rosenfield, et al. (2003) noted a two line improvement in distance visual acuity following three hours of adaptation to blur in myopes not wearing their spectacles.

Studies have also reported an improvement in visual acuity following adaptation to blur for periods of 30 min to three hours (Cufflin, et al., 2007, George & Rosenfield, 2004, Mon-Williams, et al., 1998, Rosenfield, et al., 2004). Studies on simulated blur have also noted an improvement in visual acuity following adaptation to the blur, Mon-Williams et al. (1998) noted a two line improvement in monocular visual acuity following three hours adaptation to +2.50 D blur. Cufflin, Mankowska, et al., (2004) noted a two line improvement in binocular visual acuity and improvement in mid and high spatial frequencies following three hours adaptation to +2.50 D blur. Cufflin, Mankowska, et al., (2007) also noted significant improvements in visual acuity following 30 minutes of adaptation to +1.00 D blur and the improvement in visual acuity for blur adaptation was greater among myopes compared to emmetropes. However, the magnitude of shorter term changes in visual acuity following blur adaptation and the exposure time to blur at which the level of adaptation peaks is unclear.

Studies have also noted that the improvement in visual acuity following adaptation to blur was not associated with any significant change in refractive error or other ocular parameters including pupil size (Cufflin, et al., 2007, Mon-Williams, et al., 1998, Pesudovs & Brennan, 1993, Rosenfield, et al., 2004). Along with improvements in letter acuity, studies have also reported an improvement in grating acuity at mid and high spatial frequencies following adaptation to blur and proposed that adaptation to blur may occur as a result of selective changes in the mid and high spatial frequency channels at the level of visual cortex, resulting in improvement in visual acuity (Mon-Williams, et al., 1998, Rajeev & Metha, 2010, Rosenfield, et al., 2004).

2.6 Effect of a secondary task on driving performance

Driving is a complex and demanding task and lack of attention to the road can affect driving safety. For safe driving the driver needs to identify potential hazards within the driving environment, judge and make appropriate decisions with respect to hazards and have the ability to execute these decisions in a timely fashion to avoid collisions with road hazards. It has been hypothesized that reduction in the level of cognitive resources reduces the ability to process new information, making visual processing more effortful (Wingfield, et al., 2005). Accordingly degraded visual input due to blur may reduce cognitive processing, affecting the responses to visual information while driving. Along with the cognitive workload caused by degraded visual acuity, interacting with in-vehicle devices may cause additional cognitive demand leading to driver distraction.

The rapid development of in-vehicle technology and electronic devices is likely to impose greater cognitive demands on drivers in the future which may lead to distraction and a diminished capacity to perform driving tasks (Hoedemaeker & Neerincx, 2007). Drivers usually need to interact with in-vehicle devices such as navigational and entertainment systems (e.g. radio). However, these in-vehicle devices may act as auditory and visual distracters. Interaction with the car radio is a very common task while driving, which may involve manually adjusting the dial causing visual distraction (Haigney & Westerman, 2001). Using a mobile phone while driving is one of the major factors that can distract drivers both visually (while dialling numbers) (Haigney & Westerman, 2001), and cognitively (Patten, et al., 2004). Studies have reported that using both handheld and hands-free mobile phones while driving was associated with a fourfold increase in crash risk (McEvoy, et al., 2005, Redelmeier & Tibshirani, 1997).

Navigational devices are designed to assist drivers with route information and have been the subject of a significant body of research in recent years. However, there is still a limited understanding of the effect of navigation systems on driver attention and driving behaviour (Green, 1996, Green, et al., 1993). Moldenhauer & McCrickard, (2003) investigated the effect of four navigation information modalities: audio, audio with overhead map, visual, and visual with overhead map on drivers distraction in a driving simulator. Their results showed that the visual modality with an overhead map resulted in the highest number of driving errors and longest reaction times. The audio alone and audio with map conditions also showed a small but significant increase in total reaction time. Similarly Jensen, et al, (2010) studied driving behaviour and performance for different output configurations (audio, visual and audio-visual) from a GPS, and indicated that visual output navigational instructions not only caused a substantial amount of eye fixations, but also led to a decrease in performance while driving in real traffic conditions. Adding audio output decreased the number of fixations, but had no significant effect on driving performance. Though provision of navigational information auditorily has been favoured by drivers, in recent years this has been noted as a major cause of distraction for drivers (Martin, et al., 2011).

Like visual distraction, auditory distractions also have an effect on drivers' attention. The auditory task tends to increase concentration on the road centre at the expense of fixations of the road periphery, thereby increases the complexity of the driving task (Victor, et al., 2005). In order to perform the secondary task, drivers tend to adapt their behaviour by making decisions not to compromise driving performance and engage in the secondary task (Poysti, et al., 2005). To complete a secondary task successfully and to maintain safe driving, drivers often compensate by reducing their driving speed (Horberry, et al., 2006). However, this compensatory strategy is not always successful, as drivers fail to fully compensate for their inattention to driving because they often underestimate the risks involved in performing particular secondary tasks. This was investigated by dual-task studies of simulated driving and conversing on a cellular telephone (Horrey, et al., 2008, Lesch & Hancock, 2004, Strayer & Johnston, 2001) which demonstrated that drivers failed to divide their attention adequately between driving and secondary tasks resulting in a decrease in driving performance and increased crash risk. Klauer, et al., (2006) analysed data for naturalistic driving from 100 instrumented vehicles (100 car study) and found that driver inattention caused by secondary tasks contributed to 78% of crashes and 65% of near-crashes.

There is a limited understanding regarding the effect of degraded visual acuity and performance of secondary tasks on driving performance. In a study by Wood, Chaparro, & Hickson, (2009) the effect of three visual (normal, cataract and blur) and three distracter conditions (none, visual and auditory) on driving performance was investigated. The distracters involved simple addition of numbers (e.g. 2+5=7) presented either auditorily or visually. Degraded visual acuity resulting from simulated blur or simulated cataracts with distracters (auditory and visual) significantly reduced ability to recognise road signs and increased total driving time. Wolffsohn, et al., (1998) have also suggested that there are additional accommodative changes associated with increasing cognitive load. However, the combined effect on driving performance of different levels of simulated blur and cognitive distraction caused by secondary task is poorly understood.

2.7 Summary of literature review

The increase in prevalence of uncorrected refractive errors and its negative impact on vision-related daily living activities including driving, have increased interest in this important research area. Studies have shown that driving performance was significantly affected by simulated blur under both day and night driving conditions, with a greater effect of blur at night-time. These studies have shown that blur affected road sign recognition, hazard identification and total driving time. Thus it is important to understand the potential factors underlying the impact of blur on driving performance, by measuring the effect of blur on tests that have potential links with driving performance under controlled laboratory conditions. Furthermore, studies measuring the effect of blur on visual acuity have reported an improvement in visual acuity following adaptation to blur, thus consideration of blur adaptation may also be an important factor for both laboratory and field-based experiments.

Standard visual acuity measurements using letter charts, where letters are presented for an unlimited exposure time, is the most common visual test for driving license eligibility. However, it is unclear if standard visual acuity measurements will reflect the variations in vision for briefly presented events, such as road sign and hazard while driving, which may be fixated briefly while driving at high speeds. Moreover studies have shown only weak associations between visual acuity and crash involvement. Thus the effect of blur on visual acuity measured for brief stimulus exposures may be important in understanding driving performance with blurred vision.

Given that driving is a visually demanding task, identifying potential hazards and timely reaction to these hazards is important for driving safety. Studies have noted that performing a secondary task (such as using mobile phone, using in-vehicle devices or navigational devices) while driving can cognitively slow down drivers responses to hazards on the road. However, the effect of different levels of blur and performing a secondary task on reaction time events/hazards is unknown.

Chapter 3: Rationale and research design

Studies have shown that driving performance is significantly affected by simulated blur under both day and night-time driving conditions, with the effects being greater under night-time driving conditions (Higgins & Wood, 2005, Higgins, et al., 1998, Wood, et al., 2011). It is also evident from the previous studies that interaction with in-vehicle devices can distract drivers' from the main driving task, resulting in slower reaction to hazards on the road (Haigney & Westerman, 2001, Horrey, et al., 2008, Lesch & Hancock, 2004, Martin, et al., 2011, Moldenhauer & McCrickard, 2003, Patten, et al., 2004). However the potential factors underlying the impact of blur on driving performance under different illumination conditions, and in the presence of a secondary task, on reaction times to hazards are not known. Thus the overall aim of the thesis was to investigate the effect of blur, illumination and distracters on laboratory tests that are potentially related to driving performance; these aims were investigated in Experiments 2 and 3.

In everyday conditions, individuals may often be adapted to blur resulting from their uncorrected or under/over-corrected refractive errors. This blur is often habitually present for periods ranging from months to years. In order to be able to relate the findings from Experiments 2 and 3 to real world conditions, it was important to determine the effect of blur on visual performance following this type of longer term adaptation to blur, since it is unusual for a person to be suddenly in a situation of having blurred vision (e.g. losing spectacles). Thus a preliminary study was conducted (Experiment 1) to determine the peak time of adaptation following exposure to blur; and these data were used to assist in designing the methods for Experiments 2 and 3.

The aim of the Experiment 1 was thus to determine the time course of adaptation to the induced blur, and to determine the approximate time for peak adaptation to blur, investigated for different levels of blur and under different illumination conditions. In the present study, adaptation to blur for +1.00 D and +2.00 D blur was investigated under photopic illumination conditions to determine if different amounts of blur resulted in differences in adaptation and for +2.00 D blur under photopic and mesopic illumination conditions to investigate the effect of different illumination levels on blur adaptation. Given that the focus of this study was on photopic blur adaptation, blur adaptation under mesopic illumination was tested only for the +2.00 D blur condition. This was based on our observations from pilot data that this was the condition that demonstrated the most improvement in visual acuity following blur adaptation of the blur levels considered here.

The persistence of blur adaptation was also investigated by reintroducing blur at 14 min and 28 min after removing blur following blur adaptation. This information provided us with information as to whether it was necessary to randomise the order of blur for laboratory-based experiments. Information regarding the time course of adaptation and order of testing different levels of blur informed the design of the protocols for Experiments 2 and 3.

Simulated blur has been shown to affect performance on road sign recognition and hazard identification in studies conducted under both day and night-time driving conditions; both of these measures involve targets which are presented briefly while driving at high speeds. Thus the effect of blur on visual acuity measured using stimuli of untimed exposures, such as on a standard letter chart, may not predict variations in vision with blur for such briefly presented targets while driving. The effect of blur on visual acuity for brief target presentation may be more relevant to driving than visual acuity for untimed target presentation. This information regarding the effect of blur on resolution ability for briefly presented target may be helpful in understanding the effect of blur on the ability to recognise road signs and hazards encountered while driving.

Experiment 2 was designed to understand the effect of optical blur and different illumination levels on visual acuity for target presented for short durations. Participants were tested for untimed presentations (where the target was presented for an unlimited exposure) and timed (100 ms) presentations (where the target was presented for 100 ms exposure duration). Visual acuity for these two stimulus presentations was tested for four blur conditions (0.00 D, +0.50 D, +1.00 D, +2.00 D) and two different illumination (photopic and mesopic) conditions. This information is important as poor attention to briefly exposed targets (such as road signs and hazards) may have a significant impact on safe driving performance. The effect of induced blur on visual acuity for both stimulus presentation times under different illumination conditions may be useful in understanding the potential factors underlying the impact of blur on briefly presented events for on-road driving performance under day and night-time conditions.

It has been hypothesised that degraded vision may result in a decrease in higher levels of cognitive processing, thereby making visual processing cognitively more effortful (Wingfield, et al., 2005), which may have an effect on driving performance. Studies have already indicated that dividing attention to a secondary task while driving, such as when attending to visual and auditory distractions caused by in-vehicle devices, may cognitively slow drivers' reaction times to events on the road. However, the combined effect of visual acuity impairment through induced blur and the presence of a secondary task on response times to potential hazards are poorly understood.

Experiment 3 measured the relationship between blur and reaction times for the identification of hazards using the Hazard Perception Test (HPT). The experiment included measurement of reaction times for four different blur conditions, with and without an audio distracter task that involved listening to audio instructions from a simulated satellite navigation device, which were either consistent or inconsistent with the view presented on the Hazard Perception Test. The experiment was designed to measure the combined effect of visual impairment and cognitive workload on the time taken to react to potential hazards on road.

The combination of these three experiments was designed to provide a better understanding of the effect of blur on day and night-time driving performance by measuring visual acuity for a briefly (100 ms) presented target for different levels of blur and under different illumination conditions (Experiment 2), and measuring the effect of blur and presence of secondary task on reaction times to identify potential road hazards using Hazard Perception Test (HPT) (Experiment 3). Experiment 1 was conducted to assist in the designing the methods for Experiments 2 and 3.

Chapter 4: The short-term changes in visual acuity during blur adaptation for different defocus and illumination conditions

4.1 Introduction

It is well known that blur reduces visual resolution (Smith, 1998), where the presence of blur degrades both the spatial and contrast resolution of the target (Anderson, et al., 2001, Wang & Ciuffreda, 2005). The loss in contrast sensitivity with defocus is spatial frequency dependent, affecting high spatial frequencies to a greater extent than low spatial frequencies (Charman, 1979, Green & Campbell, 1965). Studies have also reported that a decrease in illumination also reduces the resolution ability of the eye and hence visual acuity (Rabin, 1994, Simpson, et al., 1986). However, investigations have reported that the effect of blur on visual acuity does not differ between high and low illumination conditions (Johnson & Casson, 1995, Simpson, et al., 1986).

Adaptation to blur is characterised by an improvement in visual resolution following a period of exposure to blur, relative to that measured immediately after imposing blur (Cufflin, et al., 2007, George & Rosenfield, 2004, Mon-Williams, et al., 1998, Pesudovs & Brennan, 1993, Rosenfield, et al., 2004). Pesudovs & Brennan (1993) were the first to report this improvement in visual acuity following adaptation to blur in myopic participants, demonstrating a small but significant two letter improvement in visual acuity measured following fixation of a distant object for 90 min without their spectacle correction. Rosenfield, et al., (2004) extended the time frame of adaptation for three hours in myopes not wearing their spectacles and demonstrated a significant two line improvement in visual acuity after three hours compared to the first measurement immediately after removal of spectacles. Mon-Williams, et al., (1998) also found a significant four letter improvement in visual acuity for induced +1.00 D blur in emmetropes after 30 min of adaptation to blur. This experiment also demonstrated that changes in pupil size were not the cause of improvement in the visual acuity following blur adaptation, as their participants had their pupils dilated and viewed the targets through an artificial pupil. Similarly, Cufflin, et al., (2007) reported a significant one line improvement in visual acuity following 30 min of adaptation to two different levels of blur (+1.00 D and +3.00 D) and reported that the improvement in visual acuity did not differ between blur conditions.

Mon-Williams, et al., (1998) also suggested that the process of blur adaptation occurs at the level of the visual cortex, from their observation of an improvement in visual acuity in the fellow eye, following monocular adaptation to blur in the other eye. They proposed that selective improvement in high spatial frequency channels may have resulted in the improvement in visual acuity. Further support for this hypothesis that adaptation occurs at a neural level is provided by studies that noted that the improvement in visual acuity following blur adaptation is not associated with change in refractive status (Mon-Williams, et al., 1998, Pesudovs & Brennan, 1993), crystalline lens (Pesudovs & Brennan, 1993), or pupil size (Pesudovs & Brennan, 1993).

Previous studies have discussed the impact of blur adaptation on visual acuity following 30 min to three hours of blur exposure. However, the short-term changes in visual acuity (between 0 min to 30 min), both during and after blur adaptation (i.e., the time course), have not been studied. In addition, the improvement in visual acuity for blur adaptation has not been investigated under mesopic illumination conditions. For the current study, it was important to understand the effects of short-term blur adaptation on visual acuity measured in laboratory-based experiments, since this determined if there was a need for blur adaptation for participants prior to measuring visual performance with induced blur in Experiments 2 and 3. It was also important to understand the time course of the persistence of blur adaptation after blur was removed, as this would also inform the design of the methods for Experiments 2 and 3. Moreover, understanding more about the time course of blur adaptation may provide useful information about the mechanisms underlying blur adaptation.

Thus the study aimed to investigate:

- The time course of adaptation and the time of peak adaptation to induced blur.
- The effect of different levels of blur and illumination on blur adaptation.
- The persistence of blur adaptation following removal of blur.

4.2 Method

4.2.1 Participants

Fourteen young participants were recruited with an age range between 20 to 35 years (mean age 29.5 ± 2.7 years) (Table 4.1). All participants were screened for their suitability to participate in the study by a clinical eye examination and none of the participants had any history of wearing spectacles or contact lenses. Assessment for optimal refractive correction for each eye was determined using retinoscopy followed by subjective Jackson cross-cylinder and blur-back techniques using a phoropter head. After determining the optimal refractive correction, monocular and binocular distance visual acuity were measured using the ETDRS charts (Ferris, et al., 1982) at 4 m for assessment of best-corrected visual acuity (≥ 6/6 or 0.00 logMAR) with a chart luminance of 126 cd/m^2. Visual acuity was scored on a letter by letter basis. Inter-pupillary distance was adjusted in the trial-frame to ensure that the optical centre of the lens was aligned with the pupil centre for each individual.

Participants were required to: (1) have a refractive error ranging from -0.25 DS to +0.25 DS and < 0.50 DC, (2) have no ocular abnormality such as strabismus, amblyopia, corneal opacities, lens opacities or retinal abnormalities and (3) be aged 20 to 35 years. Informed consent was obtained for all participants and the research protocol was approved by the Queensland University of Technology, Human Research Ethics Committee (see Appendix 1).

Participant	Age	Gender	Refraction RE	Refraction LE	Best Corrected VA RE	Best Corrected VA LE	Best Corrected VA BE
1	27	M	+0.00 DS	+0.25 DS	-0.10	-0.12	-0.16
2	33	F	+0.25 DS	+0.00 / -0.25 X 90	0.00	0.00	-0.10
3	28	M	+0.25 DS	+0.25 DS	-0.20	-0.10	-0.22
4	30	M	+0.00 DS	+0.25 DS	-0.10	-0.10	-0.22
5	31	M	+0.25 / -0.25 X 85	+0.25 / -0.25 X 90	0.00	-0.10	-0.10
6	29	M	+0.25 / -0.25 X 90	+0.00 / -0.25 X 90	-0.12	-0.16	-0.20
7	27	F	+0.00 DS	+0.00 DS	-0.10	-0.12	-0.12
8	23	M	+0.00 DS	+0.00 DS	-0.10	-0.02	-0.16
9	30	M	+0.00 DS	+0.00 DS	-0.20	-0.18	-0.22
10	32	F	+0.25 DS	+0.25 DS	-0.14	-0.14	-0.14
11	31	F	+0.25 DS	+0.00 DS	-0.18	-0.20	-0.18
12	30	F	+0.00 / 0.50 X 180	+0.00 / 0.50 X 5	-0.12	-0.16	-0.14
13	29	M	+0.00 DS	-0.25 DS	-0.22	-0.26	-0.24
14	33	F	+0.00 DS	+0.00 DS	-0.24	-0.26	-0.26

Table 4.1. Details of age, gender, refractive error, inter-pupillary distance, binocular and monocular best corrected visual acuity (BCVA) for the fourteen participants.

4.2.2 Design of Tumbling-E visual acuity test

The study involved a repeated-measures design to investigate blur adaptation, where visual acuity was assessed for two levels of blur (+1.00 D and +2.00 D) under photopic illumination and a single blur condition (+2.00 D) under mesopic illumination using a computer-generated tumbling E test. All room lights were turned on for photopic conditions, while for mesopic conditions the fluorescent lights were turned off and the dimmer light switch turned to a predetermined point. A Topcon IM2D illumination meter was used to record 4 readings for each light condition, with the probe at eye level facing either forwards toward the screen or upward toward the ceiling, resulting in the following photopic and mesopic illumination levels: photopic (375.3 lux probe forwards; 1076.5 lux probe upwards); mesopic (2.8 lux probe forwards; 6.6 lux probe upwards).

