The Hong Kong Polytechnic University

School of Optometry

The effects of age and glare on driving

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A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

Jan 2011

<u>Certificate of Originality</u>

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TANG Yiu-bong

Abstract of thesis entitled 'The effects of age and glare on driving' submitted by Tang Yiu-bong for the degree of Doctor of Philosophy at The Hong Kong Polytechnic University in January 2011.

Purpose

This study aimed to characterise the visual experience and visual competence of commercial drivers. The effects of age and glare on contrast sensitivity, useful field of view and driving performance were evaluated.

Methods

In Experiment I, a cross-sectional study was carried out in Hong Kong for collecting the visual experience and studying the visual competence of current commercial drivers by conducting a personal interview and a vision assessment. In Experiments II to IV, three different groups of subjects were recruited from the Optometry Clinic, The Hong Kong Polytechnic University and were divided equally into two age groups, the younger group (20-29 years) and the older group (50-59 years). All subjects had visual acuity of 6/6 or better, were free from ocular structure abnormalities and any history of ocular injury and surgery. In Experiment II, they were investigated for the effect of glare on central and peripheral contrast sensitivity. In Experiment III, they were investigated for the effect of glare on the useful field of view. Different glare eccentricities were tested on contrast sensitivity and useful field of view. In Experiment IV, the driving

performance of the subjects in the presence of glare was studied using a self-built driving simulator. The effects of age and its interaction with glare were also investigated.

Results

In Experiment I, the awareness of regular eye checks among Hong Kong commercial drivers was found to be low. Tiredness, dry eye, glare intolerance, inadequate road lighting and crowded road signage were the most commonly encountered visual symptoms / difficulties reported by the commercial drivers at work. In Experiment II, peripheral contrast sensitivity was found to deteriorate in the presence of glare but the age was a factor only for central contrast sensitivity, with the older group showing worse contrast sensitivity (younger group: 1.44±0.18; older group: 1.27±0.24).

In Experiment III, ageing did not affect the central processing speed in the useful field of view test. Both younger and older subjects had reduced ability to process the information in the divided attention subtest. There was also a selective deterioration of performance when the glare sources were closer to the peripheral task (Younger group: Control: 17.97±3.79 msec, Glare sources at 7.5°: 21.93±7.20 msec; Older group: Control: 31.00±19.99 msec, Glare sources at 7.5°: 59.50±43.97 msec). In the tests of selective attention where visual distracters were presented, the younger subjects demonstrated an improved useful field of view in the presence of glare at different eccentricities (Control: 81.90±32.41 msec; Glare sources at 2.5°: 54.97±40.61 msec; Glare sources at 5.0°: 50.00±35.05 msec; Glare sources at 7.5°: 50.07±17.79 msec), but this effect was not apparent in the older subjects except the glare sources at 2.5° (Control: 159.03±54.44 msec; Glare sources at 2.5°: 129.63±58.53 msec; Glare sources at 5.0°: 135.73±53.65 msec; Glare sources at 7.5°: 152.45±48.69 msec). Younger subjects had better performance than older subjects in both the divided attention and selective attention subtests of the useful field of view.

In Experiment IV, different strategies (e.g. lower mean speed, lower mean speed before the road sign, decrease variation of lateral offset and longer completion time) in driving for compensating the glare condition were found in both older and younger drivers. Moreover, glare had significant influence on the reaction time of both older and younger drivers.

Conclusion

Glare is a visual disturbance in driving causing a deterioration of contrast sensitivity and useful field of view, especially in middle-aged / elderly drivers. Compensatory strategies in driving are adopted by drivers to cope with this adverse condition while the critical effect of glare cannot be omitted from those younger drivers.

Key words: **ageing, contrast sensitivity, driving, glare, driving simulator,**

useful field of view

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Chapter 1 Introduction

In modern society, motor vehicles are commonly employed transportation tools which move large quantities of humans and goods daily. The operations of motor vehicles serve an important role in this daily activity. Driving is a complex task which involves perception, cognition and action. It is an active process through which information is selected and transformed. Information is primarily received through vision and hearing. Perceived information is then processed by the brain for making proper decisions and executing subsequent actions to control the speed and direction of the vehicle and directing the gaze to the necessary areas - a process similar to a dynamic loop. Drivers have to make numerous decisions by interpreting the information and thus predict how a situation may evolve. Continuous adjustments are made in responding to the ever-changing perceptions in a timely manner. If there are any adverse conditions, such as bad weather, poor lighting, fatigue, distraction, alcohol consumption, certain medications and diseases which impair perception, cognition or motor functions, there may be interference with this loop and driving performance compromised; this poses a potential threat to the driver and other road users.

If a driver cannot cope with the adverse conditions, the consequence is inherently more hazardous than with other daily activities. Traffic accidents involving motor vehicles often result in unnecessary injury, death, property loss and traffic congestion. It has been summarized that inappropriate or excessive speed, alcohol consumption, medication and recreational drugs, fatigue, young male driver, vulnerable road user, travelling in darkness, vehicle and road design defects, inadequate visibility due to environmental factors and poor road user's eyesight are risk factors for crash involvement (Peden et al 2004).

Road accidents involving human casualties happen literally in all land transport systems. Injuries from road crashes cause substantial injury and mortality. The associated damage causes significant negative impacts on the economy. For example, road traffic collisions are the leading cause of injury-related death (Krug et al 2000). More than one million people die and over 20 million people worldwide are injured in motor vehicle accidents annually (Nantulya et al 2002). The economic cost of traffic accidents was estimated at about US$ 29,000 million for the United Kingdom in 1998 (Department of Environment Transport and the Regions 1999). In 2000, road traffic injuries medically cost US$ 32.6 billion and the total cost of motor vehicle crashes was over US$ 230 billion in the United States (Blincoe et al 2002). The annual damage associated with road accidents has been estimated to be around 2% of the gross national product in highly-motorised countries, such as Australia, Germany, Japan and the United Kingdom (Jacobs et al 2000). Road safety is thus a crucial global public health and economical issue. There is a need to reduce the financial cost of road accidents. A good understanding of driving performance becomes the appropriate first step to achieve this goal.

The vehicle, road and human factors are the most important issues involved in driving. Since a tremendous amount of information is received by our visual system, it is regarded as the dominant and critical sense in driving-related functions. Being an optometrist, I am particularly interested in the relationship between visual efficiency and driving performance. However, the visual system may be impaired by disease, ageing and external factors, such as glare, poor contrast, etc. To investigate if visual competence could lead to good driving performance, it is essential to consider the visual demands of the driving task. I will review the literature published recently on driving-related visual and non-visual studies in the following chapter. This review helps to identify the gaps in our knowledge relating to vision and driving.

Chapter 2 Literature review

2.1 Visual factors affecting driving

Vision contributes to about 90% of the sensory input in driving-related activities (Booher 1978, Hills 1980, Taylor 1982, Taylor 1987). It is believed that visual information is critical to driving. A number of visual parameters have been proposed to affect driving effectiveness. The question arises as to how these parameters affect driving performance.

2.1.1 Visual acuity

Visual acuity is a measure of the smallest stroke size of a high contrast optotype that can be seen and recognized. It is the most commonly assessed visual function in optometric practice and it has been widely adopted as a visual assessment in applications for a driving licence. Adequate vision enables a driver to discern details on the road. It is especially important to read signs at a distance. Poor visual acuity is believed to be associated with increased risk of road crashes. Visual acuity has been associated independently with nearly every driving task. It has been strongly associated with general driving tasks, such as driving at night and right / left hand turns (McGwin et al 2000). Previous studies have shown a consistent relationship between visual acuity and accident rates despite a low correlation coefficient value (<0.1) (Burg 1967a, Hills and Burg 1977). In a large epidemiological study, they showed that drivers with worse visual acuity had an increased risk of self-reported crashes (Ivers et al 1999) and Hofstetter (1976) reached similar conclusions. Another study also found an association of crash rates with both monocular and binocular visual acuity (Davison 1985). However, very large sample sizes were used in these studies, causing even the smallest effects to yield significant outcomes. However, some studies have shown no correlation between crash risk and poor visual acuity (Sims et al 2000, Owsley et al 2001). Gresset and Meyer (1994) found that drivers aged 70 years with poor static acuity had the same crash risk as 70 year old drivers with better visual acuity, provided that their stereoacuity was better than 200 seconds of arc. A recent large scale study also concluded that visual acuity could not predict motor vehicle crashes in a prospective study (Margolis et al 2002). Previous studies showed that aspects of driving performance, such as the ability to recognize signs and self-reported driving proficiency, was not seriously impaired even with reduced vision (Buyck et al 1988, Fonda 1989). With the consideration of both the stopping distance and the road sign size, it was suggested that even legally blind persons may be safe to drive (Fonda 1989). As visual acuity is only a small part of the whole visual function, having a good vision is not as important as expected in driving and it is not a good predictor of road accidents.