The computer-generated tumbling-E test was developed using the Psychopy psychophysics software (Jonathan, 2007) (by Dr. Philippe Lacherez, Vision & Driving laboratory, QUT). The tumbling-E target was designed in the standard illiterate E form (such that the three strokes of the letter ‘E’ were of equal width and length and were 1/5 of the overall optotype size). Flanking bars, designed to induce a crowding effect, were of equal width and length to those of the strokes of the ‘E’, were simultaneously presented on each of the four sides of the ‘E’, at a separation of half of the letter width (Shah, et al., 2010) (Figure 4.1).

“would ‘have’ just been me”

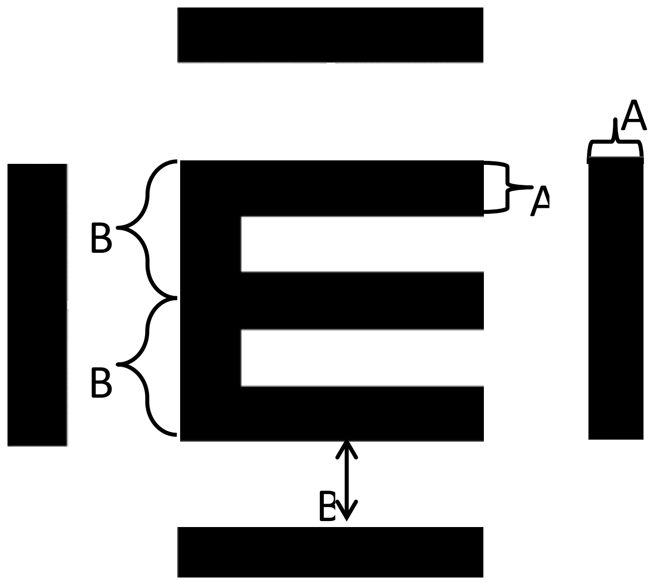

Figure 4.1. Schematic diagram of the tumbling-E target, where ‘A’ is the width of each limb and flanking bars. ‘B’ is the spacing of the flanking bars from the tumbling-E (half letter size) designed to create a crowding effect.

The tumbling-E stimulus was presented as a black letter with a luminance of 4.9 cd/ m^2 on a white background of 131.8 cd/ m^2 (96% Weber contrast), on a 30.2 x 22.6 cm LCD monitor with screen resolution of 1024 x 768 and refresh rate of 60 Hz. Each tumbling-E target was presented continuously on the screen until a response was made and was presented in one of four orientations (up, down, right or left). Participants were instructed to report the orientation which they judged the letter ‘E’ was pointing using the corresponding arrow keys on the computer keyboard and were instructed to guess even if the target orientation was difficult to identify. The estimate of the final visual acuity threshold was the smallest gap size of the letter ‘E’ that was detectable, estimated using a QUEST algorithm (Kontsevich & Tyler, 1999, Watson & Pelli, 1983).

The starting point for the QUEST algorithm initially began with a 1.3 MAR stimulus in each condition. Each run comprised 50 trials, and successive estimates were changed in log unit steps. Threshold was estimated for the 71% point on the psychometric function to equate with a normal 2-down, 1-up staircase method. This leads to a slightly more conservative estimate of threshold than the 62.5% point which is equivalent to equal probability of detection/non-detection correcting for guess rate, and therefore serves as a stricter representation of true detection ability.

For mesopic testing conditions, the room illumination was dimmed as described above and participants viewed the computer screen through 2.1 Neutral Density (ND) filters mounted in a trial frame in front of both eyes. The average luminance of the computer monitor under the photopic illumination conditions measured using a BM7 Topcon Luminance Colorimeter was 133 cd/m^2 and for mesopic conditions, the luminance of the computer monitor was 0.78 cd/m^2. The testing distance was 12 m (with participants viewing the computer screen via a mirror) under photopic testing condition and at 4 m (with +0.25 D working distance correction) under the mesopic testing condition (Figure 4.2). The testing distance under mesopic conditions was decreased in order to provide an appropriate range of resolution sizes for each set of testing conditions.

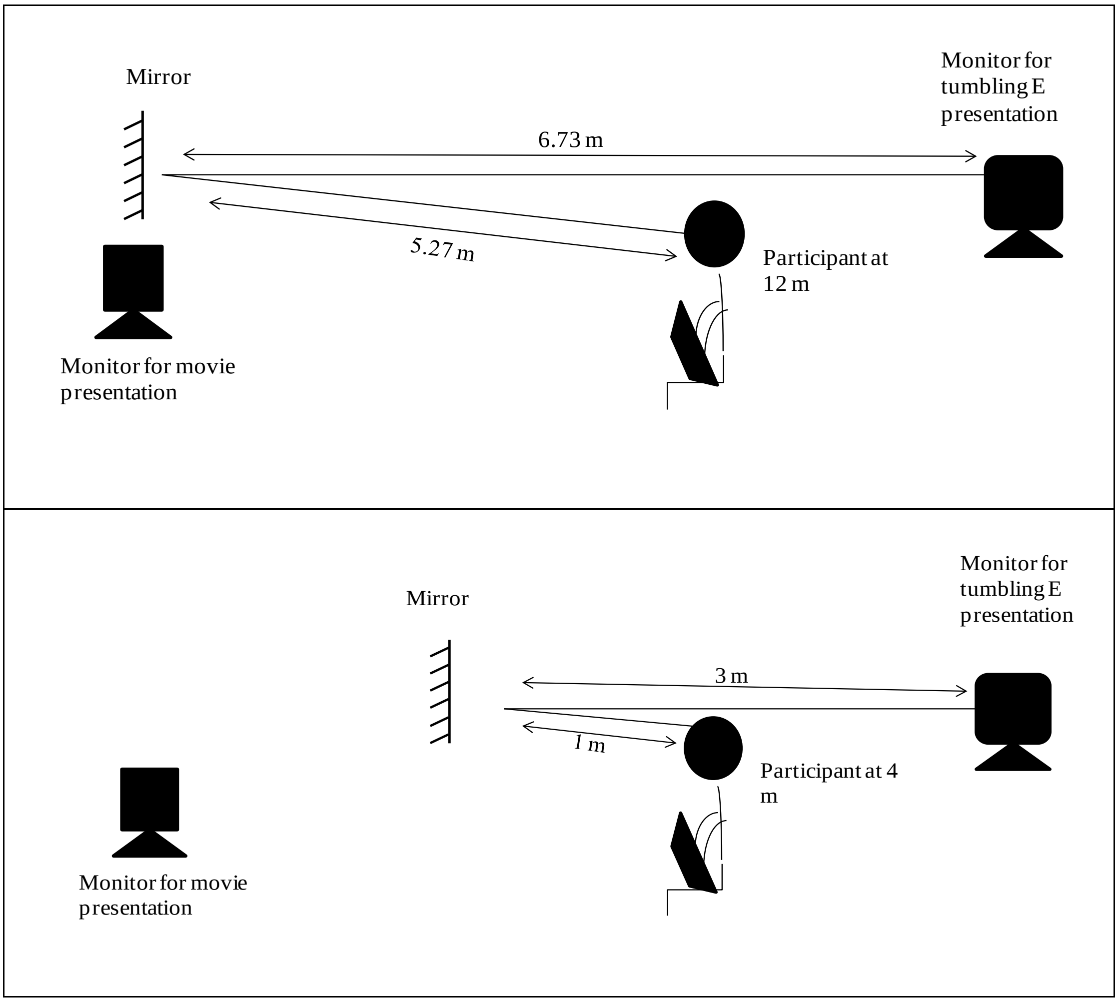

Figure 4.2. The set-up for the study, the participant was seated at 12 m for the +1.00 D and +2.00 D photopic blur conditions (upper panel) and the participant was seated at 4 m for the +2.00 D mesopic condition (lower panel).

4.2.3 Procedure

Binocular visual acuity for each participant was tested during three sessions over a period of 90 min for the +1.00 D photopic, +2.00 D photopic and +2.00 D mesopic conditions. Since the focus of this study was on photopic blur adaptation, blur adaptation under mesopic illumination was tested only for the +2.00 D blur condition. This was based on our observations from pilot data that this was the condition that demonstrated the most improvement in visual acuity following blur adaptation of the blur levels considered here. Participants wore their optimal correction and blurring lenses in a trial frame before both eyes. Each 90 min session was conducted on a different day and the 90 min session was divided into three 30 min sessions. Binocular visual acuity was measured at five time points (at 0 (baseline), 7, 14, 21, and 28 min) within each 30 min session. Each measurement of computerised visual acuity took approximately 60-90 seconds. The three 30 min sessions are described in detail below:

<u>Session 1 (control, 30 min duration)</u> (see Figure 4.3):

With optimal refractive correction for both eyes, binocular visual acuity measurements using the tumbling-E system were repeated every seven minutes over a period of 30 min. These measurements were used to determine whether there was any learning effect due to the repeated measurement of visual acuity and also helped to standardise the participant's state of light and blur adaptation.

<u>Session 2 (blur adaptation, 30 min duration)</u> (see Figure 4.3):

Session 2 started immediately after the first session by introducing blur (+1.00 D or +2.00 D) over the optimal correction in both eyes and binocular visual acuity was measured every seven minutes over a period of 30 min. The order of the blur conditions (+1.00 D or +2.00 D) was alternated between participants.

<u>Session 3 (blur recovery, 30 min duration)</u> (see Figure 4.3):

Measurements of binocular visual acuity were made with the optimal refractive correction immediately after the removal of the blur lenses for both eyes following blur adaptation. The measurements were taken at 0 (baseline), 7, 14, 21 and 28 min. This session was undertaken to determine the persistence of blur adaptation even after removing the blurring lens following blur adaptation, by measuring visual acuity for the optimal correction with brief reintroduction of blur at 14 min and 28 min.

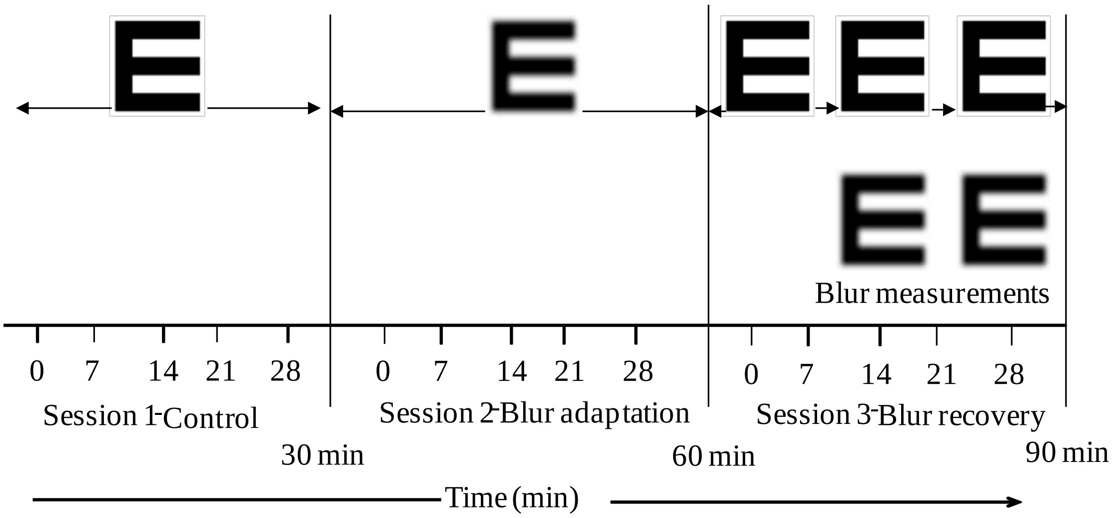

Figure 4.3. A pictorial representation of the tumbling E presentation for binocular visual acuity measures during the three 30 minute test sessions.

Participants watched a movie between visual acuity measurements on the 37.5 x 30.1 cm LCD monitor positioned at a distance of 5.27 m for five minutes to maintain constant accommodation between visual acuity measurements. Pupil size was measured using a NeurOptics electronic pupil meter in the right eye for all participants, with the other eye fixating a distant target. Pupil size was measured at the end of the first 30 min session 1 (control), at the beginning and end of the second 2 (blur adaptation) and at the end of the third session 3 (blur recovery). During session 2, pupil sizes were measured with no blur in front of the right eye, while the blur lens was present only in front of the left eye (fixating at distance).

Measurement of visual acuity for all three blur conditions took a total time of 270 min, with each blur condition (+1.00 D photopic, +2.00 D photopic and +2.00 D mesopic) tested on three separate days to avoid cross-over effects. The first and second sessions for two days were alternatively selected between +1.00 D and +2.00 D lens conditions for each participant, while the third day included the +2.00 D mesopic testing condition for all participants. The mesopic condition was always tested in the third session, given that it was predicted to be more challenging, although this may have incurred some confounding practice effects.

4.2.4 Analysis

Visual acuity values were expressed in minutes of arc (minimum angle of resolution (MAR)), given that it has previously been demonstrated that a linear relationship exists between refractive blur and MAR (Smith, 1991, 1996, Smith, et al., 1989). The group mean MAR visual acuity for each measurement was calculated for all 14 participants. Blur adaptation was defined as the change in visual acuity from 0 min to 28 min during adaptation to the blurring lenses. A two-way repeated measure ANOVA was conducted for the factors of blur (+1.00 D photopic, +2.00 D photopic) and adaptation time (0, 7, 14, 21 and 28 min) to assess the impact of blur and time on the change in MAR, and the interaction between blur and time. A second two-way repeated measure ANOVA was conducted for the factors of luminance (photopic, mesopic) and time (0, 7, 14, 21 and 28 min) for the +2.00 D blur conditions.

Persistence of blur adaptation in the recovery session (after removing blur) was measured by briefly reintroducing blur after 14 min and 28 min of clear vision. A paired t-test was conducted to compare visual acuity with blur at 14 min and 28 min post adaptation (session 3) with the first baseline measurement after the first introduction of blur (0 min) and the end of blur adaptation (28 min), to establish whether visual acuity returned to baseline levels after a period of recovery.

4.3 Results

There was no significant change in visual acuity during the control session (session 1) prior to blur adaptation in any of the three blur conditions ($F_{(4, 52)} = 0.905$, $p = 0.46$ for +1.00 D photopic, $F_{(4, 52)} = 2.390$, $p = 0.16$ for +2.00 D photopic and $F_{(4, 52)} = 1.114$, $p = 0.36$ for +2.00 D mesopic) (Figures 4.4 and 4.5). The group mean visual acuity of the five measurements recorded during the control session (session 1) were 0.64 ± 0.02 MAR for +1.00 D photopic, 0.65 ± 0.02 MAR in +2.00 D photopic and 1.13 ± 0.03 MAR for the +2.00 D mesopic condition. Introduction of blur resulted in a significant reduction in visual acuity compared to the control session (session 1) for all three blur conditions ($p < 0.01$).

A two-way repeated measure ANOVA was conducted for the main effects of blur and adaptation time on visual acuity in the photopic condition (session 2), and indicated a significant effect of blur ($F_{(1, 13)} = 49.19$, $p < 0.01$) and adaptation time ($F_{(4, 52)} = 18.94$, $p < 0.01$) on visual acuity. There was also a significant interaction between the level of blur and adaptation time ($F_{(4, 52)} = 7.55$, $p < 0.01$), where Figure 4.4 shows that the magnitude of the improvement in visual acuity was greater for the +2.00D than the +1.00D condition. Follow-up one-way repeated measures ANOVA indicated significant improvements in visual acuity for both the +1.00 D photopic ($F_{(4, 52)} = 4.314$, $p < 0.01$) and +2.00 D photopic ($F_{(4, 52)} = 13.354$, $p < 0.01$) conditions. Repeated contrasts showed that, in both the +1.00D and +2.00D conditions, the increase in visual acuity was significant between 0 min and 7 min, and between 7 min and 14 min ($p < 0.0125$), however, there was no further significant increase in visual acuity after 14 min of adaptation (Figure 4.4).

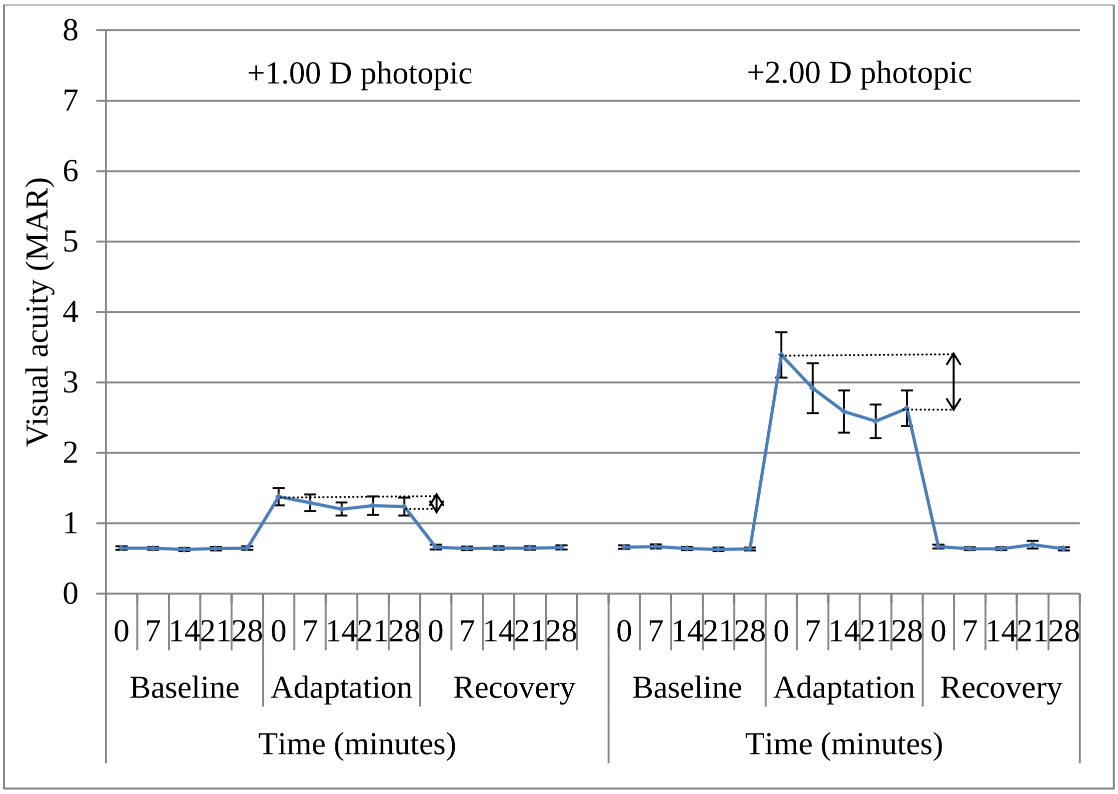

Figure 4.4. The group mean ± SE values of MAR visual acuity for the control session, adaptation session and recovery sessions for +1.00 D photopic and +2.00 D photopic. The arrows indicate the blur adaptation between the start and end of the 28 min of blur adaptation

A two-way repeated measure ANOVA conducted for the main effects of illumination (photopic and mesopic) and adaptation time for +2.00 D blur showed that there was a significant effect of illumination on visual acuity ($F_{(1, 13)} = 160.47$, $p < 0.01$) (Figure 4.5). There was also a significant improvement in visual acuity with adaptation, averaged over the two illumination conditions ($F_{(4, 52)} = 12.98$, $p < 0.01$). However, there was no significant interaction between illumination and adaptation time ($F_{(4, 52)} = 1.48$, $p = 0.22$) (Figure 4.5)

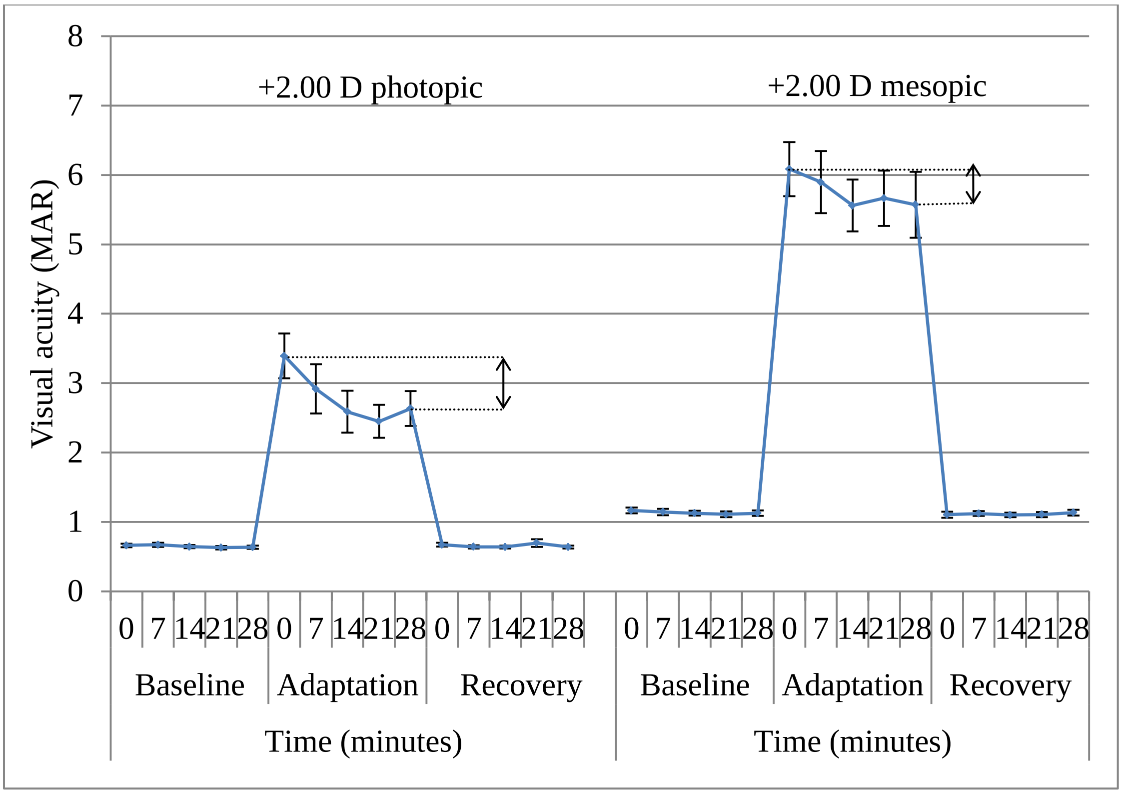

Figure 4.5. The group mean ± SE values of MAR visual acuity in baseline, adaptation and recovery sections for +2.00 D photopic and +2.00 D mesopic conditions. The arrows indicate the blur adaptation between the start and end of the 28 min of blur adaptation

Comparison of best-corrected acuity in the control session (pre blur) versus recovery (post blur) sessions

Visual acuity returned to baseline after removal of blur following blur adaptation, and there was no significant change in visual acuity in the no blur session (post-adaptation, session 3) for any of the blur conditions ($F_{(4,\ 52)}$ = 0.51, p = 0.73 for +1.00 D photopic, $F_{(4,\ 52)}$ = 1.47, p = 0.22 for +2.00 D photopic and $F_{(4,\ 52)}$ = 0.745, p = 0.56 for +2.00 D mesopic). Comparison of baseline and recovery data (pre-blur versus post-blur adaptation sessions) for best-corrected visual acuity also showed no significant difference in visual acuity measurements between sessions for any of the blur conditions, +1.00 D photopic ($F_{(1, 13)}$ = 2.371, p = 0.15), +2.00 D photopic, ($F_{(1, 13)}$ = 0.380, p = 0.54) and +2.00 D mesopic ($F_{(1, 13)}$ = 1.497, p = 0.24).

Persistence of blur adaptation after removing blur

The persistence of blur adaptation during the recovery period was studied by briefly reintroducing blur at 14 min and 28 min during the post-blur session (recovery-no blur session), after the continuous blur lens (during blur adaptation) had been removed. A paired t-test was conducted comparing acuity with the first administration of blur and after 28 min of adaptation with visual acuity after 14 and 28 min of recovery from blur. These data are shown in Figure 4.6.

The comparisons indicate that in the +1.00 D photopic condition the blur measurements during the recovery session (14 min and 28 min) were not significantly different to those at the start of blur adaptation (0 min during blur adaptation), indicating that the recovery was complete after removal of blur following blur adaptation. However, in the +2.00 D photopic and +2.00 D mesopic conditions, the blur measurements (14 min and 28 min) during the recovery session remained significantly better than that at the start of the blur adaptation (0 min during blur adaptation) ($p \leq 0.05$) (Figure 4.6). Visual acuity showed a small and insignificant recovery compared to the end of adaptation (28 min during blur adaptation) in the +1.00 D photopic, +2.00 D mesopic conditions ($p > 0.05$) and a significant recovery in +2.00 D photopic condition ($p < 0.05$) (Figure 4.6). Thus the results indicate that for higher blur levels (+2.00 D blur), blur adaptation was persistent even after 28 min of clear vision, which was the case for both illumination conditions.

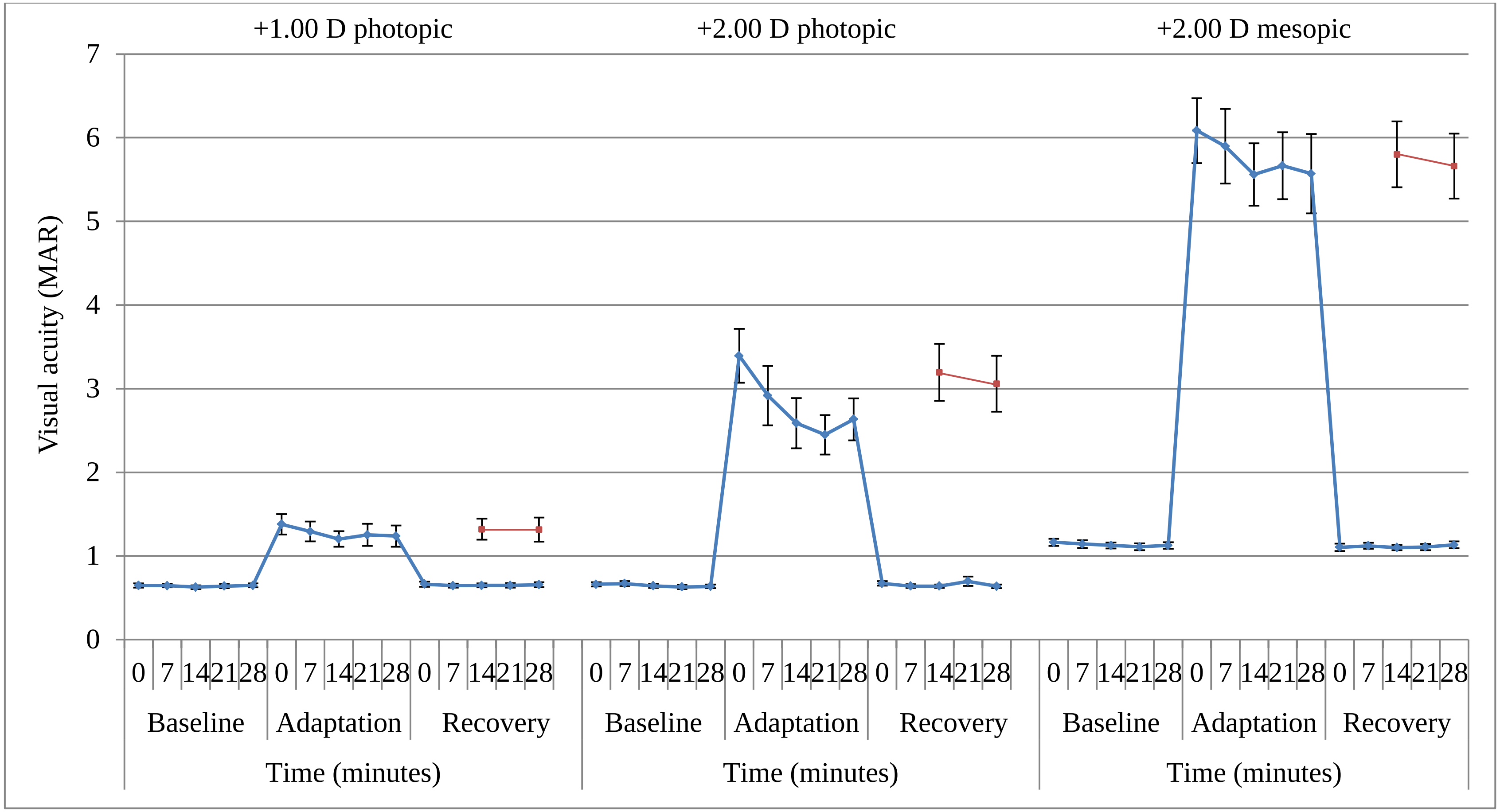

Figure 4.6. The group mean ± SE values of MAR visual acuity in baseline, adaptation and recovery sections for +1.00 D photopic, +2.00 D photopic and +2.00 D mesopic conditions. The group mean ± SE MAR visual acuity for 14 min and 28 min blur measurements during recovery session is presented in red line

Pupil size

Pupil size was measured at four different times (30, 31, 60 and 90 min) during the 90 min of testing for all three conditions and is reported in Table 4.2. There was a significant increase in pupil size with the introduction of blur [30 min (no blur) compared to 31 min (introduction of blur)] for the +1.00 D photopic ($t_{(-3.901)} = 13$, $p = 0.002$) and +2.00 photopic conditions ($t_{(13)} = -3.047$, $p = 0.009$) but not for +2.00 mesopic conditions ($t_{(13)} = -1.074$, $p = 0.30$) (Table 4.2). The increase in pupil size during blur adaptation (31 min and 60 min time points) was significant for the +2.00 D photopic condition ($t_{(13)} = -2.429$, $p = 0.03$) but not for the +1.00 D photopic ($t_{(13)} = -1.369$, $p = 0.19$) and +2.00 D mesopic conditions ($t_{(13)} = 0.452$, $p = 0.66$) (Table 4.2).

	Mean ± SD pupil size measurement (mm)				
Blur conditions	30 min (no blur)	31 min (start of blur)	60 min (end of blur)	90 min (end of no blur)	Significant differences ($p < 0.05$)
+1.00 D photopic	4.42 ± 0.51	4.63 ± 0.61	4.69 ± 0.60	4.46 ± 0.51	30 min < 31 min* 31 min < 60 min 60 min > 90 min*
+2.00 D photopic	4.38 ± 0.35	4.61 ± 0.52	4.69 ± 0.55	4.43 ± 0.43	30 min < 31 min* 31 min < 60 min* 60 min > 90 min*
+2.00D mesopic	6.43 ± 0.72	6.48 ± 0.72	6.48 ± 0.72	6.38 ± 0.69	30 min < 31 min 31 min = 60 min 60 min > 90 min

Table 4.2. The mean ± SD values of pupil size measured at the end of the baseline session (30 min), at the beginning and end of blur adaptation (31 min & 60 min) and at the end of recovery session (90 min). (*) Represents statistically significant differences in pupil size ($p < 0.05$).

4.4 Discussion

The findings from this study suggest that the adaptation to blur tends to peak at about 14 min following the initial imposition of blur, and that this level of blur adaptation is then maintained up until the 30 min measurement point. Blur adaptation resulted in a significant improvement in binocular visual acuity over the 30 min exposure to blur for all conditions. These results for the photopic illumination conditions are consistent with those of Mon-Williams, et al., (1998), who reported a four letter improvement in visual acuity for 30 min of adaptation to +1.00 D blur. Similarly

George & Rosenfield, (2004) reported an improvement in binocular visual acuity of two lines following two hours of adaptation to +2.50 D blur.

In considering a possible mechanism for the adaptation to blur, Mon-Williams, et al., (1998) suggested that blur adaptation occurs at the level of visual cortex, from their observation of an improvement in visual acuity in the fellow eye, following blur adaptation. They also noted a reduction in contrast sensitivity for mid spatial frequencies (5-25 cycles per degree {cpd}) following adaptation to +2.00 D blur, with no change in higher and lower spatial frequencies. On the other hand, Rajeev & Metha (2010) noted an improvement in sensitivity to mid and high spatial frequencies (8 and 12 cpd) and reduced sensitivity to low (0.5 and1.0 cpd) spatial frequencies following 30 min of adaptation to +2.00 D blur.

The present study also showed that blur adaptation varied depending on the level of blur. There was a group mean improvement of two letters of visual acuity for +1.00 D blur compared to a group mean improvement of seven letters for the +2.00 D blur condition, after 30 min of blur adaptation. Cufflin, Hazel, et al., (2007) also measured monocular visual acuity for +1.00 D and +3.00 D blur conditions and noted a trend towards greater adaptation with higher levels of blur, however, the differences did not reach statistical significance. The reason for a greater level of blur adaptation with increasing levels of blur is unclear.

The present study also showed that there was no significant difference in blur adaptation for +2.00 D blur under photopic and mesopic illumination conditions. There was a small increase in pupil size during blur adaptation for +1.00 D, +2.00 D blur conditions under photopic illumination and no change in pupil size during blur adaptation for +2.00 D mesopic condition. The change in pupil size for the +1.00 D photopic condition was not significant, which is consistent with previously reported data where blur adaptation had no significant effect on pupil size (Cufflin, et al., 2007). However there was a small (0.31 mm), but significant increase in pupil size during blur adaptation in the +2.00 D photopic condition. This small increase in pupil size is likely to worsen visual acuity in the presence of blur, rather than improve visual acuity, since the retinal blur circle will be larger.

Another important finding was the persistence of blur adaptation even after removal of blur following blur adaptation. Blur was reintroduced at 14 min and 28 min during the recovery session following blur adaptation and these blur measurements were compared with the start and end measurements during blur adaptation. Visual acuity for both the blur measurements during the recovery session were better than at the start of blur adaptation (0 min during blur adaptation) indicating that recovery from blur adaptation after removing blur was incomplete. This persistence of blur adaptation was noted only for +2.00 D blur under both photopic and mesopic illumination conditions, for the +1.00 D photopic condition the recovery from blur adaptation was complete after removing blur. The persistence of blur adaptation was not affected by the intervening measurements for the non blurred conditions.

4.5 Conclusion

The results from this study confirm previous work showing that visual acuity significantly improves following blur adaptation. The new findings were that blur adaptation varied with the level of blur, however, change in illumination did not affect blur adaptation. Blur adaptation was measurable at 7 min and appears to be largely complete at 14 min and this was consistent for both levels of blur and under photopic and mesopic testing conditions, indicating that the minimum adaptation time that should be given in blur experiments should be 14 min. This adaptation time of 14 min was included in all the protocols of the experiments included in this thesis. The other important finding of the study was the small but significant persistence of blur adaptation even after intervening measurements of clear vision until 28 min after removing the blur. This information assists in the design of the methodology for Experiments 2 and 3, given that these experiments involved four different levels of blur. Given that the effects of blur adaptation were shown to persist after the removal of blur, we chose not to randomise the order of the levels of blur Experiment 2 and 3; measurements were always performed from lower to higher levels of blur.

Thus the main findings of this study were that the level of blur adaptation peaked at about 14 min, which was consistent for different levels of blur and under different illumination conditions. The amount of adaptation varied with level of blur and this blur adaptation was found to persist even after the removal of blur.

Chapter 5: The effect of blur and illumination on short exposure visual acuity measurements

5.1 Introduction

The presence of blur reduces the ability to recognise and resolve the fine detailed components of a target (Anderson, et al., 2001, Wang & Ciuffreda, 2005). The reduction in contrast sensitivity with blur has been shown to be spatial frequency dependent, affecting the high spatial frequency components of the target to a greater extent with increasing blur (Green & Campbell, 1965). However, the effect of blur on visual acuity was not reported to differ between high and low illumination conditions (Johnson & Casson, 1995).

Driving is a highly visual task and the majority of the sensory input for driving is believed to be visual. Visual acuity testing is included as a screening test to determine driving fitness for first time licensing and periodic re-licensing in most countries. The current Australian standards for licensing states that drivers of private vehicles require a visual acuity of 6/12 in the better eye or binocularly, whereas commercial drivers must have a minimum of 6/9 in the better eye and 6/18 in the other eye (Lloyd, 2012). Drivers with visual acuity worse than these levels are likely to have difficulty in reading road signs and identifying hazards on the road (summerized in Schieber, 2004). Recently there has been increased interest among researchers in understanding the effect of uncorrected refractive error on driving performance, as refractive error has been reported to be the cause of reduced visual acuity in 80% of the drivers whose visual acuity was below the legal limit of 6/12

(Keeffe, et al., 2002). Studies measuring the effect of different levels of blur (from 0 to +10 D) and different light levels (using neutral density filters) on driving performance using driving simulators have reported that increased blur and reduced luminance resulted in a significant reduction in steering performance (Brooks, et al., 2005, Owens & Tyrrell, 1999).

In on-road driving experiments, which measured the effect of degrading acuity (6/6, 6/12, 6/30 and 6/60) using different levels of blur on daytime driving performance, showed that increased blur resulted in a greater reduction in driving performance ,including total driving time (drivers slowed down in the presence of blur), hazard avoidance and road sign recognition (Higgins & Wood, 2005, Higgins, et al., 1998). Similarly, Wood, et al., (2010) measured the effect of simulated cataracts and blur on night-time driving, with visual acuity reduced to approximately 6/9.5 in both visual conditions. The results showed a significant decrease in driving performance similar to that found for daytime driving, with a greater effect for simulated cataracts compared to the simulated blur condition. Comparison of the effect of blur conditions on day and night-time driving performance showed that the effect of blur on driving performance was greater under night compared to daytime conditions (Wood, et al., 2011).

Standard visual acuity assessment usually consists of static presentation of a letter chart under high room illumination conditions in which participants are given unlimited time to correctly recognise the letters. However, it is unclear whether such measures capture the variation of vision under more dynamic environments, such as driving. Moreover, studies have also showed that standard visual acuity measures are poorly associated with driving performance (Davison, 1985, Hofstetter, 1976, Humphriss, 1987, Ivers, et al, 1999, Marottoli, et al., 1998). Thus the purpose of this study was to examine whether the effects of blur on visual acuity measures for stimulus presented only briefly, better reflect the effect of blur on driving performance.

Studies have reported that visual resolution is dependent on the exposure duration of the target and that visual acuity improves with increased target duration (Baron & Westheimer, 1973, Kahneman, 1964, Keesey, 1960, Niwa & Tokoro, 1997). In the present study a target exposure of 100 ms was used to measure the effect of blur on visual acuity, as it has been shown to be the minimum exposure duration for which the temporal integration for briefly presented stimulus is largely complete and visual acuity is at normal levels (≥ 6/6), under photopic luminance levels (Baron & Westheimer, 1973, Niwa & Tokoro, 1997).

A decrease in luminance to mesopic levels degrades vision functions, such as visual acuity (Glover, et al., 1999, Rabin, 1994, Simpson, et al., 1986)**,** contrast sensitivity (Peli, et al., 1996, Sloane, et al., 1988), colour vision (Knight & Knight, 2009, Schneider & von Campenhausen, 1998, Shin, et al., 2004) and reaction times (He, et al., 1998, Viikari, et al., 2008, Walkey, et al., 2007, Zele, et al., 2013). Further studies measuring the effect of reduced luminance on brief stimulus presentation have also reported an increase in temporal integration time under mesopic conditions, leading to greater reduction in resolution ability under low compared to high luminance levels (Baron & Westheimer, 1973, Brown & Black, 1976, Niwa & Tokoro, 1997). Although studies have noted the effect of exposure duration and target luminance on visual acuity, the effect of simulated blur on visual acuity for short target durations has not been studied.

Thus, visual acuity measured for short target exposures may be important for estimating visual abilities in real-world conditions, especially while driving. Also the presence of simulated blur has been shown to have a greater effect on driving performance under night-time conditions compared to daytime (Wood, et al., 2011). The aim of the present study was to investigate the effect of blur on visual acuity for briefly presented targets compared to visual acuity for unlimited presentations under photopic and mesopic illumination conditions. By measuring the effect of blur on visual acuity for brief exposure targets in standardised laboratory conditions, we aimed to better understand the variation in vision resulting from blur on the recognition of briefly presented events while driving under photopic and mesopic conditions.