It has been found that older drivers with visual impairments, such as cataract, still satisfied the visual acuity requirements for driving (Wood and Mallon 2001). However, as visual acuity targets are relatively small and each stroke of a 6/15 letter only subtends 0.04° and whole letter subtends 0.2°, the reduced visual acuities measured under normal and non-glare conditions from cataract drivers only reflect increases in small-angle light scatter, and cannot reflect the wide-angle light scatter in cataract patients. This reinforces the view that the visual acuity test does not always provide a complete assessment of functional vision (Elliott 1993). Drivers with significant visual impairment due to the depression of peripheral sensitivity or overall decrease of contrast sensitivity and increase in glare sensitivity can also pass the driving test (Wood and Troutbeck 1995). Thus, it is now believed that visual acuity is only weakly associated with crash involvement and unsafe driving performance (Owsley and McGwin 1999) because it can only partially assess the driver's visual abilities. Apparently, other visual functions are contributing to driving performance and they have been ignored in the current driving related assessment. These functions should be identified and incorporated in the assessment system.

2.1.2 Contrast sensitivity

Contrast sensitivity measures performance in recognizing objects with different luminance contrast levels, which is better able to reflect the real visual environment as compared to the high-contrast static visual acuity test.

Clinically, it can be measured using Pelli-Robson chart (Pelli et al 1988) and Vistech test (Ginsburg 1984). It has been suggested that binocular contrast sensitivity measurements are more closely correlated with perceived visual disability than with any visual acuity measurement or monocular contrast sensitivity scores (Elliott et al 1990). Furthermore, contrast sensitivity at lower spatial frequencies has been shown to be a better indicator than visual acuity measurements of the visibility of “real world” targets such as people’s faces (Elliott et al 1990). In driving, decreased contrast sensitivity can cause difficulties in seeing the landscape or pedestrians and cyclists on the road in poor conditions, e.g. in darkness, fog and rain. Impaired contrast sensitivity has been significantly associated with difficulty in making turns, driving on high-traffic roads during rush hours and parallel parking (McGwin et al 2000). Driving performance under the effect of various simulated visual impairments was also found to be correlated with Pelli-Robson contrast sensitivity results (Wood and Troutbeck 1995). Similarly, Rubin and his co-workers (1994) reported a good correlation between Pelli-Robson contrast sensitivity of older drivers and self-reported difficulties in both daytime and night driving. Pelli-Robson contrast sensitivity of 1.25 or less was the only variable crudely associated with crash involvement. Older drivers with a history of crash involvement were almost 6 times more likely to have serious contrast sensitivity impairment in both eyes compared with those who were crash-free and it was further found that contrast impairment present in one eye was sufficient to elevate the collision risk (Owsley et al 2001). It follows that serious contrast impairment (with score less than 1.25) in one or both eyes (commonly found in cataract patients with normal visual acuity) is a threat to road safety. Thus, more studies on contrast sensitivity are anticipated in the future to evaluate the roles of visual competence in driving difficulties and crash risk.

2.1.3 Visual field

Visual field is known as the limiting extent of vision. It provides a large amount of visual input in a driving condition. In early studies, no relationship between visual field and accident rates was found (Burg 1967b, Council and Allen 1974). Nevertheless, drivers with binocular field loss have been found to have accident rates twice as high as age- and sex-matched drivers with normal visual fields. The screening of 20,000 eyes showed the incidence of visual field loss was 3.0 to 3.5% for persons aged 16-60 years but there was an increase up to 13.0% for drivers older than 65 years. Nearly half of the drivers with abnormal visual field loss were unaware of the peripheral vision problems (Johnson and Keltner 1983). Field defective drivers may compensate for the problem by head turning and restricting their driving to manageable conditions (North 1985). However, it has been reported that visual field loss in one eye does not affect crash and conviction rates (Johnson and Keltner 1983). Since the critical size of functional visual field in driving operations is smaller than the normal binocular field, the static limits of visual field testing can only provide circumstantial information. Given that the visual field decreases with age, it is still worthwhile to test the peripheral visual function of older drivers which may provide an insight to the causes of traffic accidents.

2.1.4 Useful field of view

Useful field of view (UFOV) is a computer generated test related to driving. It is a measure of peripheral functional vision under conditions of cognitive load, showing where information can be located and extracted. Its extent is smaller than the static peripheral visual field (Ball and Owsley 1993).

Useful field of view is measured when the central and peripheral tasks are performed simultaneously. The assessment tests three variables: the drivers' reaction time (i.e. speed of processing), the drivers' ability to divide their attention between central and peripheral tasks successfully (i.e. divided attention) and their ability to localize the peripheral target when it is masked by distracters (i.e. selective attention) (Owsley 1994). Both target / distracter similarity and stimulus duration are related to the size of this field. Given a constant stimulus duration, more conspicuous targets can be detected at further eccentricities while given a constant level of conspicuity, targets with a longer presentation duration can be attended at further eccentricities. Stimulus duration is commonly measured in milliseconds (msec) to quantify the useful field of view with fixed eccentricity of targets. The test is believed to provide a better functional correlation with the real world performance than other clinical tests (Ball et al 1990). The useful field of view requires higher-order processing skills which are most likely related to the driving problems experienced by older drivers (Avolio et al 1985). Older drivers with visual sensory impairment, cognitive impairment and visual attention deficits should give a test result indicating a constriction of the useful field of view (Owsley 1994). Greater risk of crashes was found for those with impaired useful field of view, such as inadequate ability to divide attention between central and peripheral tasks. The useful field of view assessment has been suggested to have greater sensitivity (89%) and specificity (81%) than those of visual acuity, contrast sensitivity, glare sensitivity, colour vision, visual fields, stereopsis and mental status in identifying the older drivers at risk for crashes (Ball et al 1993). Other studies also supported the finding that useful field of view and accident rates were consistently correlated (Owsley et al 1991, Brabyn et al 1994). In a previous study, subjects with 40% or more reduced useful field of view were about twice as likely to be involved in a crash compared with the control group (Owsley et al 1998a). It was also claimed that useful field of view may be increased by training (Ball et al 1988), but no study has shown a reduction in accident rate after this improvement. Overall, the literature suggests that useful field of view offers additional information on visual input and driving performance. More knowledge is expected to enhance the understanding of visual function and driving in the aged population.

2.1.5 Colour vision

Colour vision measures a person's ability in distinguishing between colours. Colour vision is hypothesized to affect driving performance because traffic signals and road signs are frequently colour coded. An early study found no relationship between colour vision deficiency and increased accident rates (Norman 1960). However, protans have been reported to have significantly more rear-end collisions than either normal subjects or deutans (Vingrys and Cole 1988). The conflicting results may be attributed to different entities employed for assessing the driving performance between subjects with normal and defective colour vision.

2.1.6 Glare

Glare can be classified into two types – discomfort and disability glares. Discomfort glare refers to the subjective perception of annoyance and discomfort without the impairment of vision. Disability glare, on the other hand, reduces visual acuity and contrast sensitivity. Glare disability test is the measurement of the contrast sensitivity or visual acuity deterioration in the presence of a glare source. A low contrast disability glare measurement provides a more sensitive result than high contrast charts as the low contrast disability glare measurement has a good reliability and discriminative ability (Elliott and Bullimore 1993). Increased age and decreased visual acuity account for little of the glare disability and glare disability is less dependent on the neural system as it measures the difference of visual acuity and contrast sensitivity rather than the exact value of visual acuity or contrast sensitivity. So it is more closely reflecting the level of intraocular light scatter (Adamsons et al 1992). This shows that glare disability measurement has an advantage over either measuring visual acuity or contrast sensitivity.

Although Owsley and colleagues (2001) revealed no association between glare and crash records, older drivers often complained about night driving difficulties (Owsley 1994) and often restricted night-time driving (Ball and Owsley 1991). Probably the glare sources of oncoming vehicle headlights make it very difficult for the drivers to see at night and under twilight conditions (Owsley 1994). Driving ability is thus compromised in object detection, direction control, reading of signs and critical decision making. The effect of glare on driving performance will provide useful information in understanding vision-related driving competencies.