5.2 Method

5.2.1 Participants

Twenty young subjects were recruited with an age range of 18 to 35 years (mean age 29.4 ± 3.06 years) (13 male and 7 female) (see Table 5.1). All participants were screened for their eligibility to participate in the study through a clinical eye examination; all participants were optimally corrected for their distance refractive error. Refractive error assessment for optimal refractive correction for each eye was determined using the Jackson cross-cylinder and the blur-back technique using a phoropter. Binocular distance visual acuity was measured using the ETDRS chart at a working distance of a 4 m (Ferris, et al., 1982) with the optimal refractive correction centred in the trial frame to determine the best-corrected visual acuity (≥ 6/6 or 0.00 logMAR) for a chart luminance of 126 cd/m^2.

Inclusion criteria were: (1) participants aged between 18 years to 35 years, 2) visual acuity ≥ 6/6 with refractive correction, and 3) no eye diseases. Informed consent was obtained from all participants and the research protocol was approved by the Queensland University of Technology, Human Research Ethics Committee (see Appendix 1).

Age (yrs)	Gender	Subjective refraction Right eye	Subjective refraction Left eye	IPD (mm)	BCVA Right eye (logMAR)	BCVA Left eye (logMAR)	BCVA Both eyes (logMAR)
30	M	Plano	Plano	65	-0.20	-0.18	-0.22
28	M	Plano	+0.25DS	64	-0.10	-0.12	-0.16
23	M	Plano	Plano	60	-0.10	-0.02	-0.16
33	F	+0.25DS	0.00/-0.25X90	61	0.00	0.00	-0.10
28	M	+0.25DS	+0.25DS	62	-0.20	-0.10	-0.22
29	M	+0.25/-0.25X90	0.00/-0.25X90	65	-0.12	-0.16	-0.20
31	M	Plano	Plano	64	-0.06	-0.12	-0.12
28	F	+0.25DS	+0.25DS	64	0.00	0.00	-0.10
30	F	0.00/-0.50X180	0.00/-0.25X05	64	-0.12	-0.16	-0.14
28	M	Plano	Plano	64	-0.14	-0.16	-0.16
31	M	-2.50/-0.50X180	-2.25/-0.50X180	64	-0.08	-0.06	-0.10
30	M	-3.50/-0.50X80	-2.00/-0.50X45	69	-0.02	0.00	-0.06
29	F	-2.00/-0.75X170	-1.00/-0.75X20	64	0.00	0.02	0.02
27	F	-0.75 DS	-1.00/-0.25X180	66	-0.08	-0.08	-0.12
30	M	-0.75/-0.50X90	-0.75/-0.50X90	66	-0.12	-0.12	-0.16
32	M	-2.25/-0.50X160	-2.25/-0.50X180	64	-0.06	-0.14	-0.14
35	M	-1.00 DS	-1.00 DS	66	-0.08	-0.12	-0.12
35	M	-1.75 DS	-2.25 DS	64	-0.12	-0.12	-0.14
24	F	-0.75 DS	-0.75 DS	64	-0.20	-0.20	-0.20
27	F	-3.50/-0.25X10	-4.50/-0.50X180	64	-0.02	-0.06	-0.08

Table 5.1. Details of age, gender, refractive error, inter-pupillary distance (IPD), binocular and monocular best corrected visual acuity (BCVA) using the ETDRS charts of all participants.

5.2.2 Design of the Tumbling-E method for assessing visual acuity

The study involved repeated measurements of visual acuity for both untimed and timed (100 ms) presentations using computer-generated tumbling-E stimuli. Visual acuity was measured for 0.00 D, +0.50 D, +1.00 D and +2.00 D blur conditions under photopic and mesopic illumination conditions as described for Study 1. For the untimed presentation the stimulus was presented until the participant gave a response and in the timed presentation the stimulus duration was 100 ms. For both stimulus presentation times, a random noise mask appeared for 500 ms following the stimulus presentation in order to minimise the afterimage of the stimulus displayed (Mankowska, et al., 2012, Roinishvili, et al., 2011).

5.2.3 Procedure

Testing was undertaken over a period of 80 min under both the photopic and mesopic illumination levels on two different days. At each session visual acuity was tested for four blur conditions (0.00 D, +0.50 D, +1.00 D and +2.00 D), and for each blur condition visual acuity was measured for two different target presentations (untimed and 100 ms presentation). Participants wore their optimal correction and the blurring lenses in a trial frame in front of both eyes. The configuration of the testing environment for the mesopic and photopic conditions was the same as in Study 1. In the photopic illumination condition, visual acuity for all defocus conditions was measured at a 12 m testing distance (via a mirror – see Figure 5.1). In the mesopic condition for the 0.00 D and +0.50 D blur conditions visual acuity was measured at the 12 m distance and the +1.00 D and +2.00 D blur conditions were measured at 4 m (directly looking at monitor) (Figure 5.1). These testing distances were selected for the mesopic illumination conditions in order to provide an appropriate range of resolution sizes for each set of testing conditions. At a working distance of 4 m a correction of +0.25 D was given over the optimal distance refraction and defocus was added to this total power.

A 14 min adaptation time was given for each blur condition followed by 6 min of visual acuity measurements under both illumination conditions. The 14 min blur adaptation period was selected based on the data collected in Experiment 1 which showed that visual acuity improved following 30 min of blur adaptation, with peak in visual acuity at 14 min following imposition of the blurring lens (Chapter 4). Participants watched a movie during the 14 min adaptation period on the LCD monitor positioned at a distance of 5.27 m in photopic illumination and on a monitor at 4 m for the +1.00 D, +2.00 D blur conditions under mesopic illumination conditions, to maintain constant accommodation throughout the experiment. For all participants the 14 min adaptation time was also given for the no blur conditions under both illumination conditions which assisted in standardising participants' state of light adaptation prior to visual acuity measurements (Uvijls, et al., 2001). In both illumination conditions the testing order of defocus was from lower to higher (0.00 D, +0.50 D, +1.00 D, +2.00 D), given that in the adaptation study described in Experiment 1, there was an improvement in visual acuity with blur following adaptation and this effect partly remained over 30 min, following removal of the blur lens. Thus by not randomizing the blur levels and testing the order of blur from lower to higher levels, we aimed to control for the carry-over effect of blur adaptation of higher blur levels on visual acuity measurements for lower blur levels.

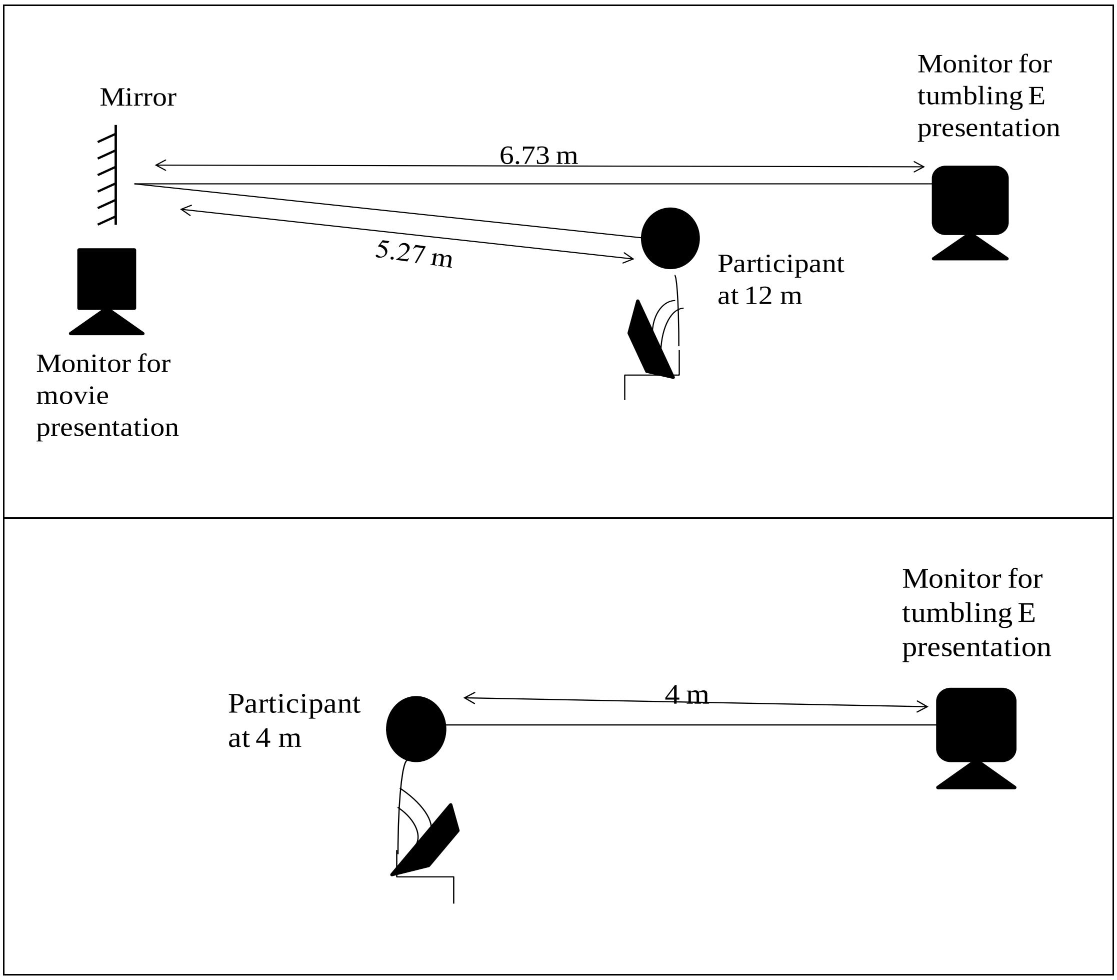

Figure 5.1. Schematic representation of the experimental setup: the participant was seated at 12 m for all four blur conditions under photopic illumination and for 0.00 D and +0.50 D blur conditions under mesopic illumination (upper panel). The working distance was 4 m for +1.00 D and +2.00 D under mesopic illumination conditions (lower panel).

5.2.4 Analysis

The group mean minimum angle of resolution (MAR) visual acuity for each blur measurement was calculated for all 20 young participants. Visual acuity was considered in MAR values, as for Experiment 1 in order to investigate the small changes in visual acuity for the effects of blur, illumination and stimulus presentation times. Binocular visual acuity was compared between the untimed and timed presentation for the four blur conditions and under two illumination conditions. A three-way repeated measures ANOVA was conducted for the factors of illumination (photopic and mesopic), presentation time (untimed and timed) and blur (0.00 D, +0.50 D, +1.00 D and +2.00 D) to analyse the impact of illumination, presentation time and blur on visual acuity.

5.3 Results

There was a significant main effect of illumination level ($F_{(1, 19)} = 172.594$, $p < 0.01$), stimulus presentation time ($F_{(1, 19)} = 250.01$, $p < 0.01$) and blur ($F_{(3, 57)} = 163.91$, $p < 0.01$) on visual acuity. There was a significant three-way interaction between presentation time, illumination level and blur for visual acuity ($F_{(3, 57)} = 5.27$, $p = 0.003$). In addition, there were also significant two-way interactions noted for the main effects of illumination and stimulus presentation time ($F_{(1, 19)} = 74.45$, p < 0.01), illumination and blur ($F_{(3, 57)} = 41.35$, $p < 0.01$) and stimulus presentation time and blur ($F_{(3, 57)} = 51.46$, $p < 0.01$) (Table 5.2).

Effects	Df	F-value	*p*-value
Illumination	1	172.594	$P < 0.01$*
Blur	3	163.912	$P < 0.01$*
Presentation time	1	250.012	$P < 0.01$*
Presentation time X bBlur	3	51.464	$P < 0.01$*
Illumination X Blur	3	41.358	$P < 0.01$*
Illumination X Presentation time	1	74.450	$P < 0.01$*
Illumination X Blur X Presentation time	3	5.276	$P = 0.003$*

*Table 5.2. Three-way ANOVA and follow up two-way ANOVA showing effect of blur, illumination and presentation time on visual acuity, Note: *= p < 0.01 for statistical significance.*

Follow-up two-way ANOVAs were thus conducted for the factors of presentation time and blur on visual acuity under photopic and mesopic illumination conditions separately, to determine the simple main effects of blur and stimulus presentation time on visual acuity for both illumination conditions. There were significant main effects of stimulus presentation time on visual acuity (for photopic $F_{(1, 19)} = 74.74$, $p < 0.01$ and for mesopic conditions $F_{(1, 19)} = 193.04$, $p < 0.01$). Pairwise comparison of presentation time indicates that visual acuity was reduced to a greater extent for the timed (100 ms) presentation compared to the untimed presentations under both illumination conditions ($p < 0.01$) (Figure 5.2).

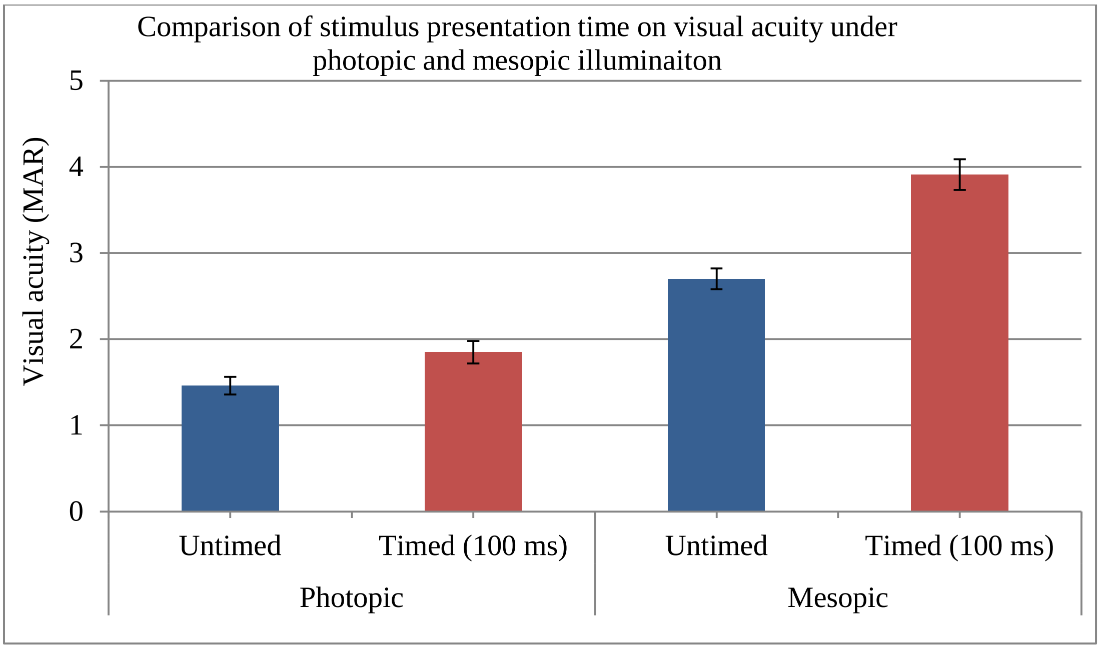

Figure 5.2. The group mean ± SE comparison of untimed and timed (100 ms) stimulus presentation under photopic and mesopic illumination conditions.

There were also significant simple main effects of blur on visual acuity under both illumination conditions, with a greater effect of blur under mesopic ($F_{(357)} = 155.50$, $p < 0.01$), compared to photopic illumination conditions ($F_{(3,\ 57)} = 103.387$, $p < 0.01$). Mean visual acuity reduced significantly with increasing blur compared to baseline (no blur) for both stimulus presentation times under both illumination conditions and all pairwise comparisons of all four blur conditions were significant ($p < 0.01$) (Table 5.3). In addition, there were also significant interactions between the simple effects of blur and presentation time under both illumination conditions (photopic $F_{(3,\ 57)} = 19.672$, $p < 0.01$ and mesopic $F_{(3,\ 57)} = 28.451$, $p < 0.01$). The effect of the four blur conditions (0.00 D, +0.50 D, +1.00 D and +2.00 D) on visual acuity was greater for the timed presentation under both illumination conditions, with the greatest effect of blur on visual acuity being for the timed mesopic condition ($F_{(3,\ 57)} = 209.188$, $p < 0.01$), followed by the untimed mesopic condition ($F_{(3,\ 57)}$ =

151.514, $p < 0.01$), the photopic timed condition ($F_{(3, 57)} = 123.918$, $p < 0.01$), with least effect in the untimed photopic condition ($F_{(3, 57)} = 67.533$, $p < 0.01$) (Figure 5.4). Moreover, as can seen in Figure 5.4, the differential increase in the effect of blur with the timed presentation was greater in the mesopic (Figure 5.3 B) than in the photopic condition (Figure 5.3 A)

Blur condition	Photopic illumination		Mesopic illumination	
	Untimed	Timed (100 ms)	Untimed	Timed (100 ms)
0.00 D	0.71 ± 0.11	0.87 ± 0.19	1.25 ± 0.18	1.84 ± 0.36
+0.50 D	0.89 ± 0.38	1.08 ± 0.39	1.87 ± 0.49	2.83 ± 0.76
+1.00 D	1.27 ± 0.61	1.60 ± 0.89	2.58 ± 0.61	3.70 ± 0.76
+2.00 D	2.95 ± 1.11	3.85 ± 1.12	5.07 ± 1.26	7.20 ± 1.94

Table 5.3. The group mean ± SE of MAR visual acuity measurements for the four blur conditions, presented for both untimed and timed (100 ms) presentations, under photopic and mesopic illumination conditions.

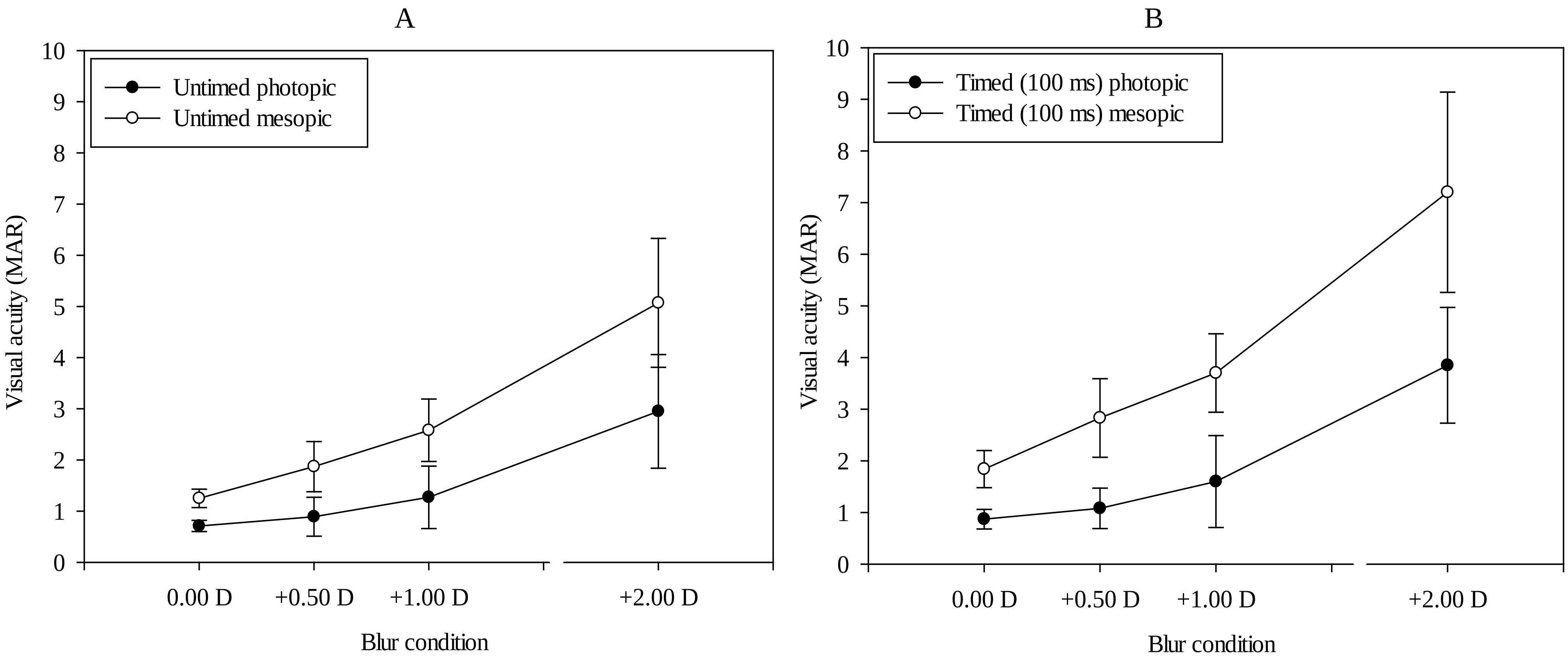

Figure 5.3. The group mean ± SE visual acuity for 0.00 D, +0.50 D, +1.00 D, and +2.00 D conditions comparing untimed and timed (100 ms) stimulus presentation and under photopic and mesopic illumination.

There was also significant effect of blur ($F_{(1, 19)} = 194.31$, $p < 0.01$) and illumination ($F_{(3, 57)} = 16.62$, $p < 0.01$) on pupil size. In addition there was also a significant interaction between blur and illumination ($F_{(3, 57)} = 7.06$, $p < 0.01$) on pupil size. Pairwise comparison of pupil size showed that increasing blur resulted in a significant increase in pupil size under photopic illumination ($p < 0.01$), and a decrease in illumination resulted in a significant increase ($p < 0.01$) in pupil size compared to the photopic testing condition. However, it can be seen from Table 5.3, that there was no significant change in pupil size with increasing blur under mesopic illumination (Table 5.4) ($p > 0.05$).

Illumination conditions	0.00 D	+0.50 D	+1.00 D	+2.00 D
Photopic	4.3 ± 0.64	4.4 ± 0.64	4.5 ± 0.67	4.7 ± 0.68
Mesopic	6.8 ± 0.74	6.8 ± 0.72	6.8 ± 0.71	6.8 ±0.74

Table 5.4. Group mean ± SD of pupil size measured in four blur conditions and under photopic and mesopic illumination conditions.

5.4 Discussion

The findings from this study indicate that there was a significant decrease in visual acuity with increasing blur for both stimulus presentation times. Importantly the decrease in visual acuity was greater for the timed (100 ms) presentation compared to the untimed presentation under both illumination conditions. Decrease in illumination to mesopic levels exacerbated the effects of both blur and stimulus duration, such that there was a much greater decrease in visual acuity for the brief (100 ms) presentation under the mesopic testing condition compared to visual acuity for the untimed mesopic condition, and for the timed and untimed conditions under photopic illumination.

Group mean visual acuity for the no blur condition under photopic illumination was better than 1.0 MAR (less than 6/6) for both untimed and timed (100 ms) presentations. However, visual acuity for the no blur condition with the timed presentation was approximately one line worse compared to visual acuity for the untimed presentation. This reduction in visual acuity for a brief stimulus presentation compared to stimuli presented for longer exposure durations, is in accord with findings from previous studies (Kono, et al., 1991, Niwa & Tokoro, 1997)

The presence of even a small amount of blur (+0.50 D) resulted in a significant reduction in visual acuity, which further worsened with increasing blur levels (+1.00 D and +2.00 D) for both stimulus presentation times. These results are in accord with previous studies which reported similar effect of increasing blur levels on visual acuity, measured using standard untimed target presentations (Johnson & Casson, 1995, Plainis, et al., 2011, Radhakrishnan, et al., 2004, Schmidt, 1994). The current study also showed that the effect of blur on visual acuity was greater in the timed (100 ms) presentation compared to the untimed presentation under photopic conditions. The possible explanation for the greater effect of blur on visual acuity for the timed presentation may be a result of the combined effect of blur and reduced resolution ability for brief stimulus presentations. Applying these findings to real-world conditions, especially while driving, suggests that the presence of even small amounts of blur (+0.50 D) may significantly reduce recognition ability for targets which may be presented briefly while driving on high speed roads, such as road signs and hazards. Supporting this, studies measuring the effect of simulated blur on on-road driving performance, showed that increasing blur results in a significant decrease in performance measures that involved briefly appearing targets, including recognition of road signs and hazards (Higgins & Wood, 2005, Higgins, et al., 1998).

Decreasing illumination from photopic to mesopic levels further exacerbated the effect of blur on visual acuity for both untimed and timed presentations. The possible reason for the greater effect of blur under mesopic illumination may be a result of the increased pupil size relative to that measured under photopic illumination. The increase in pupil size results in a decrease in depth-of-focus (Legge, et al., 1987, Tucker & Charman, 1986, Wang & Ciuffreda, 2004) and an increase in higher order aberrations (Hashemian, et al., 2012, Kawamorita & Uozato, 2006, Tabernero, et al., 2009). In addition, the increased pupil size under mesopic illumination leads to a larger retinal blur circle (Green, et al., 1980, Ogle & Schwartz, 1959). Thus the presence of blur may be an additive effect leading to an increased effect of blur under mesopic conditions. The difference in testing distances under the two illumination conditions may have also contributed to a small difference in pupil size (0.07 mm), leading to a change in accommodation of about 0.17 D (Buehren & Collins, 2006). However, this small change in accommodation was compensated for by providing an appropriate working distance (+0.25 D) correction while testing at 4 m. Johnson & Casson, (1995) measured the effect of increasing blur levels on visual acuity for untimed stimulus presentation under high and low illumination conditions and reported that the effect of blur was not exacerbated under low compared to high illumination conditions. The reason for the difference in results between studies is unclear. Possible explanations include the fact that Johnson & Casson, (1995) did not use briefly presented targets and also included a relatively small sample size. It should be noted that in the present study the mesopic condition was always presented on the third session, so participants had already had a significant level of practice in completing the task prior to this assessment. While this is acknowledged as a limitation, it is important to note that the results cannot be ascribed to a simple practice effect, as it would be predicted that practice should lead to lesser effects of blur (or greater adaptation), rather than greater effects of blur as evidenced here.

The decrease in illumination also exacerbated the effect of stimulus presentation time on visual acuity measured in our study. This greater decrease in visual acuity for brief stimulus presentation is considered to be a result of an increase in temporal integration time under mesopic compared to photopic illumination conditions (Baron & Westheimer, 1973, Brown & Black, 1976, Niwa & Tokoro, 1997). In the current study there was also a much greater effect of blur on visual acuity for the timed mesopic condition compared to the timed presentation under photopic illumination, which result from a combined effect of blur and the timed presentation under mesopic conditions. These findings suggest that blur may result in a greater reduction in the ability to recognise briefly presented hazards while driving under low lighting conditions, as in night-time, compared to daytime driving. These findings are also consistent with an on-road driving experiment that showed that blur had a significant effect on driving performance under day and night-time conditions, with the effect being greater during the night compared to day time conditions (Wood, et al., 2011)

5.5 Conclusion

The results of this experiment provides a basis for predicting how blur will affect an individual's visual resolution ability for target presented for unlimited exposures (such as a stationary target), in comparison to briefly presented targets in real world conditions, especially while driving. These results suggest that even a small amount of blur, which may result from uncorrected or under-corrected refractive errors, may impact on the identification and resolution of dynamic and briefly presented events while driving at high speeds, such as road sign recognition and hazard identification. The findings also suggest that the effect of blur on events presented briefly while driving may be much greater under low lighting conditions. In the following experiment (Experiment 3) we further investigated the effect of blur and auditory distracters on reaction time to such dynamically presented driving hazards using a computer-based test.

Chapter 6: The effect of blur and secondary task on reaction time to hazards in Hazard Perception Test (HPT)

6.1 Introduction

Hazard perception measures the ability of drivers to anticipate and identify dangerous situations while driving on the road (Horswill, et al., 2008). Assessment of hazard perception usually involves measurement of reaction times to potential hazards such as traffic conflicts presented in filmed driving scenes, in which participants anticipate actions such as slowing down of the vehicle speed by braking or taking action to avoid a collision with other road users (see Horswill & McKenna, 2004 for a review). A number of studies have shown that performance on laboratory-based measures of hazard perception predict crash involvement (Horswill & McKenna, 2004, McKenna & Horswill, 1999, Quimby, et al., 1986). However, there has been limited investigation of how degraded visual acuity affects reaction times to hazards in Hazard Perception Test (HPT).

It is well known that a decrease in target visibility affects response times (Breitmeyer, 1975, Plainis & Murray, 2002). This is thought to occur because the degraded visual image makes the initial levels of visual processing more cognitively difficult and reduces the higher level of cognitive resources available to process new information (Wingfield, et al., 2005). Rabbitt (1968) proposed the theory of ‘effortfulness’, where the increased effort associated with trying to encode visual information in the presence of masking noise increases the cognitive load, which in turn reduces the ability to perceive and respond to visual information. Similarly the visual information available while driving may be degraded due to refractive blur or cataracts and this may cognitively slow down a driver's reaction to hazards. Marrington, et al., (2008) measured the hazard anticipation ability of drivers using the Hazard Perception Test when viewing through filters which simulated mild and moderate levels of cataract. Moderate simulated cataract reduced the hazard detection and anticipation abilities of participants. Similarly studies of on-road driving performance with simulated blur have shown that increased levels of blur result in a greater reduction in the ability of drivers to detect and avoid hazards positioned on the roadway (Higgins & Wood, 2005, Higgins, et al., 1998, Wood, et al., 2011). However, in these closed road studies, detection ability was measured for static and large low contrast road hazards which do not represent dynamically presented hazards, such as moving vehicles, pedestrians and cyclists on the road. Importantly, the effect of blur on reaction times to such dynamically presented hazards has not been investigated.

Along with degraded vision, performing any secondary task can also slow down drivers' reactions to hazards (Horswill & McKenna, 2004). With the developments in technology and in-vehicle devices there has been increased interest in understanding the distraction caused by these devices while driving. Interacting with in-vehicle devices (secondary tasks) requires the driver to divide their attention away from the main driving task (Poysti, et al., 2005). Studies have reported that the distraction caused by interacting with any secondary task while driving can result in crash involvement (Horrey, et al., 2008, Klauer, et al., 2006, Lesch & Hancock, 2004, Strayer & Johnston, 2001). Along with visual distraction caused by adjusting a radio or dialling number on a mobile phone (Haigney & Westerman, 2001), listening to auditory information while driving also causes distraction (Horrey & Wickens, 2006). Although previous studies have noted that driving performance in the presence of auditory route information has been better compared to visually presented information (Jensen, et al., 2010, Moldenhauer & McCrickard, 2003), recent research on navigational devices noted that navigational audio instructions are also a major cause of distraction while driving (Martin, et al., 2011).

Since the time for processing the visual information increases with blur, it is of interest to study the combined effects of an auditory secondary task (similar to output from any navigational or in-vehicle device) and degraded vision on reactions to hazards. Thus, the present study aimed to investigate the effect of different levels of blur on reaction times to hazards and to investigate if the additional presence of an auditory distracter task (navigational audio instructions similar satellite navigation devise) further exacerbates the effects of blur on reaction times to hazards.

6.2 Methods

Twenty young participants who had prior driving experience and a current driving license participated in the study. The age range of the participants was between 18 to 35 years (mean age of 29.4±3.2). The participants included 11 males and 9 females and all participants were screened for vision impairment via refractive assessment and clinical examination. Refractive error was measured for each participant to provide optimally corrected distance visual acuity. Binocular visual acuity was assessed with optimal correction using a 4 m ETDRS with a chart luminance of 126 cd/m^2. The inclusion criteria were: 1) visual acuity better than 6/6 with refractive correction, 2) no eye diseases, and 3) current driving license. Informed consent was obtained from all participants and the research protocol was approved by the Queensland University of Technology, Human Research Ethics Committee (see Appendix 1).

The study was a repeated measures design and participants were tested for four visual conditions (0.00 D, +0.50 D, +1.00 D and +2.00 D). For each visual condition the reaction time for identification and response to hazards was measured in the no distracter and distracter conditions (i.e., with simulated satellite navigation audio instructions) using the Hazard Perception Test (HPT). Participants were required to view HPT video clips on a LCD touch screen monitor (30.2 cm x 22.6 cm) with screen resolution of 1024 x 768, refresh rate of 60 Hz, to identify potential hazards. The reaction time to identify the hazard in the driving scene was recorded for all four visual conditions.

6.2.1 Design of Hazard Perception Test

The Hazard Perception Test (HPT) is a video presentation of traffic scenes recorded from the driver's perspective (Horswill & McKenna, 2004). Participants are required to react to a potential hazard in the driving scene by touching the image of the hazard on a touch-screen. In the experiment a hazard was defined as *"a situation in which a collision or near collision with another road user (including stationery vehicles, cyclists, or pedestrians) would occur unless you take some type of evasive action (slowing, steering, etc.)"* (Wallis & Horswill, 2007). The primary outcome measure was the reaction time of the participant to respond to the hazard after it appeared on the screen.

The HPT in the present study comprised 80 video clips of different driving scenes with one driving event in each clip that was considered to be a hazard. For each video clip, simulated satellite navigation audio instructions were recorded (similar to audio instructions from a commercial satellite navigation device). The 80 video clips with audio instructions were divided into 40 video clips with audio instructions that were possible to follow and 40 video clips with instructions that were not possible to follow according to the driving scene. These 80 video clips were randomised into eight sets (with 10 different driving video clips in each set), which were then randomized between participants. The reaction time to hazards for each blur condition was tested twice, once without audio instructions (during which the volume of the computer was switched off) and the second time with audio instructions (the audio distracter condition).

In the no distracter condition participants simply had to identify the hazard and tap the hazard on the touch-screen monitor. In the audio distracter condition the participants were required to respond to the hazard while simultaneously listening to the navigational audio instructions. Each video clip had one or more navigational audio instructions, with at least one audio instruction synchronised with the point in time at which the hazard should become apparent to the participant. This was used to distract the participant's attention away from the hazard in the video clip. At the end of each clip in the HPT, a one second gap was allowed for the participant to respond to the navigational audio instructions and the response was recorded using a voice recorder and scored as the number of correct and incorrect responses. For example, in a driving scene in which the car is driving on a road with a possibility of a right turn 100 m ahead of the driver, the navigational instructions in the video clip would say ‘turn right 100 m ahead.... turn right 50 m ahead......turn right immediately’. The participant had to look for hazards (traffic conflicts) in the driving scene while listening to the audio instructions and simultaneously look for the right turn at the distances indicated in the audio instructions. Participants also had to respond as to whether or not they felt that it was possible to follow the satellite navigation instruction given during the during the one second gap following the presentation as ‘Yes’ or ‘No’. Participants were given instructions and a practice session was conducted with sample videos for both the no distracter and distracter conditions before the actual testing, to ensure that participants clearly understood the testing procedures.

6.2.2 Procedure

The reaction time measurements for hazard perception were tested for four visual conditions (0.00 D, +0.50 D, +1.00 D and +2.00 D), with the room lights extinguished. The wide diversity of scenes and lighting conditions presented in the hazard perception video clips meant that the luminance levels ranged from 5 to 40 cd/m^2. The total testing time for all four conditions took approximately 84 min, with the measurement time for each blur condition being approximately 21 min (14 min of blur adaptation and 7 min of testing). In all conditions, the HPT was tested for the no distracter condition first, followed by the audio distracter condition for all participants. While this lack of randomisation is a potential limitation in the study it was undertaken in order to ensure that the easier condition was presented prior to the more difficult condition.

Participants wore their optimal correction and an additional +2.00 D working distance correction for the 50 cm testing distance, plus the blur lens in a trial frame before both eyes. The 14 min adaptation time for all blur conditions before the reaction time measurements was based on the time of peak adaptation results from Experiment 1 (Chapter 4). During the 14 min adaptation period the participant watched a movie on the same monitor at a distance of 50 cm to maintain constant accommodation throughout the experiment. An adaptation period of 14 min was also used for the normal vision (no blur) condition to allow participants to adapt to the room lighting conditions and to maintain constant accommodation. The testing order of the blur conditions was not randomised, but instead tested from low to high powers. This was done to systematically control for the adaptation effect of larger blur levels, which may have affected the reaction time measurements for the other blur conditions based on the results of Experiment 1.

6.2.3 Analysis

Participants' reaction times to each hazard were recorded as the deviation from the group mean, since the hazards in each of the video clips varied and there is no objective measure to determine when a given hazard might first become apparent as a hazard to an ideal observer. The mean response time across all incidents was then added to the mean deviation scores to assist in interpretation of outcomes (Horswill, et al., 2011). A two-way repeated measure ANOVA was conducted for the effects of blur and distracter conditions on the reaction time to hazards. A separate two-way repeated measure ANOVA was also conducted for the effects of blur and distracter conditions on hazard detection ability of participants (total number of hazards correctly detected for each blur condition).

6.3 Results

There was a significant effect of blur on the reaction time to hazards ($F_{(3, 57)} = 7.912$, $p < 0.01$). The mean reaction time increased for higher levels of blur in comparison to the no blur condition. In pairwise comparisons, the increase in reaction time for +0.50 D blur was small and insignificant ($p > 0.05$) compared to the no blur condition. Both the +1.00D and +2.00D conditions differed significantly from the plano condition, and from the +0.50D condition (p< 0.05).

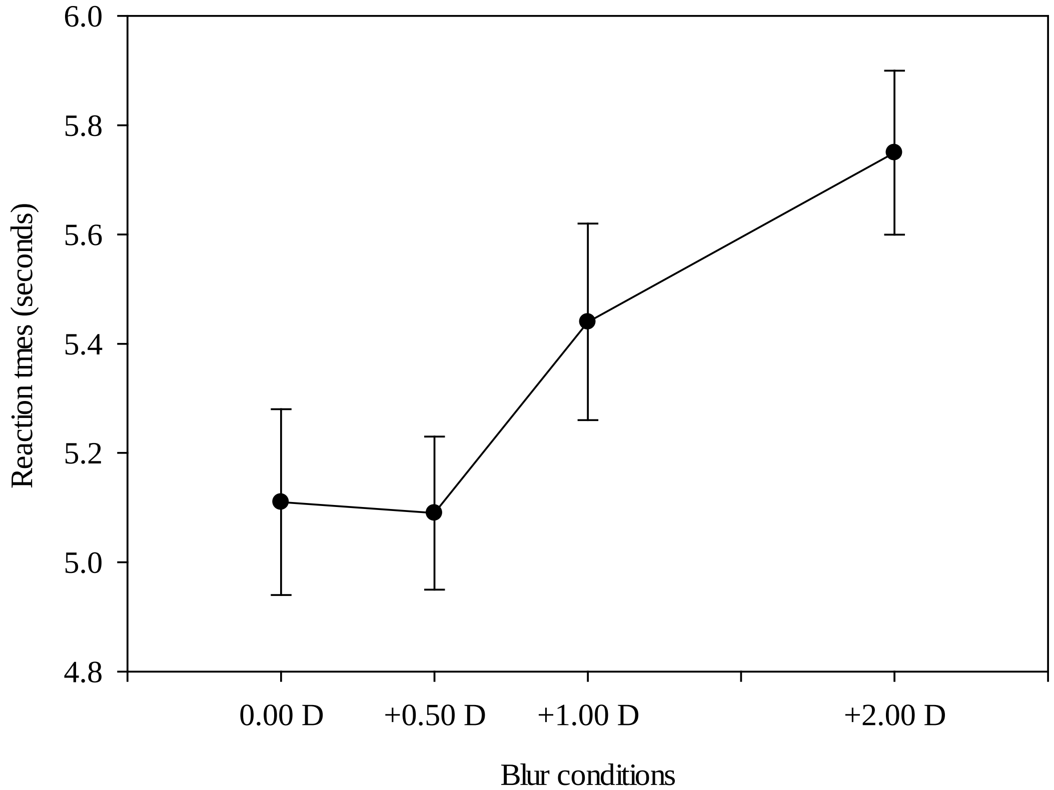

Figure 6.1. Group mean (SE) normalised reaction times as a function of blur conditions.