2.1.7 Dynamic visual acuity

The ability to resolve details of a moving target is known as dynamic visual acuity. It is a test which assesses both the spatial and temporal visual abilities. It has been suggested that dynamic visual acuity done at low luminance would provide a test of visual ability related to night driving (Anderson and Holliday 1995). A higher correlation was found between dynamic visual acuity and crash rates compared with other visual functions (Burg 1967b, Henderson and Burg 1973, Shinar et al 1975). However, it has not been adopted as a vision requirement for driving because there is no standard measuring technique and no well-established normal values (Wood 2002b). Moreover, the dynamic visual acuity test is a test with poor reproducibility (Hills 1980) and the correlation with driving performance is still too weak for the prediction of a person's ability to drive safely with reasonable confidence (Charman 1997). Given the inherent test limitation of dynamic visual acuity, the test has not been considered useful by the clinical community.

2.1.8 Binocular vision

Early studies have shown higher accident rates in the drivers with monocular vision, especially those accidents occurring at road junctions (Kite and King 1961, Keeney 1968, Liesmaa 1973). McKnight and his co-workers (1991) later found that safety levels were not significantly different between monocular and binocular truck drivers. This finding also agrees well with those of another study (Edwards and Schachat 1991). Furthermore, there was no performance loss under simulated monocular vision (Wood and Troutbeck 1995). Even when drivers have two functional eyes, they may have integrative binocular problems. Previous studies have reported no correlation between phoria and accident rates (Burg 1967b, Humphriss 1987). Nevertheless, a weak correlation was found between accident frequency and vertical phoria (Davison 1985), but not with horizontal phoria. It has been suggested that poor stereopsis is associated with higher accident rates (Humphriss 1987). However, Shute and Woodhouse (1990) believed that this correlation may result from other associated factors causing poor stereopsis, such as reduced visual acuity in one eye. This argument is further supported by Rubin and co-workers (1994) who reported that stereopsis was not correlated with self-reported driving problems among elderly individuals. Hence, the role and influence of binocular vision in driving is still not well understood.

2.1.9 Ageing

Ageing brings a slow but inevitable loss of physical capabilities in the whole body including vision. Reduction of average optical performance progressively increases with age due to more significant intraocular scattering and optical aberration (Artal et al 1993, Guirao et al 1999). Anatomically, pupils of aged people become smaller which reduces the amount of light entering the eye. This change in the pupils affects the ability to detect objects (Campbell and Green 1965, Hernandez et al 1996), especially at low light levels. The problem is made worse because of slower dark adaptation in the elderly (Jackson et al 1999). Thus, driving at night or at dusk would be compromised. The prevalence of visual impairment also increases significantly in the elderly. Cataract, an opacification of the crystalline lens, is a common cause of vision impairment in adults over 60 years old, affecting almost half of those aged 75 to 85 years (Owsley and McGwin 1999). Keltner and Johnson (1987) reported that older drivers have a higher number of crashes per distance travelled than drivers in other adult age groups. Older drivers were also found to perform significantly worse in sign detection and took a longer time to complete a fixed driving course than did younger drivers (Wood et al 2009). Hazard perception ability was also significantly slower for drivers aged 75 years or more; this is linked with increased crash risk (Horswill et al 2009). Self-reported visual problems associated with driving were also increased significantly among a large sample of older drivers. Visual functions that were found to represent significant problems for older drivers included: difficulty reading signs, instrument panels that were too dim, difficulty in judging speed of self and others, glare and problems with situation awareness in the peripheral visual field (Kline et al 1992). These findings strongly suggest that reduced visual function may contribute significantly to driving problems among the older population. As the population is ageing, problems of older drivers would raise more concerns from the public. More studies are expected in the ageing population.

2.1.10 Common eye diseases affect driving

Various ocular pathologies have been found to affect driving performance. Drivers with cataract had 2.5 times more crashes than age-matched controls (Owsley et al 1999). A previous report also showed that cataract surgery improved driving performance significantly as measured in a closed-road circuit (Wood and Whittam 2001). Glaucoma patients were also 3.6 times more likely to be involved in traffic accidents (Owsley et al 1998b) and glaucoma-induced field loss was shown to have increased real world and simulator accident rates (Szlyk et al 2005). Similarly, drivers with age related macular degeneration were also reported to have worse performance in both an interactive driving simulator and an on-road test than a group of age-matched controls (Szlyk et al 1995). Szlyk and co-workers (1992) reported that patients with retinitis pigmentosa also performed significantly worse than normally sighted control subjects who were age-, gender- and driving experience-matched in a driving simulator. Actually, the poor driving performance associated with the ocular diseases can be accounted for by different aspects of their degraded visual functions. For example, cataract patients may have decreased static visual acuity, contrast sensitivity, stereopsis and increased glare sensitivity; similarly glaucoma patients may have restricted visual field and useful field of view.

2.2 Non-visual factors affecting driving

There are a number of non-visual factors affecting driving performance. In the literature, the studies are summarised as in the followings.

2.2.1 Attention and cognitive status

Mental status can be evaluated by various tests such as Mattis Organic Mental Status Syndrome Examination which is designed for testing the cognitive status of the elderly. Visuospatial ability can also be assessed using the Rey-Osterreith test, the “Trail making test” and the Wechsler Adult Intelligence Scale (Revised) (Ball et al 1993).

Many older drivers are most likely to experience a variety of attention problems. These diminished capabilities offer the best explanation for elevated risk in drivers aged 66 years or above (Decina and Staplin 1993). For elderly drivers with deficits in selective attention and divided attention, together with a slowing in the rate of visual information processing, this will result in a restriction in the size of the useful field of view and it was proposed that most crashes caused by older drivers were due to alleged “driver inattention” (Ball et al 1993). Inattention also increases the detrimental effect of any given visual impairment for the older driver as compared with a younger driver and thus creates a higher risk of traffic crashes (Ball et al 1993, Owsley 1994).

As the population is ageing, the driving population includes a greater proportion of older drivers who are suffering from both visual sensory deficits and cognitive problems. Their response to central and peripheral targets will be much delayed and this causes potential dangers to the drivers themselves and to other road users.

2.2.2 Reaction time

Older driver had a 3 seconds increase in the central reaction time and a 5.2 seconds increase in the peripheral reaction time when compared with younger subjects (Wood and Troutbeck 1995). The findings of increased reaction times for the older driver were due to ageing changes. To compensate for this deficit, the older drivers should either increase the stopping distance or decrease the speed of the vehicle. The extra distance that would be travelled by the elderly compared to young drivers when stopping in response to a stimulus in peripheral view was calculated (Table 2.2.1).

Although there is a trend predicted that increasing age requires an increase in reaction time, there are very few studies about the predictability of reaction time on crash involvement or how the reaction time being affected under pathological visual impairments.

Table 2.2.1. Extra stopping distance travelled by the elderly in response to a stimulus in peripheral view (Wood and Troutbeck 1995).

	Extra Distance by the Elderly Travelled	
Speed (km/h)	Metres	Equivalent Car Lengths
40	58	8
50	72	10
60	87	12
70	101	14
80	116	16

2.3 Comparison of the driving-related studies

The experiments carried out by the previous studies have several differences:

2.3.1 Open vs Closed circuits

Studies comparing the driving performance of the older and the younger drivers have been carried using open and closed driving circuits or even using driving simulators. Generally, all the testing methods have shown that older drivers with or without visual impairment scored worse driving performance than the younger and middle-aged drivers with normal vision (Wood 1999, Wood and Mallon 2001).

For the open circuit experiments, using an open road with both high and low traffic density can encompass a range of driving situations that are typically encountered during normal driving conditions. Thus the actual driving performance can be assessed (Wood and Mallon 2001). However, the open circuit provides little or no control over stimulus and response events. Moreover, it may be dangerous to test simulated visual impairments using open circuit conditions because the subjects may not adapt to the simulated visual condition and cause accidents involving other vehicles on the road. On the contrary, the closed circuit test can overcome these problems (Ball and Owsley 1991). Similar to the closed circuit, all the stimuli and events can be controlled in the driving simulator. However, the perceived control of simulator and the environment may not be the same as operating real vehicles. Subjects may take considerable time to familiarize themselves with the system. Subjects may also encounter motion sickness during the experiment. The advantage of driving simulators over closed circuits is that all the vehicle's parameters, such as speed, position relative to the lane, angle of steering wheel and reaction time can be accurately recorded by the computer controlling the simulator.