The two-way repeated measure ANOVA also showed a significant effect of auditory distracter condition on reaction time, such that the group mean reaction time was significantly greater for the distracter condition (5.57 ± 0.12) compared to the no distracter condition (5.35 ± 0.13) ($F_{(1, 19)}$ = 1.538, p = 0.02) (Figure 6.2). There was no significant interaction between the factors, indicating that the effect of blur levels on reaction time was of similar magnitude under both the no distracter and distracter conditions ($F_{(3, 57)}$ = 1.119, p = 0.35).

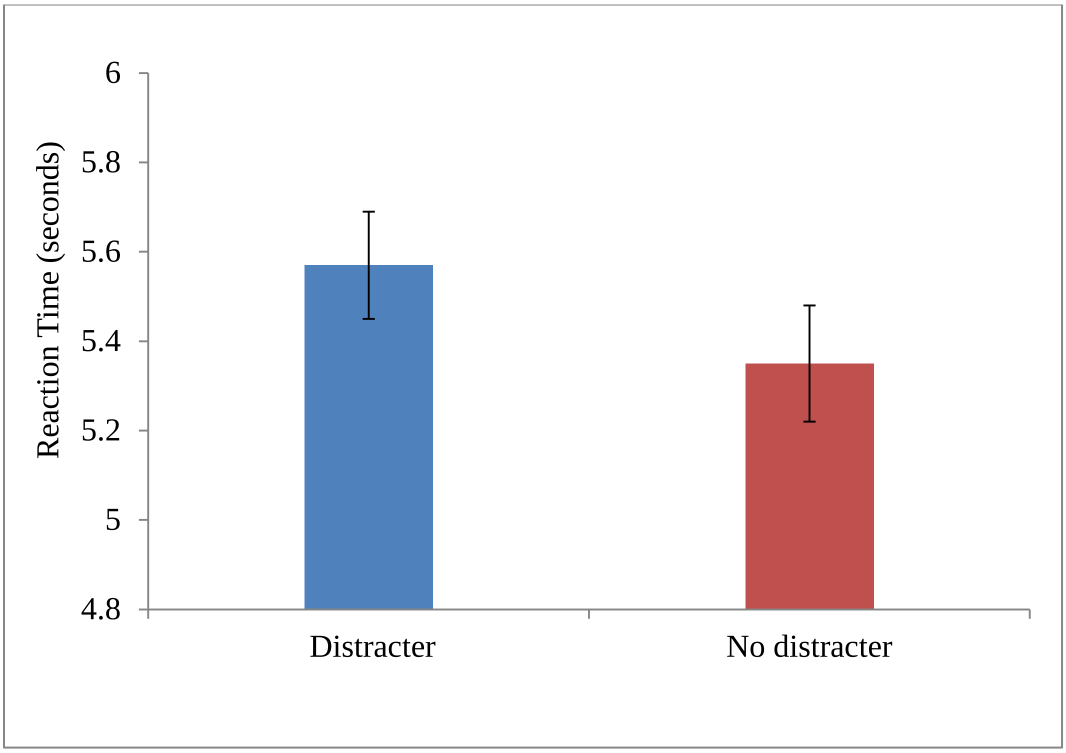

Figure 6.2. Group mean (SE) normalised reaction time as a function of distracter conditions.

With regards to the number of hazards detected in the no distracter and distracter conditions, the two-way repeated measure ANOVA showed that there was no significant effect of blur (F (3, 57) = 2.224, p = 0.09) and auditory distracters ($F_{(1, 19)}$ = 1.472, p = 0.24) on the number of hazards detected. Also there was no significant interaction between the main effects blur and auditory distracters on hazard detection ($F_{(3, 57)}$ = 1.153, p = 0.33). In each blur conditions participants were able to correctly detect over 80% of the hazards in both the no distracter and with distracter conditions as shown in Table 6.1.

	% Hazards Detected	
Visual Condition	No-Distracter	Distracter
Plano	86.5 (2.2)	86.5 (2.7)
+0.50	83.5 (2.5)	79.0 (3.4)
+1.00	81.0 (2.9)	81.5 (3.3)
+2.00	86.0 (2.2)	78.5 (3.4)

Table 6.1: Group mean (standard error) for the percentage of hazards correctly detected as a function of visual and distracter condition

6.4 Discussion

The findings of this study indicate that the reaction time to hazards increased with an increase in the level of blur and there was also a significant increase in mean reaction time in the presence of an auditory distracter task, however, there was no significant interaction between the blur and distracter factors.

Participants' reaction time for the +0.50 D blur condition was not significantly different to the baseline (no blur) however, in the +1.00 D and +2.00 D bur conditions, the participants were significantly slower in reacting to hazards compared to baseline. The decrease in visual contrast of the HPT driving scenes (test stimuli) for higher levels of blur may have resulted in slower recognition and processing of the environmental cues from the driving scene (Harley, et al., 2004, Pashler, 1984). This may have concomitantly reduced the higher level of cognitive processes available for perception of the hazard (Wingfield, et al., 2005), resulting in slower reactions to the hazards in the driving scene. The results from the study also showed that blur did not have any effect on the total number of hazards detected, suggesting that blur slowed down participants' reaction to hazards in the driving scene but their ability to accurately detect the hazard was not affected. Wood, Chaparro, Anstey, et al., (2009) also noted that even a modest decrease in visual acuity from simulated cataracts slowed performance on cognitive tests that measured processing speed, visual attention and selective attention, however, this was not accompanied by any change in cognitive test accuracy.

The mean reaction time also increased in the presence of an audio distracter (satellite navigation instructions) compared to the no distracter condition. Charlton, (2009) noted that conversing on a hands-free mobile phone significantly increased reaction time to hazards and reduced the ability to avoid road and traffic hazards in a simulator driving study. Similarly Recarte & Nunes, (2003) in an on-road driving experiment noted that the presence of a secondary task resulted in increased mental workload and late detection and slower responses to hazards in the driving environment. These findings are consistent with the proposed theory of 'effortfulness' (Rabbitt, 1968), which suggests that processing of auditory information from a secondary task, such as route information from a satellite navigation device, may result in a reduction in higher level cognitive processes, reducing the cognitive resources available for recognising and processing the visual information from the driving scene. This may explain our findings of a slower reaction time to hazards when performing the secondary auditory distracter task in the present study. While the decision to present the no-distracter condition first in all cases, followed by the distracter condition, may have influenced the results, the results cannot be simply ascribed to practice, as in general, practice will improve reaction times, rather than slow them. Nor would we believe that significant fatigue would have occurred over the time-scale considered here.

The present study showed an additive effect of blur and distracter on reaction times to hazards, however there was no significant interaction between blur and distracter conditions. Wood, Chaparro, & Hickson, (2009) measured on-road driving performance for different visual (normal, cataract and blur) and distracter (no distracter, audio and visual) conditions and noted that driving performance was worse in the visually impaired conditions and that performance was further degraded in the presence of distracters (audio and visual) for the visual impairment conditions. A potential explanation for the finding that blur did not exacerbate the effect of distracters on reaction times in this study may be due to differences in methodology between studies. The present study was conducted under controlled laboratory conditions where participants' reactions to the hazards required visual and cognitive attention, whereas in the study by Wood, Chaparro, & Hickson, (2009), the on-road driving additionally needed participants to physically engage in driving performance (controlling the steering wheel, applying accelerator and brakes) while simultaneously performing a distracter task, providing an additional cognitive load. Thus secondary tasks in real-world driving conditions may make driving performance and hazard identification more challenging than was evident in testing conducted under laboratory conditions.

6.5 Conclusion

The increase in hazard detection time with blur observed in this study underscores the importance of drivers using their optimal refractive correction while driving. Though the presence of distracters did not interact with blur, there was an additive effect of blur and the secondary distracter task, such that the mean reaction time was slower in both the presence of blur and the secondary task. This suggests that driving performance may become more challenging when there is a combination of degraded vision and a secondary task which may potentially include tasks such as conversing on a mobile phone, talking to a co-passenger and listening to the instructions from navigation devices.

Chapter 7: Conclusions

Performance of vision-related daily activities involves acquisition of visual information that is often dynamic in nature. For example, driving involves continuous acquisition of visual information such as vehicles, pedestrians, cyclists and road signs that can assist the driver to make appropriate decisions and maintain safe control of the vehicle. Optimal visual acuity enables better resolution and performance of such dynamic visual tasks; decreased visual acuity due to uncorrected refractive error may thus reduce the recognition ability of such dynamic events and impact on driving performance. Therefore the findings from the experiments in this thesis can be used to better understand the potential factors influencing the impact of blur on dynamic and briefly presented visual information, particularly while driving.

In Experiment 1 (Chapter 4) we studied the temporal dynamics of blur adaptation for different levels of blur and under photopic and mesopic testing conditions. These findings assisted us in designing the methodology for the later experiments. In Experiment 2 (Chapter 5) we investigated the effect of different levels of blur on visual acuity for short target exposures compared to untimed target presentations under photopic and mesopic illumination conditions. Finally, in Experiment 3 (Chapter 6) we studied the impact of different levels of blur and an auditory distracter task on reaction times to potential hazards in road scenes using the Hazard Perception Test.

Blur adaptation

Many individuals habitually experience small levels of blur due to uncorrected refractive errors. However, the human eye has some capacity to adapt to blur, with a small improvement in visual acuity occurring after constant exposure to blur. This phenomenon is sometimes noticed by myopic individuals who are not wearing their spectacles. In Experiment 1 (Chapter 4) we measured the time course of adaptation to different levels of blur under both photopic and mesopic illumination conditions. We found that the improvement in visual acuity reached a peak at about 14 min after introducing the blur, with no further increase in visual acuity, and that this time frame was consistent for different levels of blur and under both photopic and mesopic illumination conditions. This information was used in the design of the subsequent experiments described in Chapter 5 and Chapter 6, to ensure some control on the level of blur adaptation during these experiments.

The results also showed that the improvement in visual acuity following blur adaptation varied with the level of blur. There was greater adaptation for higher levels of blur, which may be a result of greater improvement in resolution to high spatial frequency channels at the level of visual cortex compared to improvement for lower blur levels (Mon-Williams, et al., 1998). A decrease in illumination to mesopic levels did not show a significant effect on blur adaptation compared to adaptation under photopic illumination.

Another finding was a small and significant persistence of blur adaptation up until 28 min after removing the blur. This information also assisted in designing the methodology for the later experiments, by informing the testing order of blur conditions, to minimise the carry-over effect of higher blur levels on visual performance measured for lower levels of blur. To minimise these effects, different blur levels were not randomised, but were measured from lower to higher blur levels in the experiments described in Chapter 5 and Chapter 6.

The effect of blur, illumination and presentation time

Many of the visual tasks that are performed in everyday conditions require recognition of objects that are only briefly visible. This can occur as we use eye and head movements to scan a scene, or through the movement of objects within the scene. Traditional measurements of the effects of blur on visual functions allow participants almost unlimited time to resolve targets, such as visual acuity charts. However, there is little information on the effects of blur on vision when targets are presented for only a brief period of time.

The findings from Experiment 2 (Chapter 5) showed that increasing the level of blur (0.00 D, +0.50 D, +1.00 D and +2.00 D) resulted in a greater reduction in visual acuity for both untimed and timed (100 ms) stimulus presentations under photopic illumination conditions, with the important finding being that the effect of blur on visual acuity was greater for brief stimulus presentations. As reported in previous studies, there is greater reduction in resolution ability for smaller optotypes (fine details) for briefly presented stimuli compared to stimuli presented for longer durations (Kono, et al., 1991, Niwa & Tokoro, 1997). Thus the increased effect of blur on briefly presented stimulus may be a result of the combined effect of blur and shorter stimulus exposures under photopic illumination levels. These laboratory findings can be related to on-road driving performance as visual information available while driving is often only briefly viewed. Moreover, studies measuring the effect of blur on on-road driving performance have reported that blur results in a decrement in the ability to recognise road signs and hazards, targets which may be fixated only briefly at the fovea while driving (Higgins & Wood, 2005, Higgins, et al., 1998).

A decrease in illumination to mesopic levels showed a much greater decrease in visual acuity for a briefly presented stimulus, compared to photopic illumination, which has been reported in previous studies (Baron & Westheimer, 1973, Brown & Black, 1976, Niwa & Tokoro, 1997). There was also an exacerbation of the effect of blur under mesopic illumination, such that the effect of blur on visual acuity for brief presentations was much greater than for photopic illumination, with even the +0.50 D condition resulting in a much greater decrease in visual acuity for brief presentations. The increased effect of blur under an mesopic illumination conditions may be a result of increased pupil size, leading to an increase in the retinal blur circle (Green, et al., 1980, Ogle & Schwartz, 1959) and the much greater effect of blur on brief (100 ms) presentation may be a result of the combined effect of blur and brief stimulus presentations under mesopic illumination conditions. These laboratory findings are relevant to on-road driving and consistent with the study by Wood, et al. (2011) who reported that the effects of blur on driving performance were greater at night compared to daytime conditions.

Translating these findings to real-world driving conditions suggests that there may be a greater reduction in recognition ability for briefly presented targets (such as road signs and hazards) while driving, compared to stationary targets or those that are presented for unlimited durations. The presence of even low levels of blur from uncorrected or under-corrected refractive errors (+0.50 D) may reduce ability to resolve the fine details of such briefly presented visual information while driving. This increased effect of blur on briefly presented targets while driving may further worsen with decrease in illumination lower levels (as in night-time driving). Thus the increased effect of blur on resolution of briefly presented targets may be one of the factors underlying the impact of blur on driving performance under both day and night time conditions, which has been shown to worsen under night-time driving conditions.

Importantly the findings showed that the effect of blur on resolution ability was less for targets presented for unlimited exposure durations (as typically used in measuring visual acuity using a standard letter chart) in comparison to targets presented briefly. These findings suggest that the variation in vision for small uncorrected refractive errors measured using standard visual acuity charts may not represent the impact of blur on resolution of dynamic and briefly presented events, such as in real world driving conditions. These findings suggest that in clinical settings, visual acuity assessment for brief stimulus presentations is likely to be a more sensitive test in determining the impact of refractive errors on real-world visual function.

The impact of blur on reaction time to hazards in the presence of an auditory distraction

Along with correctly resolving the details of dynamic and briefly presented visual information while driving, timely reaction to potential hazards is important for safe driving. However, in a driving situation it is common to have auditory distractions such as a radio, passenger talking or auditory route information from navigation devices. Therefore in Experiment 3 (chapter 6) we measured the impact of different levels of blur on reaction times to potential hazards using the Hazard Perception Test, both in the presence and absence of an auditory distracter. It was found that reaction times to hazards increased with increased levels of blur, except in the +0.50 D condition where the increase in reaction time was not significant compared to the no blur condition. This may be the result of higher levels of blur degrading vision, thus slowing the processing of environmental cues from the driving scene (Harley, et al., 2004, Pashler, 1984). This leads to increased mental workload by reducing the resources available to detect hazards in the driving scene (Wingfield, et al., 2005) resulting in slower reaction times.

The study also showed that presence of the auditory distracter task (satellite navigation instructions) along with the blurred vision conditions resulted in an added effect on reaction times, such that participants were slower in reacting to hazards in the distracter condition compared to the no distracter condition. Previous studies on simulator and on-road driving performance have also shown that performing a secondary task while driving resulted in increased mental workload leading to an increase in reaction time to hazards (Charlton, 2009, Recarte & Nunes, 2003). Thus the additive effects of the secondary auditory task and degraded vision on reaction times may result from increased cognitive load, leading to a reduction in the ability of the participant to adequately divide their attention between the visual task and the secondary auditory task, leading to a slower reaction to hazards in the driving scene.

A simulator driving study by Victor, et al., (2005) that measured the gaze pattern for reactions to hazards in a driving scene, reported that increased cognitive workload due to auditory distracters resulted in increased drivers concentrating on the road centre at the expense of glances at targets presented in the periphery of the road scene, resulting in tunnel vision. However, it was not possible to investigate peripheral gaze patterns and tunnel vision effects in our study, given that reaction times to hazards in our study were tested at a close working distance and hence across a relatively small area of the visual field compared to the previously reported simulator study.

Our findings suggest that a decrease in visual acuity due to uncorrected refractive errors can increase mental workload and slow down the ability of the drivers to react immediately to potential hazards on road. In our study the reaction times to hazards for lower levels of blur (+0.50 D) was not significantly different to baseline (no blur) condition. However, given that on-road driving performance involves drivers having to physically engage in driving performance (controlling steering, applying accelerator and brakes) and continuously respond to the visual information received from the road, the presence of even lower levels of blur may result in increased mental workload, affecting driving performance. The presence of auditory distractions while interacting with the in-vehicle devices (listening to radio or directional route instruction) may additionally increase mental workload and decrease the ability of the driver to respond to hazardous situations while driving.

Future research directions

The findings from Experiment 2 showed a greater effect of blur on visual acuity for brief stimulus presentation under both high and low illumination conditions, which support findings of the effect of blur on driving performance under day and night-time conditions. However, future studies should further investigate whether visual acuity measurement for brief stimulus presentations better predicts on-road driving performance, particularly, measures such as road sign recognition and hazard identification. In the current study, the effect of blur and illumination on visual acuity for brief stimulus presentation was investigated, keeping the contrast of the target unchanged. Given that a decrease in ambient illumination reduces the visual acuity and contrast sensitivity of drivers (Andre, 1996, Sturgis & Osgood, 1982), future research could also investigate these relationships for targets of different contrast levels.

In Experiment 3 (Chapter 6) the findings suggest that performing auditory distracter task in the presence of blur may result in cognitive slowing leading to slower reaction times to hazards. However, this increase in cognitive workload while performing a secondary task may result in increased concentration on the road centre and decrease the ability to detect targets in the road periphery (Victor, et al., 2005), which was not investigated in our experiment. Thus it is recommended that future studies investigate reaction time measurements on a large screen, in conjunction with the measurement of eye movements, in order to investigate the effect of blur on fixation, gaze patterns and reaction times to hazards presented in the periphery.

It is worth noting that, as with all exploratory research of this nature, there is the probability of type I errors occurring due to the number of independent analyses conducted. It was not possible with the limited samples used in all three experiments in the current study to control all statistical analyses for this increased error, as this would have reduced the power of the analyses to detect meaningful findings. Thus it is necessary that further research is undertaken to verify and further extend these analyses.

Summary

This thesis investigated the effects of blur on visual performance in conditions that reflect aspects of driving. While the loss in visual acuity with blur is here is well documented, the additional effect of briefly presented stimuli was investigated and shown to further diminish vision performance in the presence of blur, which was exacerbated with decreased illumination (such as night driving). Similarly, we investigated whether blur slowed reaction times to hazards while interacting with in-vehicle devices (such as listening to instructions from satellite navigation devices).

The findings of the effect of blur on laboratory tests from Experiment 2 and Experiment 3 were obtained following a period of adaptation to blur (which was based on the results from Experiment 1). The blur adaptation factor was an important consideration, since in real-world conditions individuals may adapt to small levels of blur as a result of inappropriate refractive corrections. Thus the findings from both Experiments 2 and 3 indicate that even after adaptation to blur, there can be a significant impact of blur on the recognition of briefly presented events and that the addition of auditory distracters can further slow down the ability to react to potential hazards.

These findings assist in understanding the factors underlying the impact of uncorrected refractive errors on driving performance. These studies also highlight the potential importance of correcting refractive errors to improve the ability of drivers to react in visually demanding situations.

Appendices

Appendix 1:

Queensland University of Technolo Brisbane Australia	PARTICIPANT INFORMATION FOR QUT RESEARCH PROJECT
The impact of blur, illumination and distracters on tests related to driving performance	

Research Team Contacts	
Professor Joanne Wood School of Optometry 31385701 j.wood@qut.edu.au	Dr Philippe Lacherez School of Optometry 3138 5713 p.lacherez@uq.edu.au
Professor Michael Collins School of Optometry 3138 5702 m.collins@qut.edu.au	Sumanth Virupaksa School of Optometry 31385708 Sumanth.virupaksa@student.qut.edu.au

Description

This project is being undertaken as part of a Master's research project undertaken by Mr. Sumanth Virupaksha, School of Optometry, QUT. The project is funded by the Queensland Masters Scholarship (QMS). The funding body will not have access to the data obtained during the project.