2.3.2 Crash rate vs Crash frequency

Accidents are difficult to measure because: (i) accidents are rare events; the researcher has the statistical burden of trying to predict such improbable events, (ii) accidents have multiple causes; some might be independent of driver errors, and (iii) the accident frequency might be difficult to gauge. Older people view driving as an important symbol of personal independence, so the older drivers with recent accidents might be reluctant to report them. The two most common valid dependent measures of driving performance are accident frequency (number of crashes during a given period of time) and accident rate (number of crashes per miles driven during a given period of time) (Ball and Owsley 1991, Ball et al 1993).

Of these two measures, accident frequency (ether self-reported or state reported) is more frequently used in the literature. It has been recommended that using a 5-year period maximizes the predictive relationships of all variables that are crash frequency related (Ball et al 1993). Accident frequency rather than accident rate is more commonly used because: (i) for the calculation of accident rate, the subjects were asked about mileage from a few of perspectives, like, “how many miles were driven during a week’s time?”, “how many trips taken per day?”, “the average distance of a trip”. The replies to these questions result in a group of inconsistent estimates of number of miles driven and thus the mileage correction was not performed, (ii) the accident frequency might better predict driving performance in a controlled laboratory setting or on a driving simulator, and (iii) using accident frequency recorded by the state / government agency as a dependent and standardized measure is advantageous over other sources (Ball et al 1993).

2.3.3 Self-reported vs Government-published crash rates

There are advantages and disadvantages in collecting crash frequency reported by the government or by the drivers. For self-reported crashes, the advantage of using this data is the ease of obtaining the information by simply asking the drivers directly through a questionnaire. The disadvantage is that self-reported information from older drivers is usually unreliable, as compared with the government records. In addition, drivers tend not to report the crashes in which they were involved (Ball et al 1993).

The advantage of using the government-reported crashes is that the record provides not just the number of crashes but also detailed information. For example, the circumstances surrounding each crash are useful to determine fault and to subdivide the crashes into different types (Ball et al 1993). Also the government record is maintained in a standardized format and the data can be retrieved from a computer database. Since the information is used by various agencies to formulate public policy and also by insurance companies to set rates (Ball and Owsley 1991), the crash frequency collected from this channel is considered reliable from a statistical perspective.

2.3.4 Snellen vs Number plate tests

In the United Kingdom, applicants for a car driver's licence need to satisfy a minimum visual standard, which is reading a standard car number plate at a specified distance in good daylight. The applicants can wear their habitual refractive correction and then read a plate displaying letters and figures 79 mm high and 50 mm wide at 20 m or 79 mm high and 57 mm wide at 20.5 m (Driver and Vehicle Licensing Agency 2008). The British number plate test is equivalent to decimal visual acuity of 0.55 to 0.60 (Drasdo and

Haggerty 1981).

The Snellen test that is widely accepted by the United Nations Economic Commission for Europe, requires driving licence applicants to have Snellen acuity of at least 0.5 binocularly, or at least 0.4 in one eye and 0.2 in the other, or 0.8 in one eye for monocular vision (Drasdo and Haggerty 1981), and the Snellen test is also accepted by the states in America with the minimum standards range from 20/40 to vision less than 20/200 (Fishbaugh 1995).

According to the Drasdo and Haggerty's study (1981), the Snellen test was a more standardized task and was expected to give more repeatable results while reading the number plate as a standard visual task also helps in spot-checking the drivers in traffic. However, as the Snellen test was evaluated in an indoor condition, it was probably less relevant to the real driving tasks. For the number plate test, it was a more complex demand on the visual system and might be more closely related to a driver's visual tasks. Drivers can also assess their own vision as if they still meet the number plate test requirement without the need of any special equipment. However, the testing condition cannot be standardized and it remains the major drawback of this assessment.

A number of differences exist between these two tests: (i) the number plate test has different characters which can diminish the possibility of guessing the threshold situations, (ii) the close packing of the characters in the number plate test can raise particular difficulties in some forms of amblyopia or unsteady fixation, and (iii) the number plate test has a higher ambient luminance than the Snellen test; intraocular scattering is more effective in diminishing the contrast of the retinal image in the number plate test. It has also been noted that these two tests required different visual demands which affect candidates with different visual defects to different extents (Drasdo and Haggerty 1981).

2.4 Vision assessment for driving

2.4.1 Current situation

Because of the need for safety on the roads, licensing authorities need to ensure the person who is granted a driving licence for a particular class of vehicle is physically and mentally fit to drive that vehicle. Since vision is a critical sense, it is necessary to validate the visual status of drivers. To become a vehicle operator, an individual must demonstrate the minimum vision competency to meet the legal expectation of a local transport authority. However, there is no international consensus on the adoption of vision testing and the associated standards to assess one's visual fitness for driving. Visual fields, visual acuity and colour vision are assessed commonly for candidate drivers (Charman 1985). The establishment of vision-related licensing standards aims to remove accident-prone individuals from driving seats. On the other hand, the licensing standard should not be so excessively restrictive that it removes the rights of a competent individual to drive. In striving for a balance, it is not uncommon to note that vision standards of different authorities vary (Charman 1985, Fishbaugh 1995). In the United States of America, for example, different states adopt various visual acuity levels and the visual field tests are conducted only in selected states (Fishbaugh 1995). Debates on the validity of different systems are mounting but we do not have evidence in the literature to justify the implementation of a universal standard (Casson and Racette 2000). The Hong Kong government has a system in place to ensure all drivers are visually fit to drive. The minimum visual requirement to obtain a private driving licence is to read a number-plate binocularly with a visual acuity equivalent of 6/15 to 6/20 (Transport Department 2005b). The licence is renewed every 10 years without the need of any assessment until 70 years or age. A similar visual acuity requirement is enforced in the United Kingdom, but a binocular field assessment is also included in the United Kingdom (Driver and Vehicle Licensing Agency 2008). Since the lighting conditions, testing distance and plate design have not been standardised for the number-plate test (Charman 1997), the effectiveness of this test is not well documented. It is questionable to judge one's visual fitness based solely on a number-plate test. After they have passed the vision test and obtained their first licence, if drivers do not have or do not notice any physical or visual changes, no further evaluation is required to get their licences renewed. At age 70 years, a medical certificate is required for license renewal. There is thus a large gap of uncertainty regarding the driver's visual status.

Vocational drivers are responsible for the safety of their passengers and goods. They also spend long hours on the road under widely varying conditions. Moreover, buses and coaches regularly approach groups of people waiting at bus stops. Any loss of control at this moment may lead to multiple fatalities. Fare-paying passengers have a legal expectation of higher safety and driver's fitness than those of a private car passenger. Large goods vehicles impose a greater risk than private cars, with the possibility of causing damage to other road users and an increase in the risk of death or serious injury in collision because of greater momentum. Large goods vehicles require longer braking distances and this becomes very critical in urgent situations. They may also carry dangerous loads. Therefore the medical assessment process for drivers of large vehicles and those carrying fare-paying passengers is commonly more stringent. The minimum visual acuity requirement in Hong Kong is to attain at least 6/9 for the better eye and at least 6/12 for the worse eye. Horizontal visual field size should be at least 120° (Rehabaid Society 2006).

2.4.2 Inadequacy of the current situation

In Hong Kong, the main visual assessment tools are visual acuity and visual field evaluation. However, many studies have suggested that these vision assessments are not sufficient to show the whole picture of drivers' vision. For example, it has been shown that drivers with cataract could have quite good visual acuity, which probably surpassed the minimum legal requirement for applying the driving licence, especially in the early lens opacities (Brown 1993, Lasa et al 1993, Wood and Troutbeck 1995). Thus, these drivers with significant visual impairment, arising from depression of peripheral sensitivity or overall decrease of contrast sensitivity and increase in glare sensitivity, can still pass the driver's licence test.

The most common complaints of elderly drivers are poor vision for night-time driving and being "almost blinded" by sunlight (Wood and Troutbeck 1995). Glare and dim illumination are conditions under which they experience difficulties in daily life. Older drivers also suffer from problems in reading highway signs and signals, driving during rush hours and at night (Kline et al 1992). In terms of vehicle operations, an older driver with relatively advanced cataract would be expected to have visual acuity below the required level for driving (Wood and Troutbeck 1995). Since the visual acuity test does not always provide a complete assessment of functional vision (Elliott 1993), contrast sensitivity test and glare disability test have been suggested to supplement the visual acuity test (Elliott 1993, Wood and Troutbeck 1995).