The purpose of this project is to investigate the effect of Blur and change in lighting condition on performance of tests that are predictive of driving performance. Participants have to perform computer based tests with four different positive powered lenses in front of the eye to blur their vision under two (bright &dim) room light conditions. It is important to test for effect of blur and change in lighting on these tests because usually driver's face problem during night. So the main purpose is to observe if the effect of amount of blur or change in lighting condition or both conditions effect performance on these tests.

The research team requests your assistance in order to collect important data to inform the research.

Participation
Your participation in this project is voluntary. If you do agree to participate, you can withdraw from participation at any time during the study without comment or penalty. Your decision to participate will in no way impact upon your current or future relationship with QUT (for example your grades). After the study has been completed, it will not be possible to withdraw your contribution, as data will be stored in a non-identified form.
Your participation will involve completing four simple computer-based tasks, and simple visual assessments (eye-charts and a screening eye examination) at QUT, and will take approximately 3 – 4 hours of your time.
Expected benefits
There are not potential benefits for the participant but this research underlying cause for reduced performance of drivers during night and also help us designing on road driving experiment which in-turn help in predicting drivers with uncorrected refractive error during licensing.
Risks
To our knowledge, there are no risks beyond normal day-to-day living associated with your participation in this project.

Confidentiality
All comments and responses are anonymous and will be treated confidentially. The names of individual persons are not required in any of the responses.

Consent to Participate
We would like to ask you to sign a written consent form (enclosed) to confirm your agreement to participate.

Questions / further information about the project
Please contact the researcher team members named above to have any questions answered or if you require further information about the project.

Concerns / complaints regarding the conduct of the project
QUT is committed to researcher integrity and the ethical conduct of research projects. However, if you do have any concerns or complaints about the ethical conduct of the project you may contact the QUT Research Ethics Unit on +61 7 3138 5123 or email ethicscontact@qut.edu.au. The Research Ethics Unit is not connected with the research project and can facilitate a resolution to your concern in an impartial manner.

Thank you for helping with this research project. Please keep this sheet for your information.

Queensland University of Technology Brisbane Australia	CONSENT FORM FOR QUT RESEARCH PROJECT

The impact of blur, illumination and distracters on tests related to driving performance

Name ____

Signature ____

Date __________ / __________ / __________

Please return this sheet to the investigator

Appendix-2:

The effect of blur and illumination on short exposure visual acuity measurements

Virupaksha, Sumanth[1]; Wood, Joanne[1]; Collins, Michael[1]; and Lacherez, Philippe[1]

[1]School of Optometry and Vision Science, Vision Improvement Domain, Institute of Health & Biomedical Innovation, Queensland University of Technology, Brisbane, QLD.

Introduction:

- It is well known that blur reduces visual acuity
- Visual acuity is usually measured using standard letter charts where the stimulus is presented for an unlimited duration under a high illumination levels
- However in the real world, objects which require recognition may be visible only briefly, under range of illumination levels
- The effects of blur and illumination on recognition of briefly presented targets is unknown

Aim:

- To assess the effects of blur and low illumination on visual acuity for brief, as well as untimed stimulus presentations

Methods:

- Twenty young, visually normal subjects (mean age 29.4 ± 3.06 years) (13 male and 7 female)
- Binocular visual acuity was measured for 0.00 D, +0.50 D, +1.00 D and +2.00 D blur conditions, in the testing order of lower to higher powers
- For each blur condition there was 14 min of adaptation to the blur, followed by measurement of visual acuity
- Visual acuity was measured using a computer generated tumbling-E target for two target presentation times (Figure 1):
  - ➢ Untimed presentation (target presented for unlimited exposure time)
  - ➢ Short presentation (target exposure of 100 ms)

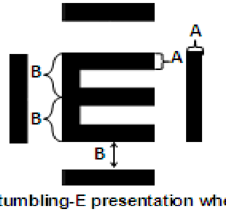

Figure 1: The tumbling-E presentation where A is the width of each limb and flanking bars and B is the distance between tumbling-E and flanking bars (half letter size).

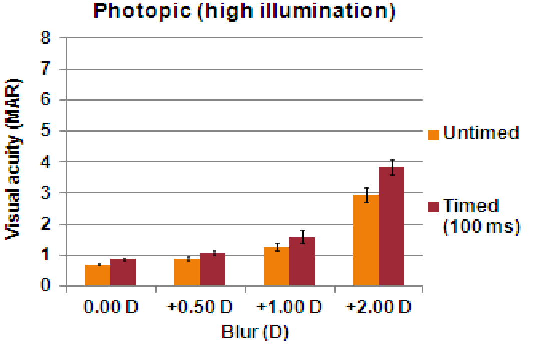

Figure 2: Visual acuity (mean ± SE) for both stimulus presentation times under photopic illumination

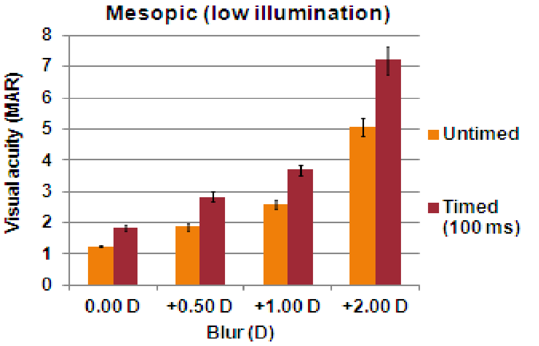

Figure 3: Visual acuity (mean ± SE) for both stimulus presentation times under mesopic illumination

- The letter 'E' was presented randomly in one of four directions. Participants were required to detect the correct orientation of the 'E' and the final estimate of visual acuity was derived using a Quest algorithm
- All measurements were performed under photopic illumination (500 lux) and mesopic illumination (1 lux) on two different days
- Statistical analysis: A three-way ANOVA was conducted for the effects of blur, illumination and target presentation times

Results:

- Visual acuity decreased significantly with increasing blur ($p<0.01$), as has been reported previously
- The effect of blur on visual acuity was greater under mesopic illumination compared to visual acuity under photopic illumination ($p<0.01$) (Figures 2 and 3)
- The effect of blur on visual acuity was also significantly different between both target presentation times ($p<0.01$), with a greater decrease for the 100 ms presentation compared to the untimed presentation (Figures 2 and 3)
- The effect of blur for the 100 ms presentation was much greater under mesopic illumination ($p<0.01$) (Figure 3)

Conclusions:

- The effect of blur on visual acuity was exacerbated for a short presentation time compared to that for an untimed presentation
- The effect of blur on visual acuity was much greater for short presentations under low illumination conditions compared to the other testing conditions

Real World Implications:

- The findings illustrate the importance of correcting even low levels of refractive error (blur) to enable better recognition of briefly presented targets, particularly under low lighting conditions. This may be important in real-world settings, such as driving at night.

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References

Adeoye, A, Oladehinde, M, Onakoya, A. Visual functions of commercial drivers in relation to road accidents in Nigeria. *Indian Journal of Occupational and Environmental Medicine*, (2007). *11*(2), 71-75.

Anderson, RS, McDowell, DR, Ennis, FA. Effect of localized defocus on detection thresholds for different sized targets in the fovea and periphery. *Acta Ophthalmologica Scandinavica,* (2001). *79*(1), 60-63.

Andre, JT. Visual functioning in challenging conditions: effects of alcohol consumption, luminance, stimulus motion, and glare on contrast sensitivity. *Journal of Experimental Psychology: Applied,* (1996). *2*(3), 250-269.

Baldock, MRJ, Mathias, J, McLean, J, Berndt, A. Visual attention as a predictor of on-road driving performance of older drivers. *Australian Journal of Psychology,* (2007). *59*(3), 159-168.

Ball, KK, Owsley, C, Sloane, ME, Roenker, DL, Bruni, JR. Visual attention problems as a predictor of vehicle crashes in older drivers. *Investigative Ophthalmology and Visual Science,* (1993). *34*(11), 3110-3123.

Barlow, HB. Temporal and spatial summation in human vision at different background intensities. *The Journal of Physiology*, (1958). *141*(2), 337-350.

Baron, WS, Westheimer, G. Visual acuity as a function of exposure duration. *Journal of the Optical Society of America A,* (1973). *63*(2), 212-219.

Breitmeyer, BG. Simple reaction time as a measure of the temporal response properties of transient and sustained channels. *Vision Research,* (1975). *15*(12), 1411-1412.

Brooks, JO, Tyrrell, RA, Frank, TA. The effects of severe visual challenges on steering performance in visually healthy young drivers. *Optometry and Vision Science,* (2005). *82*(8), 689-697.

Brown, JL, Black, JE. Critical duration for resolution of acuity targets. *Vision Research,* (1976). *16*(3), 309-315.

Buehren, T, Collins, MJ. Accommodation stimulus response function and retinal image quality. *Vision Research,* (2006). *46*(10), 1633-1645.

Burg, A. The relationship between vision test scores and driving record: additional findings (Report 68-27). *Los Angeles: Department of Engineering*, (1968).

Campbell, FW, Green, DG. Optical and retinal factors affecting visual resolution. *Journal of Physiology*, (1965). *181*(3), 576-593.

Cao, D, Lee, BB, Sun, H. Combination of rod and cone inputs in parasol ganglion cells of the magnocellular pathway. *Journal of Vision*, (2010). *10*(11).

Cao, D, Pokorny, J. Rod and cone contrast gains derived from reaction time distribution modeling. *Journal of Vision,* (2010). *10*(2).

Cao, D, Pokorny, J, Grassi, MA. Isolated mesopic rod and cone electroretinograms realized with a four-primary method. *Documenta ophthalmologica,* (2011). *123*(1), 29-41.

Charlton, SG. Driving while conversing: cell phones that distract and passengers who react. *Accident Analysis and Prevention*, (2009). *41*(1), 160-173.

Charman, WN. Effect of refractive error in visual tests with sinusoidal gratings. *British Journal of Physiological Optics,* (1979). *33*(2), 10-20.

Charman, WN. Night myopia and driving. *Ophthalmic and Physiological Optics,* (1996). *16*(6), 474-485.

Chia, EM, Mitchell, P, Ojaimi, E, Rochtchina, E, Wang, JJ. Assessment of vision-related quality of life in an older population subsample: The Blue Mountains Eye study. *Ophthalmic Epidemiology*, (2006). *13*(6), 371-377.

Coleman, AL, Yu, F, Keeler, E, Mangione, CM. Treatment of uncorrected refractive error improves vision-specific quality of life. *Journal of the American Geriatrics Society,* (2006). *54*(6), 883-890.

Cross, JM, McGwin, G, Rubin, GS, Ball, KK, West, SK, Roenker, DL, Owsley, C. Visual and medical risk factors for motor vehicle collision involvement among older drivers. *British Journal of Ophthalmology,* (2009). *93*(3), 400-404.

Cufflin, MP, Hazel, CA, Mallen, EAH. Static accommodative responses following adaptation to differential levels of blur. *Ophthalmic and Physiological Optics,* (2007). *27*(4), 353-360.

Cufflin, MP, Mankowska, A, Mallen, EAH. Effect of blur adaptation on blur sensitivity and discrimination in emmetropes and myopes. *Investigative Ophthalmology and Visual Science,* (2007). *48*(6), 2932-2939.

Dandona, R, Dandona, L. Refractive error blindness. *Bulletin-World Health Organisation,* (2001). *79*(3), 237-243.

Dandona, R, Dandona, L, Srinivas, M, Giridhar, P, McCarty, CA, Rao, GN. Population-based assessment of refractive error in India: the Andhra Pradesh eye disease study. *Clinical and Experimental Ophthalmology,* (2002a). *30*(2), 84-93.

Dandona, R, Dandona, L, Srinivas, M, Sahare, P, Narsaiah, S, Muñoz, SR, Pokharel, GP, Ellwein, LB. Refractive error in children in a rural population in India. *Investigative Ophthalmology and Visual Science,* (2002b). *43*(3), 615-622.

Davison, PA. Inter-relationships between British drivers visual abilities, age and road accident histories. *Ophthalmic and Physiological Optics*, (1985). *5*(2), 195-204.

Decina, LE, Staplin, L. Retrospective evaluation of alternative vision screening criteria for older and younger drivers. *Accident Analysis and Prevention,* (1993). *25*(3), 267-275.

Erdogan, H, Ozdemir, L, Arslan, S, Cetin, I, Sumer, H. Prevalence of refraction errors and color blindness in heavy vehicle drivers. *International Journal of Ophthalmology,* (2011). *4*(3), 319-322.

Ferris, FL, Kassoff, A, Bresnick, GH, Bailey, I. New visual acuity charts for clinical research. *American Journal of Ophthalmology,* (1982). *94*(1), 91-96.

George, S, Rosenfield, M. Blur adaptation and myopia. *Optometry and Vision Science,* (2004). *81*(7), 543-547.

Glover, S, Kelly, M, Wozniak, H, Moss, N. The effect of room illumination on visual acuity measurement. *Australian Orthoptic Journal,* (1999). *34*, 3.

Green, DG, Campbell, FW. Effect of focus on the visual response to a sinusoidally modulated spatial stimulus. *Journal of the Optical Society of America,* (1965). *55*(9), 1154-1157.

Green, DG, Powers, MK, Banks, MS. Depth of focus, eye size and visual acuity. *Vision Research,* (1980). *20*(10), 827-835.

Green, P. Customer needs, new technology, human factors, and driver science research for future automobiles. *Journal of the Society of Mechanical Engineers,* (1996).

Green, P, Hoekstra, E, Williams, M, Wen, C, George, K. Examination of a videotape-based method to evaluate the usability of route guidance and traffic information systems. *University of Michigan, Transportation Research Institute, Final Report,* (1993).

Gruber, N, Mosimann, UP, Müri, RM, Nef, T. Vision and Night Driving Abilities of Elderly Drivers. *Traffic Injury Prevention,* (2012). *14*(5), 477-485.

Guest, DJ, Jennings, JB. A survey of drivers vision in Victoria. *The Australian Journal of Optometry,* (1983). *66*(1), 13-19.

Haigney, D, Westerman, SJ. Mobile (cellular) phone use and driving: a critical review of research methodology. *Ergonomics,* (2001). *44*(2), 132-143.

Harley, E, Dillon, A, Loftus, G. Why is it difficult to see in the fog? How stimulus contrast affects visual perception and visual memory. *Psychonomic Bulletin and Review,* (2004). *11*(2), 197-231.

Hashemian, SJ, Soleimani, M, Foroutan, A, Joshaghani, M, Ghaempanah, MJ, Jafari, ME, Yaseri, M. Ocular higher-order aberrations and mesopic pupil size in individuals screened for refractive surgery. *International Journal of Ophthalmology,* (2012). *5*(2), 222.

He, Y, Bierman, A, Rea, MS. A system of mesopic photometry. *Lighting Research and Technology,* (1998). *30*(4), 175-181.

Higgins, KE, Wood, JM. Predicting components of closed road driving performance from vision tests. *Optometry and Vision Science,* (2005). *82*(8), 647-656.

Higgins, KE, Wood, JM, Tait, A. Vision and driving: selective effect of optical blur on different driving tasks. *Human Factors,* (1998). *40*, 224-232.

Hills, B, Burg, A. Reanalysis of California driver-vision data: general findings. Abridgement. *Transportation Research Record (681),* (1978). (681).

Hills, BL. Vision, visibility, and perception in driving. *Perception,* (1980). *9*(2), 183-216.

Ho, G, Scialfa, CT, Caird, JK, Graw, T. Visual search for traffic signs: the effects of clutter, luminance, and aging. *Human Factors,* (2001). *43*(2), 194-207.

Hoedemaeker, M, Neerincx, M. Attuning in-car user interfaces to the momentary cognitive load. *Foundations of Augmented Cognition*, (2007). 286-293.

Hofstetter, HW. Visual acuity and highway accidents. *Journal of American Optometric Association,* (1976). *47*(7), 887-893.

Holden, BA. Uncorrected refractive error: the major and most easily avoidable cause of vision loss. *Community Eye Health,* (2007). *20*, 37-39.

Horberry, T, Anderson, J, Regan, MA, Triggs, TJ, Brown, J. Driver distraction: the effects of concurrent in-vehicle tasks, road environment complexity and age on driving performance. *Accident Analysis and Prevention*, (2006). *38*(1), 185-191.

Horgas, AL, Wilms, H-U, Baltes, MM. Daily life in very old age: everyday activities as expression of successful living. *The Gerontologist*, (1998). *38*(5), 556-568.

Horrey, WJ, Lesch, MF, Garabet, A. Assessing the awareness of performance decrements in distracted drivers. *Accident Analysis and Prevention,* (2008). *40*(2), 675-682.

Horrey, WJ, Wickens, CD. Examining the impact of cell phone conversations on driving using meta-analytic techniques. *Human Factors,* (2006). *48*(1), 196-205.

Horswill, MS, Anstey, KJ, Hatherly, C, Wood, JM, Pachana, NA. Older drivers' insight into their hazard perception ability. *Accident Analysis and Prevention,* (2011). *43*(6), 2121-2127.

Horswill, MS, Marrington, SA, McCullough, CM, Wood, JM, Pachana, NA, McWilliam, J, Raikos, MK. The hazard perception ability of older drivers. *The Journals of Gerontology Series B,* (2008). *63*(4), 212-P218.

Horswill, MS, McKenna, FP. Drivers' hazard perception ability: situation awareness on the road. *A cognitive approach to situation awareness: theory and application,* (2004). (Banbury, S & Tremblay, S, eds.), 155-163.

Humphriss, D. Three South African studies on the relation between road accidents and drivers' vision. *Ophthalmic and Physiological Optics,* (1987). *7*(1), 73-79.

Hunt, L, Morris, JC, Edwards, D, Wilson, BS. Driving performance in persons with mild senile dementia of the Alzheimer type. *Journal of the American Geriatrics Society,* (1993). *41*(7), 747-752.

Ip, JM, Saw, S-M, Rose, KA, Morgan, IG, Kifley, A, Wang, JJ, Mitchell, P. Role of near work in myopia. Findings in a sample of Australian school children. *Investigative Ophthalmology and Visual Science,* (2008). *49*(7), 2903-2910.

Ivers, RQ, Mitchell, P, Cumming, RG. Sensory impairment and driving: the Blue Mountains Eye Study. *American Journal of Public Health,* (1999). *89*(1), 85-87.

Jaggernath, J, Naidoo, K. Uncorrected refractive errors. *Indian Journal of Ophthalmology,* (2012). *60*(5), 432-437.

Jensen, BS, Skov, MB, Thiruravichandran, N. Studying driver attention and behaviour for three configurations of GPS navigation in real traffic driving. *Proceedings of the 28th international conference on Human factors in computing systems.* Atlanta, Georgia, USA: ACM; 2010:1271-1280.

Johnson, CA, Casson, EJ. Effects of luminance, contrast, and blur on visual acuity. *Optometry and Vision Science,* (1995). *72*(12), 864-869.

Jonathan, P. PsychoPy Psychophysics software in Python. *Journal of Neuroscience Methods*, (2007). *162*(1–2), 8-13.

Kahneman, D. Temporal summation in an acuity task at different energy levels-a study of the determinants of summation. *Vision Research,* (1964). *4*(11–12), 557-566.

Kawamorita, T, Uozato, H. Changes of natural pupil size and ocular wavefront aberrations under the binocular and the monocular conditions. *Journal of Vision,* (2006). *6*(13), 54.

Keeffe, JE, Jin, CF, Weih, LM, McCarty, CA, Taylor, HR. Vision impairment and older drivers: who’s driving? *British Journal of Ophthalmology,* (2002). *86*(10), 1118-1121.

Keesey, UT. Effects of involuntary eye movements on visual acuity. *Journal of the Optical Society of America,* (1960). *50*(8), 769-773.

Klauer, SG, Dingus, TA, Neale, VL, Sudweeks, JD, Ramsey, DJ. The impact of driver inattention on near-crash/crash risk: an analysis using the 100-car naturalistic driving study data (Report No. DOT HS 810 594). *National Highway Traffic Safety Administration,* (2006).

Knight, R, Knight, E. Surface color matching under uniform vs. non-uniform mesopic light levels. *Journal of Vision,* (2009). *9*(14), 61.