It has been suggested that other types of visual processing deficits had greater influence on crash risk than did acuity impairment (Owsley et al 2001). Older drivers showed not only a decline in visual performance on most tests but also an increase in reaction times, general psychomotor slowing and cognitive changes (attention and recognition which might lead to a reduced ability to perform two tasks at the same time); together with any visual impairment, this could easily cause unsafe driving (Wood and Troutbeck 1994). To test both visual function and cognitive function, recent researches recommended the useful field of view test. This test can assess both visual and cognitive skills and thus provide a more global measure of visual information processing than any sensory tests alone (Owsley 1994). It is time to look for alternative testing methods which can improve the test efficiency for licensing requirements.

Since visual tests are only conducted at the entry point of the licensing system and no further evaluations are mandated in the subsequent renewals until 70 years of age, a question arises as to whether these drivers being granted a licence will continue to meet the visual challenges on the road in the following years. If the renewal policy only requests medical proof for drivers aged 70 years or above, a decrease in the driver's visual capability before this age is likely to cause a problem in the road system.

There is evidence that older drivers compensate for visual impairments by modifying their driving behaviour. It appears that drivers ‘at risk’ will build up a safety strategy on their own to avoid risky situations, such as night driving and high traffic roads etc (Ball et al 1998). However, commercial vehicle drivers have little flexibility to choose when and where to drive. They cannot compensate by modifying their driving behaviour in order to avoid risky situations even if they have visual impairments. There are few studies available in the literature to characterise the visual performance of these drivers. In particular, the effects of glare cannot be easily quantified through routine eye tests.

Educating older drivers on self-regulation can minimize crash risks and increase road safety (Owsley 1994). However, such education is not always effective. Individuals with visual or mental problems may fail to recognize their impairments, and thus prudence and self-regulation may fail (Wood and Troutbeck 1995, Ball et al 1998, Wood and Mallon 2001). In addition, even the accident frequency among the elderly may be comparable to the youngsters; older drivers may cause more burden on the medical services as they are more vulnerable to the impact-induced damage than the young drivers due to the relative fragility of the aged body. Regular driving assessment is indicated to maintain a good competence level in order to protect this group of drivers (Shipp and Penchansky 1995, Mantyjarvi et al 1998).

Chapter 3 Experimental questions (hypotheses)

3.1 Experiment I – Survey of visual attributes for commercial drivers in Hong Kong

3.1.1 Objectives

1. To study the visual experience of commercial drivers
2. To study the visual competence of commercial drives

3.2 Experiment II – The effects of age and glare on the contrast sensitivity functions

3.2.1 Objective

1. To investigate the effects of glare eccentricity and age on central and peripheral contrast sensitivity

3.2.2 Null hypotheses

1. There are no differences in contrast sensitivity at different glare eccentricities.

2. There are no differences in contrast sensitivity at different ages.
3. There are no interactions between glare and age in contrast sensitivity.

3.3 Experiment III – The effects of age and glare on the useful field of view

3.3.1 Objective

1. To investigate the effects of glare eccentricity and age on useful field of view

3.3.2 Null hypotheses

1. There are no differences in the useful field of view under conditions of glare.
2. There are no differences in the useful field of view at different ages.
3. There are no interactions between glare and age in the useful field of view.

3.4 Experiment IV – The effects of age and glare on simulated driving performance

3.4.1 Objective

1. To study the effects of age and glare on simulated driving performance.

3.4.2 Null hypotheses

1. There are no differences in simulated driving performance for different glare conditions.
2. There are no differences in the simulated driving performance between younger and older individuals.
3. There are no interactions between glare and age in driving performance.

Chapter 4 Experiments

4.1 Experiment I – Survey of visual attributes for commercial drivers in Hong Kong

4.1.1 Introduction

Hong Kong is a very busy aviation and maritime hub. It accommodates approximately seven million inhabitants and more than half million licenced motor vehicles in a tiny city. Land transportation of merchandise and people are important activities to support export and import industries. The road system in Hong Kong is dominated by heavy public transport and commercial vehicle operations. The total public transport passenger-journeys reached four billions in 2009 (Census and Statistics Department 2010). The transport industry plays a strategic role in the economic development of Hong Kong; a good and reliable land transport system will sustain the economic growth.

Hong Kong has a higher accident rate of public service vehicles compared with the United Kingdom (Evans and Courtney 1985). Although only 30% of vehicles licenced in Hong Kong (motorcycles excluded) are of a commercial nature (Transport Department 2009a), about 66% of notified accidents on the government records involved one or more commercial vehicles. Taxis, light goods vehicles and public buses are among the most common categories of vehicles involved in accidents (Transport Department 2009b). A high risk of fatal and serious-injury involving goods vehicle has also been found (Yau 2004). Commercial vehicles are being operated for a longer period per day and they carry valuable lives and / or merchandise. In the case of road accidents, the economical impacts on the society are considerable. In 2009, around 14 thousand accidents involved personal injuries (Transport Department 2009c) and the gross economical claim amounts to HK$1.7 billion (Office of the Commissioner of Insurance 2009). Furthermore, more than half of the fatal accidents involving pedestrians are associated with truck and bus collisions (Cameron et al 2004).

Since vision is a critical sense leading to road safety as reviewed, it is necessary to validate the visual status of drivers. However, there is no international consensus on the adoption of vision test and associated standards to assess one's visual fitness for driving (Desapriya et al 2008). The Transport Department of the Hong Kong Government has a system in place to ensure all drivers are visually fit to drive. The minimum visual requirement to obtain a private driving licence is to read a number plate binocularly with a visual acuity (VA) equivalent of 6/15 to 6/20 (Transport Department 2005b). Since the number plate test has not been standardised for lighting condition, testing distance and plate design (Charman 1997), the effectiveness of this visual validation is not well documented. It is questionable to judge one's visual fitness based solely on a number plate test. The vision standards for commercial drivers are stricter than those for private drivers. The minimum visual acuity requirement is to attain at least 6/9 for the better eye and at least 6/12 for the worse eye. Horizontal visual field size should be at least 120° (Rehabaid Society 2006). However, these visual tests are conducted at the entry point of the licensing system. No further evaluations are mandated in the subsequent renewals until 70 years of age (Transport Department 2005a). A further question arises as to whether these drivers, after they have been granted a licence, will continue to meet the visual challenges on the road in the following years.

Whether or not a person is fit to drive hinges extensively on the visual competence and ergonomic demands; drivers with inadequate vision may unwittingly pose considerable risks to other road users. The visual performance of commercial drivers constitutes one of the important considerations in road safety. To date, the visual status of commercial drivers in Hong Kong has not been documented.

There is also a need to understand the visual issues from the drivers' perspective. I addressed these issues by surveying the visual experience and competence of commercial vehicle drivers. These drivers are frequent road users and they should represent the driving community in Hong Kong. The results will provide useful information to understand the efficiency of current licensing system.

4.1.2 Methods

A cross-sectional study was carried out in Hong Kong, with current commercial vehicle drivers recruited from 12 locations. A total of 420 drivers participated in the study. They had an average driving experience of 23.2±10.7 (SD) years. Franchised public bus and taxi drivers accounted for 46.9% and 33.1% of the sample, respectively. Other subjects mainly operated public light buses (8.1%), private bus (2.1%), light (2.9%) and medium-sized goods vehicles (1.2%). Written informed consent was obtained from each subject. The study was approved by the University Human Subjects Ethics Sub-committee.

Part I: Visual attributes survey

A personal interview was conducted for each participant using a structured questionnaire (Appendix A). It covered five visual and four driving-related environmental questions. All subjects (409 males and 11 females), with an average age of 52.0±8.8 (SD) years, completed the survey.

Part II: Vision tests

After the survey, the subjects were invited to participate in the following vision tests. Only 360 subjects (349 males and 11 females) consented to join the assessment (response rate 85.7%). The average age of drivers who completed part II was 53.0±8.4 (SD) years. A commercially available vision screener (Visiotest™ Essilor, France) and Randot® Stereotests (Stereo Optical Co., Inc., USA) were used to assess distance and near visual acuities (monocular and binocular conditions), colour vision, horizontal visual field limits and stereopsis. The subjects wore near spectacles in the stereopsis assessment and habitual distance spectacles in all other tests.

Distance visual acuity was compared against 2 passing criteria; (a) $6/18^{+2}$ as equivalent to the number plate test adopted by the Hong Kong transport authority for private driving licence and (b) $6/12^{+2}$ as the minimum requirement for the worse eye in driving commercial vehicles. For near, $6/18^{+2}$ was chosen as the passing criterion. The failing criteria for other components were: stereoacuities worse than 70 sec of arc, naming two or more incorrect pseudo-isochromatic plates and a temporal visual field less than 70º.

The data were analysed using the Statistical Package for Social Sciences 16.0 software (SPSS Inc., Chicago) and GraphPad InStat 3.0 for Windows 95 (GraphPad Software Inc., California). Frequency was counted for each variable. Association between some of the parameters collected from the survey and the screening were analyzed using Chi-square test. It was considered as significant if $p < 0.05$.

4.1.3 Results

The age (unpaired t-test, $t = 1.616$; $p > 0.05$) and driving experience (unpaired t-test, $t = 1.309$; $p > 0.05$) of the subjects participating in the two parts of the survey did not differ statistically while subjects not participating the vision tests were significantly younger (unpaired t-test, $t = -5.485$; $p < 0.001$) and had less driving experience (unpaired t-test, $t = -5.639$; $p < 0.001$). Subjects drove from 3.2 to 119.0 hours per week, with a mean of 52.9±17.5 (SD) hours. They sometimes (1-2 nights per week; 24.5%) and often (3-7 nights per week; 22.6%) had to work night shifts.

Part I: Visual attributes survey

In this sample, 18.6% of subjects were required by law to wear visual aids. However, 26.7% wore prescription glasses and 10.2% put on their prescription sunglasses when driving. Over half of the sample (58.6%) used tinted ophthalmic lenses (plano or prescription). Almost one-third of the participants (29.5%) did not use any visual aids while driving (Figure 4.1.1). Nearly a quarter of subjects (23.3%) had no eye examination before the study and 39.1% had received an examination more than two years prior to the study. Only 23.8 % had their last eye examination within one year in either optometric or ophthalmologic practices (Figure 4.1.2). The results also showed that 4.1% were aware of colour vision difficulty. The remaining drivers did not know of (10.2%) or acknowledge (85.7%) this problem. The most commonly reported refractive errors were astigmatism (37.4%) and myopia (28.1%), whereas 51.7% did not know of any refractive problems (Figure 4.1.3). A majority of this sample (75.5%) also reported presbyopia.

The driving-related symptoms are summarised in Figure 4.1.4. Only 18.3% did not report any symptoms; the rest reported one or more symptoms in the workplace. The leading five personal symptoms were: tiredness of eyes (51.4%), itching eyes (44.5%), tearing (28.3%), dry eye (25.5%) and headache (19.8%).

Of the environmental issues, 61.9% and 35.2% had problems recognising the signage on the road side and on the road surface, respectively (Figure 4.1.5 and 4.1.6). In addition, 35.2% revealed that there was too much information on the road side signage. Inappropriate location (29.1%) and unclear information (22.9%) on the signs were two other major problems frequently encountered. On the road surface signage, unclear (18.8%) and insufficient (18.3%) information were occasionally reported. More than half of the drivers (52.9%) also commented that the lighting system caused problems at work. Among which, 29.5% found that the fluctuations of road brightness affected their driving and 19.1% reported that the lights in the tunnels were too dim. Generally, insufficient brightness was experienced by 16.2% of the subjects (Figure 4.1.7). A significant number of drivers experienced glare-induced problems caused by the sunlight (79.1%) and oncoming headlights (63.1%). Another 28.3% found that the advertising boards were the glare sources (Figure 4.1.8). Only 9.8% had no problems related to glare.

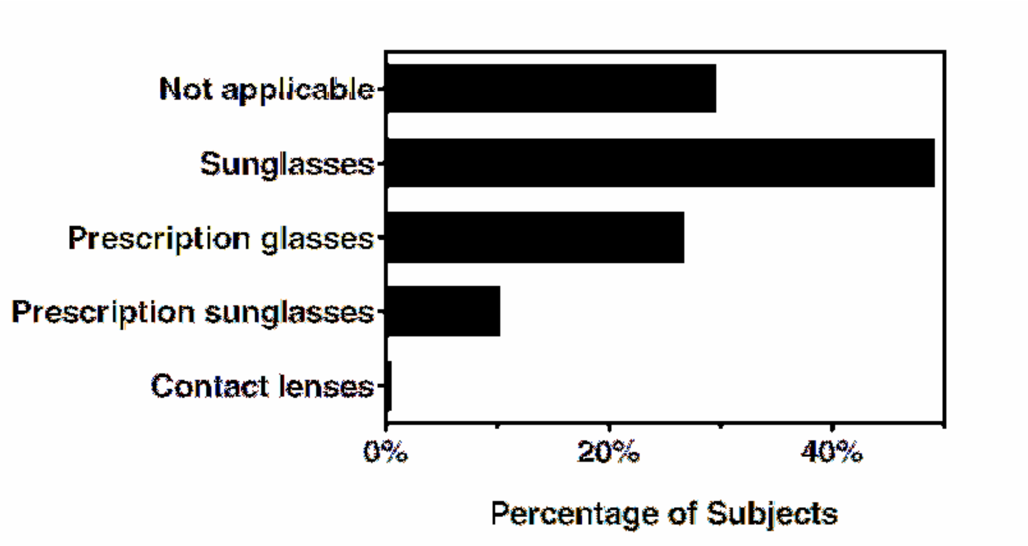

Figure 4.1.1. Visual aids used at work.

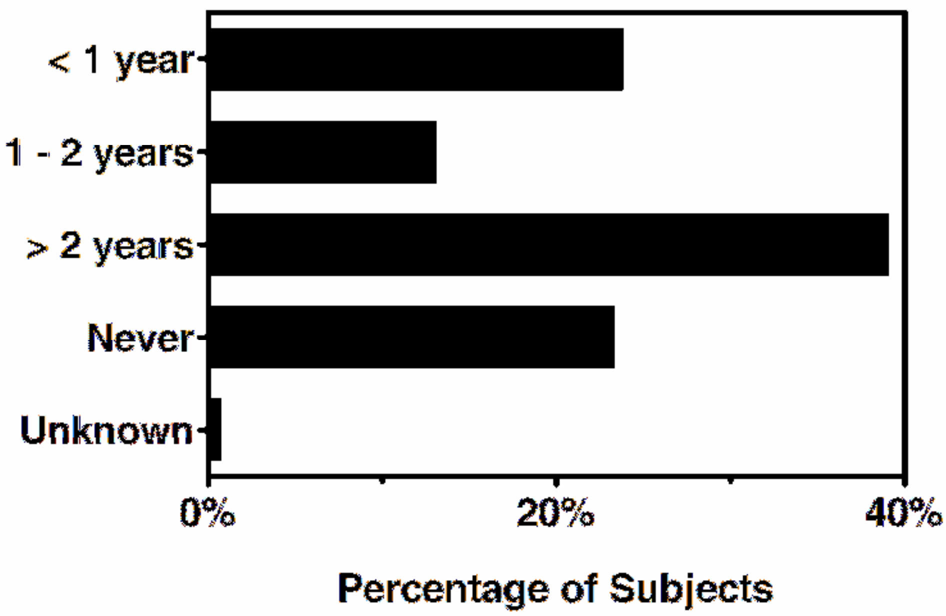

Figure 4.1.2. History of last eye examination.

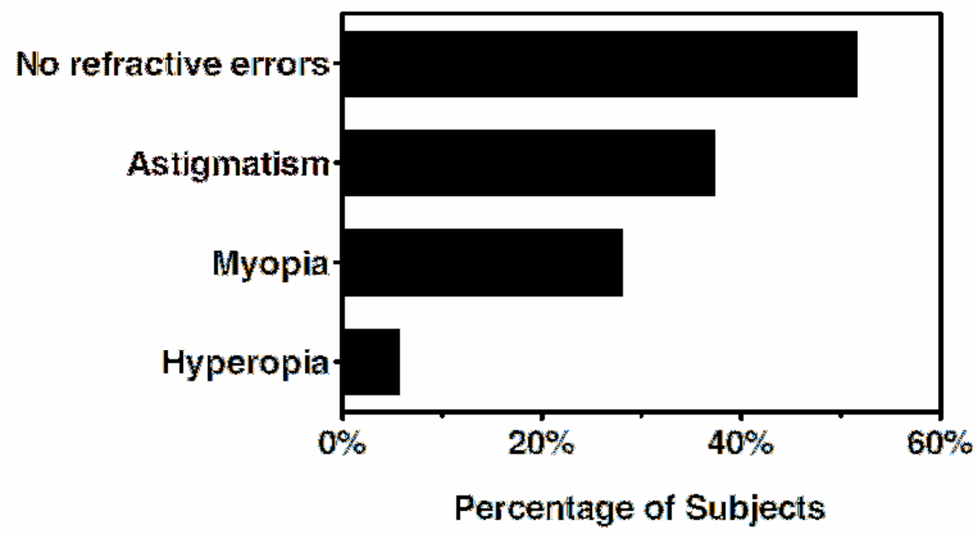

Figure 4.1.3. Refractive disorders.