Kono, M, Yamade, S, Hukami, K. Temporal integration in diseased eyes. I. Exposure duration in visual acuity testing. *Nippon Ganka Gakkai Zasshi,* (1991). *95*(2), 184.

Kontsevich, LL, Tyler, CW. Bayesian adaptive estimation of psychometric slope and threshold. *Vision Research,* (1999). *39*(16), 2729-2737.

Lamoureux, EL, Saw, SM, Thumboo, J, Wee, HL, Aung, T, Mitchell, P, Wong, TY. The impact of corrected and uncorrected refractive error on visual functioning: The Singapore Malay Eye study. *Investigative Ophthalmology and Visual Science,* (2009). *50*(6), 2614-2620.

Legge, GE, Mullen, KT, Woo, GC, Campbell, F. Tolerance to visual defocus. *Journal of Optical Society if America A,* (1987). *4*(5), 851-863.

Lesch, MF, Hancock, PA. Driving performance during concurrent cell-phone use: are drivers aware of their performance decrements? *Accident Analysis and Prevention,* (2004). *36*(3), 471-480.

Lloyd, S. Assessing fitness to drive for commercial and private vehicle drivers (medical standards for licensing and clinical management guidelines, a resource for health professionals in Australia). *Occupational Medicine,* (2012). *62*(6), 472-473.

Mankowska, A, Aziz, K, Cufflin, MP, Whitaker, D, Mallen, EAH. Effect of blur adaptation on human parafoveal vision. *Investigative Ophthalmology and Visual Science,* (2012). *53*(3), 1145-1150.

Marottoli, RA, Richardson, ED, Stowe, MH, Miller, EG, Brass, LM, Cooney, LM, Tinetti, ME. Development of a test battery to identify older drivers at risk for self-reported adverse driving events. *Journal of American Geriatrics Society,* (1998). *46*(5), 562-568.

Marrington, SA, Horswill, MS, Wood, JM. The effect of simulated cataracts on drivers' hazard perception ability. *Optometry and Vision Science,* (2008). *85*(12), 1121-1127.

Martin, L, Tomáš, M, Jan, K, Holger, Q, Christophe, C. In-car dictation and driver's distraction: a case study. *Proceedings of the 14th international conference on Human-computer interaction: towards mobile and intelligent interaction environments - Volume Part III.* Orlando, FL: Springer-Verlag; 2011:418-425.

McCloskey, LW, Koepsell, TD, Wolf, ME, Buchner, DM. Motor vehicle collision injuries and sensory impairments of older drivers. *Age and Ageing,* (1994). *23*(4), 267-273.

McEvoy, SP, Stevenson, MR, McCartt, AT, Woodward, M, Haworth, C, Palamara, P, Cercarelli, R. Role of mobile phones in motor vehicle crashes resulting in hospital attendance: a case-crossover study. *British Medical Journal,* (2005). *331*(7514), 428.

McKenna, FP, Horswill, MS. Hazard perception and its relevance for driver licensing. *International Association of Traffic and Safety Sciences research,* (1999). *23*(1), 36-41.

Moldenhauer, M, McCrickard, DS. Effect of information modality on geographic cognition in car navigation systems. *Conference on Human-Computer Interaction (INTERACT'03)* 2003.

Mon-Williams, M, Tresilian, JR, Strang, NC, Kochhar, P, Wann, JP. Improving vision: neural compensation for optical defocus. *Proceedings of the Royal Society of London Series B: Biological Sciences,* (1998). *265*(1390), 71-77.

Murthy, GVS, Gupta, SK, Ellwein, LB, Muñoz, SR, Pokharel, GP, Sanga, L, Bachani, D. Refractive error in children in an urban population in New Delhi. *Investigative Ophthalmology and Visual Science,* (2002). *43*(3), 623-631.

Nirmalan, PK, Tielsch, JM, Katz, J, Thulasiraj, RD, Krishnadas, R, Ramakrishnan, R, Robin, AL. Relationship between vision impairment and eye disease to vision-specific quality of life and function in rural India: The Aravind comprehensive eye survey. *Investigative Ophthalmology and Visual Science*, (2005). *46*(7), 2308-2312.

Niwa, K, Tokoro, T. Measurement of temporal summation of visual acuity with use of modified tachistoscope. *Japanese Journal of Ophthalmology,* (1997). *41*(6), 403-408.

Ogle, KN, Schwartz, JT. Depth of focus of the human eye. *Journal of Optical Society of America,* (1959). *49*(3), 273-279.

Owens, DA, Sivak, M. Differentiation of visibility and alcohol as contributors to twilight road fatalities. *Human Factors,* (1996). *38*(4), 680-689.

Owens, DA, Tyrrell, RA. Effects of luminance, blur, and age on nighttime visual guidance: a test of the selective degradation hypothesis. *Journal of Experimental Psychology,* (1999). *5*(2), 115.

Owens, DA, Wood, JM, Owens, JM. Effects of age and illumination on night driving: a road test. *Human Factors,* (2007). *49*(6), 1115-1131.

Owsley, C, Ball, KK, McGwin, G, Sloane, ME, Roenker, DL, White, MF, Overley, ET. Visual processing impairment and risk of motor vehicle crash among older adults. *Journal of the American Medical Association,* (1998). *279*(14), 1083-1088.

Pashler, H. Evidence against late selection: stimulus quality effects in previewed displays. *Human Perception and Performance,* (1984). *10*(3), 429-448.

Patten, CJD, Kircher, A, Ostlund, J, Nilsson, L. Using mobile telephones: cognitive workload and attention resource allocation. *Accident Analysis and Prevention,* (2004). *36*(3), 341-350.

Peli, E, Arend, L, Labianca, AT. Contrast perception across changes in luminance and spatial frequency. *Journal of the Optical Society of America*, (1996). *13*(10), 1953-1959.

Pesudovs, K. Involvement of neural adaptation in the recovery of vision after laser refractive surgery. *Journal Of Refractive Surgery,* (2005). *21*(2), 144-147.

Pesudovs, K, Brennan, NA. Decreased uncorrected vision after a period of distance fixation with spectacle wear. *Optometry and Vision Science*, (1993). *70*, 528-528.

Plainis, S, Murray, IJ. Reaction times as an index of visual conspicuity when driving at night. *Ophthalmic and Physiological Optics,* (2002). *22*(5), 409-415.

Plainis, S, Murray, IJ, Charman, WN. The Role of Retinal Adaptation in Night Driving. *Optometry & Vision Science,* (2005). *82*(8), 682-688.

Plainis, S, Murray, IJ, Pallikaris, IG. Road traffic casualties: understanding the night-time death toll. *Injury Prevention,* (2006). *12*(2), 125-138.

Plainis, S, Petratou, D, Giannakopoulou, T, Atchison, DA, Tsilimbaris, MK. Binocular summation improves performance to defocus-induced blur. *Investigative Ophthalmology and Visual Science*, (2011). *52*(5), 2784-2789.

Poysti, L, Rajalin, S, Summala, H. Factors influencing the use of cellular (mobile) phone during driving and hazards while using it. *Accident Analysis and Prevention,* (2005). *37*(1), 47-51.

Quimby, A, Maycock, G, Carter, I, Dixon, R, Wall, J. Perceptual abilities of accident involved drivers (Reasearch Report 27). *Transport and Research Laboratory.* Crowthorne, UK; 1986.

Rabbitt, PMA. Channel-capacity, intelligibility and immediate memory. *Experimental Psychology,* (1968). *20*(3), 241-248.

Rabin, J. Luminance effects on visual acuity and small letter contrast sensitivity. *Optometry and Vision Science,* (1994). *71*(11), 685-688.

Rabin, J. Optical defocus: differential effects on size and contrast letter recognition thresholds. *Investigative Ophthalmology and Visual Science,* (1994). *35*(2), 646-648.

Radhakrishnan, H, Pardhan, S, Calver, RI, O'leary, DJ. Unequal reduction in visual acuity with positive and negative defocusing lenses in myopes. *Optometry and Vision Science*, (2004). *81*(1), 14-17.

Rahi, JS, Peckham, CS, Cumberland, PM. Visual impairment due to undiagnosed refractive error in working age adults in Britain. *British Journal of Ophthalmology,* (2008). *92*(9), 1190-1194.

Rajeev, N, Metha, A. Enhanced contrast sensitivity confirms active compensation in blur adaptation. *Investigative Ophthalmology and Visual Science,* (2010). *51*(2), 1242-1246.

Raju, P, Ramesh, SV, Arvind, H, George, R, Baskaran, M, Paul, PG, Kumaramanickavel, G, McCarty, C, Vijaya, L. Prevalence of refractive errors in a rural south Indian population. *Investigative Ophthalmology and Visual Science,* (2004). *45*(12), 4268-4272.

Recarte, MA, Nunes, LM. Mental workload while driving: effects on visual search, discrimination, and decision making. *Journal of Experimental Psychology: Applied,* (2003). *9*(2), 119-137.

Redelmeier, DA, Tibshirani, RJ. Association between cellular-telephone calls and motor vehicle collisions. *New England Journal of Medicine,* (1997). *336*(7), 453-458.

Resnikoff, S, Pascolini, D, Mariotti, SP, Pokharel, GP. Global magnitude of visual impairment caused by uncorrected refractive errors in 2004. *Bulletin of the World Health Organization,* (2008). *86*(1), 63-70.

Rice, TM, Peek-Asa, C, Kraus, JF. Nighttime driving, passenger transport, and injury crash rates of young drivers. *Injury Prevention,* (2003). *9*(3), 245-250.

Richardson, ED, Marottoli, RA. Visual attention and driving behaviors among community-living older persons. *Journals of Biological and Medical Sciences Series A,* (2003). *58*(9), M832-M836.

Roinishvili, M, Chkonia, E, Stroux, A, Brand, A, Herzog, MH. Combining vernier acuity and visual backward masking as a sensitive test for visual temporal deficits in aging research. *Vision Research,* (2011). *51*(4), 417-423.

Rosenfield, M, Hong, SE, George, S. Blur adaptation in myopes. *Optometry and Vision Science,* (2004). *81*(9), 657-662.

Rosenfield, M, Portello, JK, Hong, SE, Ren, L, Ciuffreda, KJ. Decay of blur adaptation. *Investigative Ophthalmology and Visual Science,* (2003). *44*(5), 4315-.

Rubin, GS, Ng, ESW, Bandeen-Roche, K, Keyl, PM, Freeman, EE, West, SK, Team, tSP. A prospective, population-based study of the role of visual impairment in motor vehicle crashes among older drivers: The SEE Study. *Investigative Ophthalmology and Visual Science,* (2007). *48*(4), 1483-1491.

Sagberg, F. Driver health and crash involvement: A case-control study. *Accident Analysis and Prevention,* (2006). *38*(1), 28-34.

Saunders, RM. The critical duration of temporal summation in the human central fovea. *Vision Research,* (1975). *15*(6), 699-703.

Saw, SM, Foster, PJ, Gazzard, G, Friedman, D, Hee, J, Seah, S. Undercorrected refractive error in Singaporean Chinese adults: The Tanjong Pagar survey. *Ophthalmology,* (2004). *111*(12), 2168-2174.

Saw, SM, Gazzard, G, Koh, D, Farook, M, Widjaja, D, Lee, J, Tan, DTH. Prevalence rates of refractive errors in Sumatra, Indonesia. *Investigative Ophthalmology and Visual Science*, (2002). *43*(10), 3174-3180.

Schieber, F. Highway research to enhance safety and mobility of older road users. *Transportation in an Aging Society,* (2004). 125.

Schmidt, PP. Sensitivity of random dot stereoacuity and snellen acuity to optical blur. *Optometry and Vision Science,* (1994). *71*(7), 466-473.

Schneider, N, von Campenhausen, C. Color and lightness constancy in different perceptual tasks. *Biological Cybernetics,* (1998). *79*(6), 445-455.

Seet, B, Wong, TY, Tan, DTH, Saw, SM, Balakrishnan, V, Lee, LKH, Lim, ASM. Myopia in Singapore: taking a public health approach. *British Journal of Ophthalmology,* (2001). *85*(5), 521-526.

Shah, N, Laidlaw, DAH, Brown, G, Robson, C. Effect of letter separation on computerised visual acuity measurements: comparison with the gold standard Early Treatment Diabetic Retinopathy Study (ETDRS) chart. *Ophthalmic and Physiological Optics,* (2010). *30*(2), 200-203.

Shimizu, N, Nomura, H, Ando, F, Niino, N, Miyake, Y, Shimokata, H. Refractive errors and factors associated with myopia in an adult Japanese population. *Japanese Journal of Ophthalmology,* (2003). *47*(1), 6-12.

Shin, J, Yaguchi, H, Shioiri, S. Change of color appearance in photopic, mesopic and scotopic vision. *Optical Review,* (2004). *11*(4), 265-271.

Shrestha, S, Bhat, K, Binu, V, Barthakur, R, Natarajan, M, Subba, S. Pattern of refractive errors among the Nepalese population: a retrospective study. *Nepalese Journal of Ophthalmology,* (2010). *2*(2), 87-96.

Simpson, TL, Barbeito, R, Bedell, HE. The effect of optical blur on visual acuity for targets of different luminances. *Ophthalmic and Physiological Optics,* (1986). *6*(3), 279-281.

Sloane, ME, Owsley, C, Alvarez, SL. Aging, senile miosis and spatial contrast sensitivity at low luminance. *Vision Research,* (1988). *28*(11), 1235-1246.

Smith, EL. Environmentally induced refractive errors in animals. *In M Rosenfeld & B Gilmartin (Eds), Myopia and nearwork,* (1998). 57-90.

Smith, G. Relationship between spherical refractive error and visual acuity. *Optometry and Vision Science,* (1991). *68*(8), 591-598.

Smith, G. Visual acuity and refractive error is there a mathematical calculation? *Optometry Today,* (1996). 22-27.

Smith, G, Jacobes, R, Chan, C. Effect of defocus on visual acuity as measured by source and observer methods. *Optometry and Vision Science,* (1989). *66*(7), 431-435.

Smith, T, Frick, K, Holden, B, Fricke, T, Naidoo, K. Potential lost productivity resulting from the global burden of uncorrected refractive error. *Bulletin of the World Health Organization,* (2009). *87,* 431-437.

Stockman, A, Sharpe, LT. Into the twilight zone: the complexities of mesopic vision and luminous efficiency. *Ophthalmic and Physiological Optics,* (2006). *26*(3), 225-239.

Strayer, DL, Johnston, WA. Driven to distraction: dual-task studies of simulated driving and conversing on a cellular telephone. *Psychological Science,* (2001). *12*(6), 462-466.

Sturgis, SP, Osgood, DJ. Effects of glare and background luminance on visual acuity and contrast sensitivity: implications for driver night vision testing. *Human Factors,* (1982). *24*(3), 347-360.

Sullivan, JM, Flannagan, MJ. The role of ambient light level in fatal crashes: inferences from daylight saving time transitions. *Accident Analysis and Prevention,* (2002). *34*(4), 487-498.

Tabernero, J, Atchison, DA, Markwell, EL. Aberrations and pupil location under corneal topography and Hartmann-Shack illumination conditions. *Investigative Ophthalmology and Visual Science,* (2009). *50*(4), 1964-1970.

Thiagalingam, S, Cumming, RG, Mitchell, P. Factors associated with undercorrected refractive errors in an older population: the Blue Mountains Eye Study. *British Journal of Ophthalmology,* (2002). *86*(9), 1041-1045.

Tucker, J, Charman, W. Depth of focus and accommodation for sinusoidal gratings as a function of luminance. *American Journal of Optometry and Physiological Optics,* (1986). *63*, 58-70.

Uvijls, A, Baets, R, Leroy, B, Kestelyn, P. Mesopic visual acuity requirements for driving licences in the European union-research report. *Bulletin of the Belgian Society of Ophthalmology,* (2001). *282,* 71-77.

van Rijn, LJ, Nischler, C, Michael, R, Heine, C, Coeckelbergh, T, Wilhelm, H, Grabner, G, Barraquer, RI, van den Berg, TJTP. Prevalence of impairment of visual function in European drivers. *Acta Ophthalmologica,* (2011). *89*(2), 124-131.

Victor, T, Harbluk, J, Engström, J. Sensitivity of eye-movement measures to in-vehicle task difficulty. *Transportation Research Part F: Traffic Psychology and Behaviour,* (2005). *8*(2), 167-190.

Viikari, M, Ekrias, A, Eloholma, M, Halonen, L. Modeling spectral sensitivity at low light levels based on mesopic visual performance. *Clinical ophthalmology,* (2008). *2*(1), 173.

Vision2020. The right to sight: global initiative for prevention of avoidable blindness; action plan- 2006-2011. *Bulletin,* (2011).

Vitale, S, Ellwein, L, Cotch, M, Ferris, FLIII, Sperduto, R. Prevalence of refractive error in the United States, 1999-2004. *Archives of Ophthalmology,* (2008). *126*(8), 1111-1119.

Walkey, H, Orreveteläinen, P, Barbur, J, Halonen, L, Goodman, T, Alferdinck, J, Freiding, A, Szalmás, A. Mesopic visual efficiency II: reaction time experiments. *Lighting Research and Technology,* (2007). *39*(4), 335-354.

Wallis, TSA, Horswill, MS. Using fuzzy signal detection theory to determine why experienced and trained drivers respond faster than novices in a hazard perception test. *Accident Analysis and Prevention,* (2007). *39*(6), 1177-1185.

Wang, B, Ciuffreda, KJ. Depth-of-focus of the human eye in the near retinal periphery. *Vision Research,* (2004). *44*(11), 1115.

Wang, B, Ciuffreda, KJ. Foveal blur discrimination of the human eye. *Ophthalmic and Physiological Optics,* (2005). *25*(1), 45-51.

Watson, A, Pelli, D. Quest: A Bayesian adaptive psychometric method. *Attention, Perception and Psychophysics,* (1983). *33*(2), 113-120.

West Sk, Rubin GS, Broman A, Munoz B, Bandeen-Roche K, Turano K. How does visual impairment affect performance on tasks of everyday life?: The SEE project. *Archives of Ophthalmology,* (2002). *120*(6), 774-780.

Wingfield, A, Tun, PA, McCoy, SL. Hearing loss in older adulthood: what it is and how it interacts with cognitive performance. *Current Directions in Psychological Science,* (2005). *14*(3), 144-148.

Wolffsohn, JS, McBrien, NA, Edgar, GK, Stout, T. The influence of cognition and age on accommodation, detection rate and response times when using a car head-up display (HUD). *Ophthalmic and Physiological Optics,* (1998). *18*(3), 243-253.

Wood, JM, Chaparro, A, Anstey, KJ, Hsing, YE, Johnsson, AK, Morse, AL, Wainwright, SE. Impact of simulated visual impairment on the cognitive test performance of young adults. *British Journal of Psychology,* (2009). *100*(3), 593-602.

Wood, JM, Chaparro, A, Carberry, T, Chu, BS. Effect of simulated visual impairment on night-time driving performance. *Optometry and Vision Science,* (2010). *87*(6), 379-386.

Wood, JM, Chaparro, A, Hickson, L. Interaction between visual status, driver age and distracters on daytime driving performance. *Vision Research,* (2009). *49*(17), 2225-2231.

Wood, JM, Collins, M, Chaparro, A, Marszalek, R, Carberry, T, Lacherez, P, Chu, BS. Refractive blur reduces both day and night-time driving performance and alters driver gaze patterns. *Investigative Ophthalmology and Visual Science,* (2011). *52*(6), ARVO E-Abstract 2813.

Wood, JM, Owens, DA. Standard measures of visual acuity do not predict drivers' recognition performance under day or night conditions. *Optometry and Vision Science,* (2005). *82*(8), 698-705.

Wu, H-M, Seet, B, Yap, EP-H, Saw, S-M, Lim, T-H, Chia, Kee-Seng. Does education explain ethnic differences in myopia prevalence? A population-based study of young adult males in Singapore. *Optometry and Vision Science,* (2001). *78*(4), 234-239.

Zele, AJ, Maynard, ML, Feigl, B. Rod and cone pathway signaling and interaction under mesopic illumination. *Journal of Vision,* (2013). *13*(1).