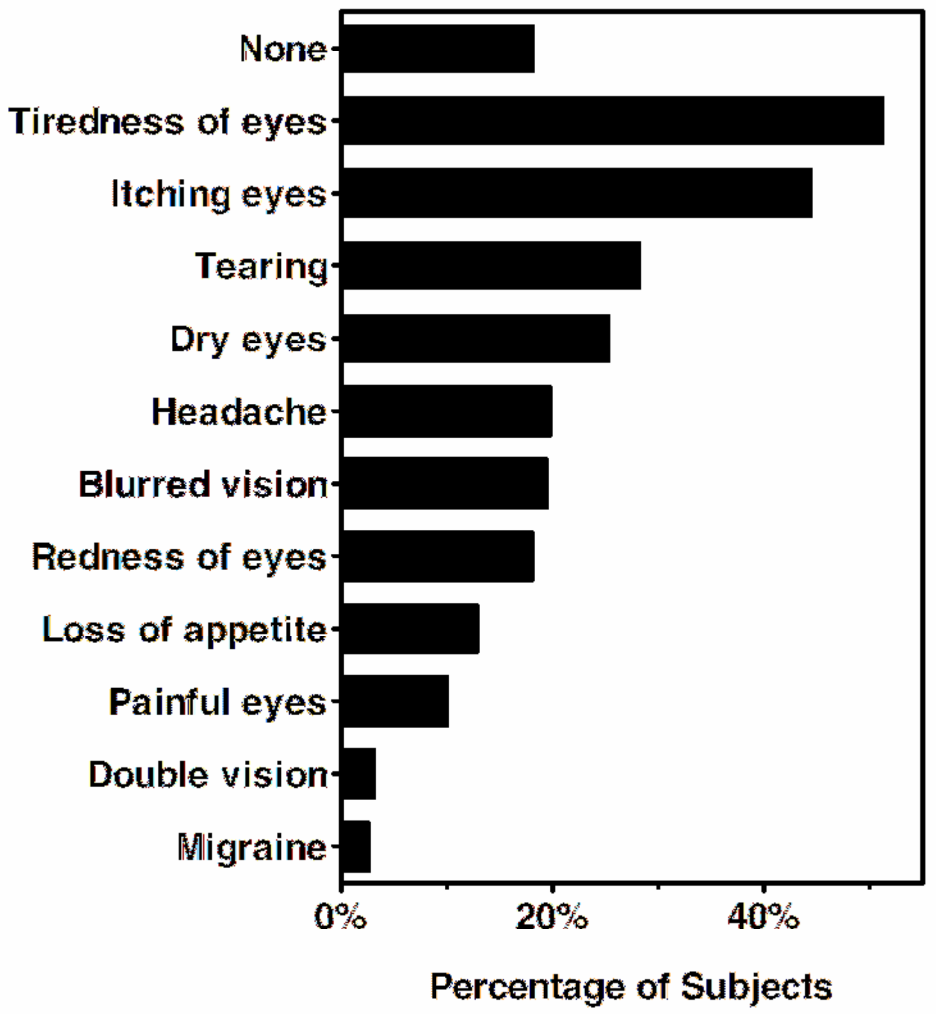

Figure 4.1.4. Visual and physical symptoms at work.

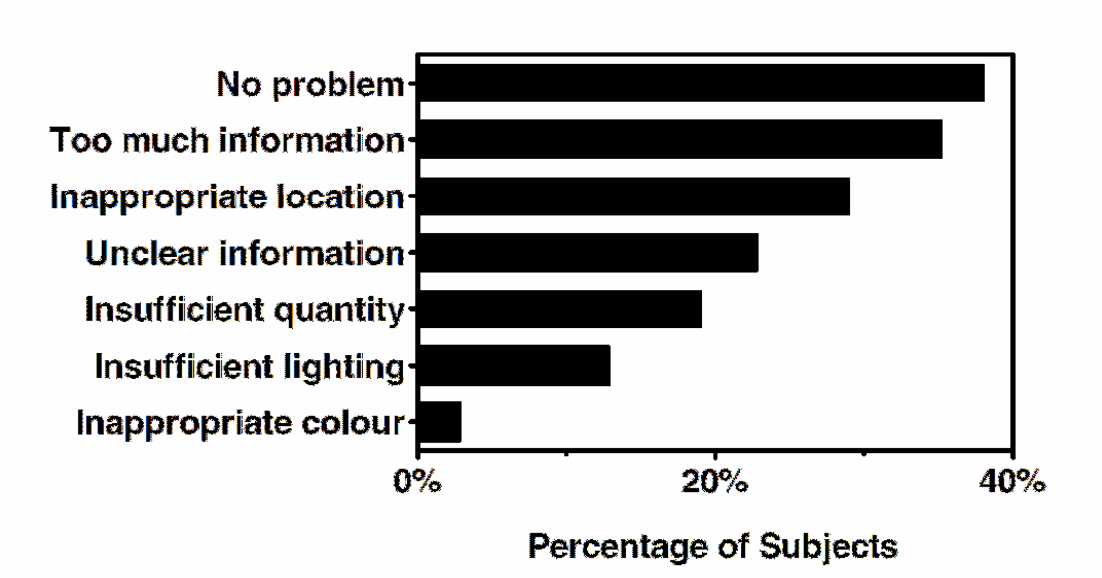

Figure 4.1.5. Problems of road side signage.

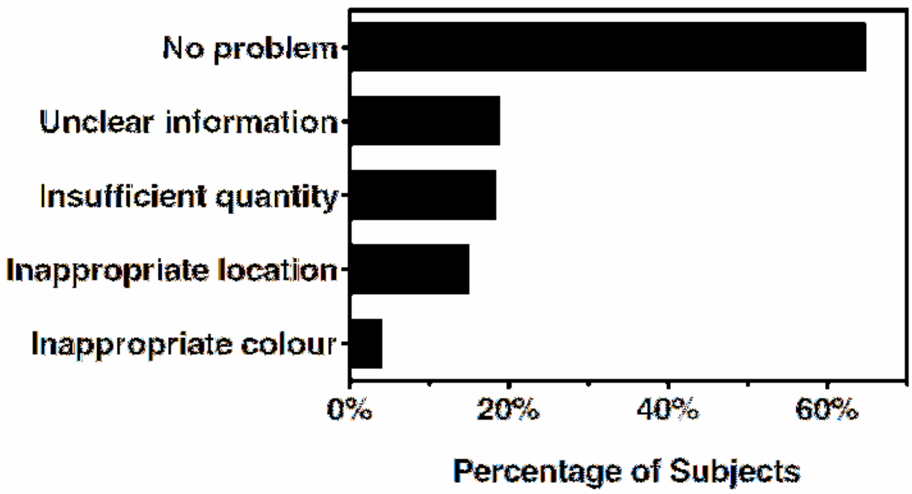

Figure 4.1.6. Problems of road surface signage.

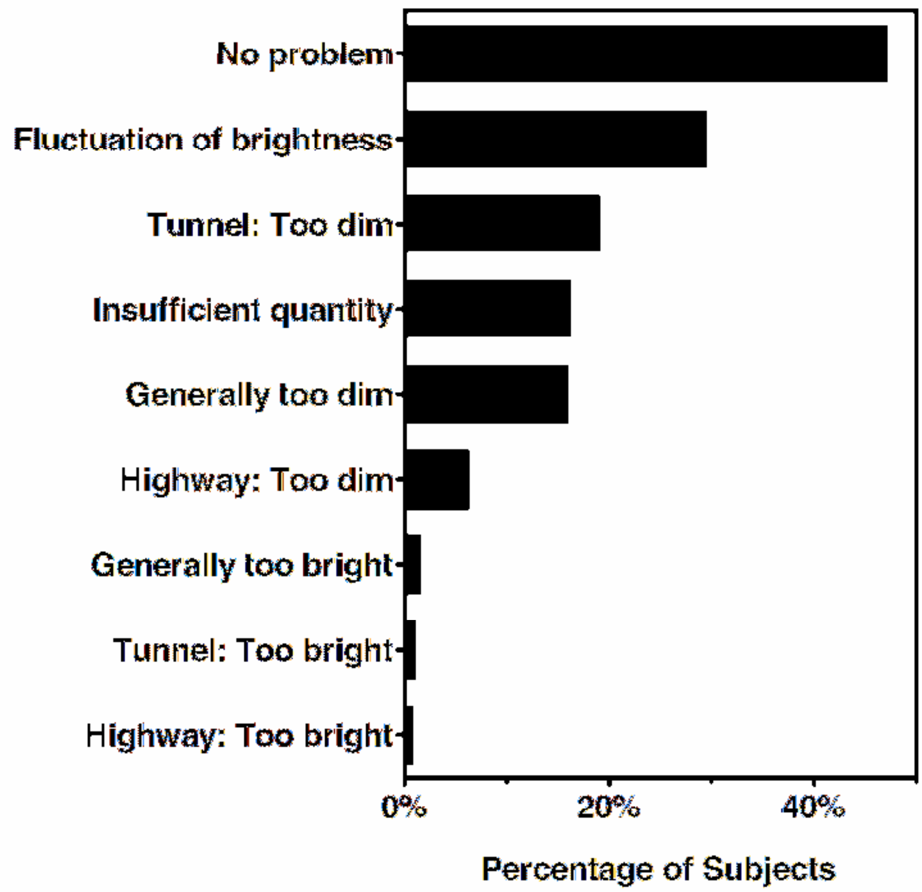

Figure 4.1.7. Problems of brightness sensation in driving.

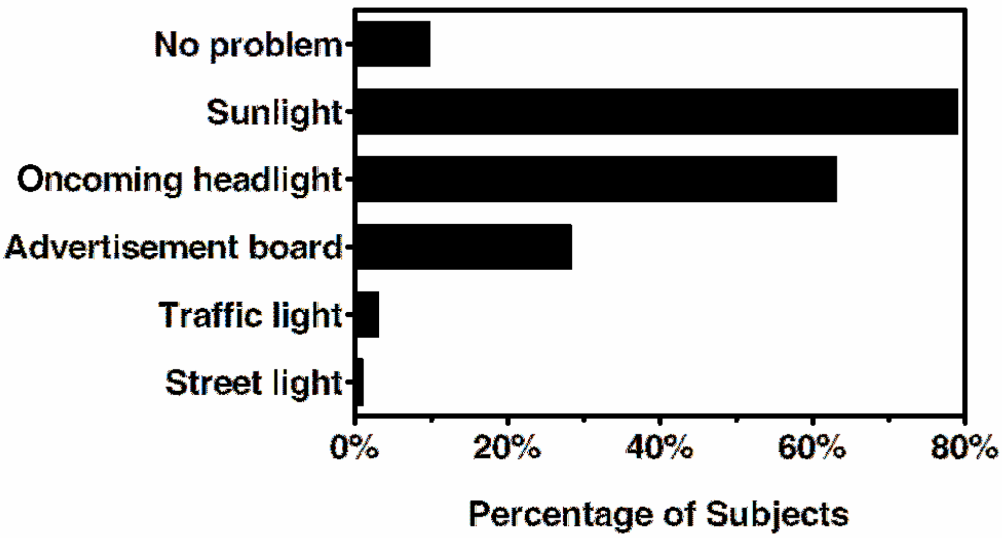

Figure 4.1.8. Problems of glare sources in driving.

Part II: Vision tests

Figure 4.1.9 shows that 18.9% failed the legal private driving licence monocular distance VA requirement and 6.1% could not meet the criterion binocularly. If the commercial driving licence requirement was used, almost twice as many subjects (37.5%) failed monocularly and 13.9% could not reach the standard binocularly. For near, 81.1% could not read near tasks properly when they were using their habitual optical aids, either wearing no spectacles (72.5%) or wearing the distance spectacles (20.0%) at work (Figure 4.1.10). When the measurement was taken binocularly, the percentage of failures became 64.7%.

Table 4.1.1 shows that 18.1% had worse than 70 sec of arc stereoacuity as revealed by the Randot® stereotests. For the colour vision assessment, 9.7% could not pass the colour vision test under binocular conditions (Table 4.1.1). For the horizontal visual field, 1.9% and 0.8% had their temporal field size less than 70º in their right and left eyes, respectively.

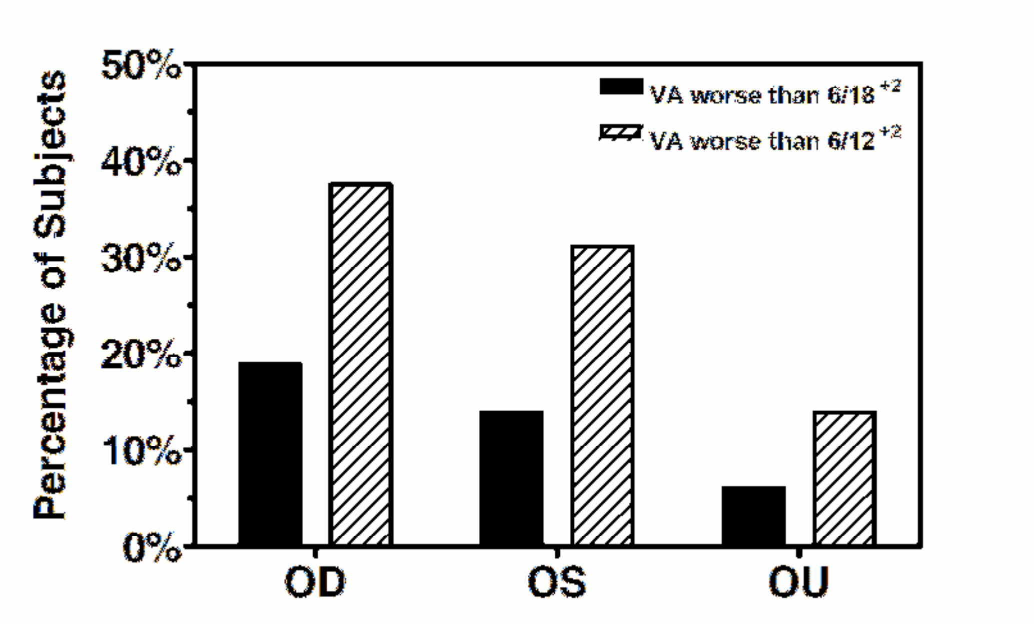

Figure 4.1.9. Failure rates of distance visual acuity tests using 2 different criteria.

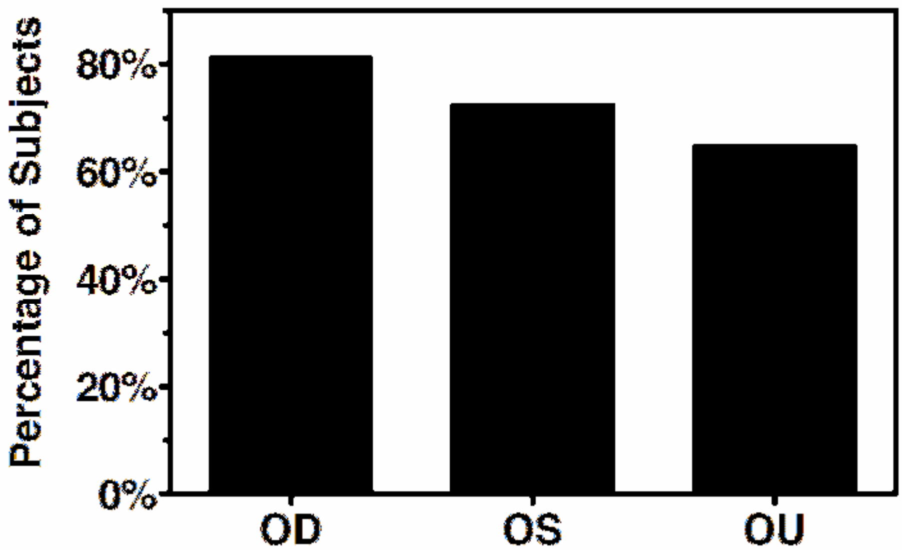

Figure 4.1.10. Failure rates of near visual acuity tests (VA worse than $6/18^{+2}$).

Table 4.1.1. Test results of stereotest and colour vision test (n = 360).

	Number of subjects failed	**Percentage of subjects failed**
Stereotest	65	18.1%
Colour Vision Test	35	9.7%

Part III: Associations

Drivers who used prescribed optical aids were correlated significantly with when they had their last eye examination (phi = 0.325; χ^2 = 37.765; p < 0.001); with having previous eye examination (phi = 0.276; χ^2 = 27.202; p < 0.001); and with near visual acuity outcomes (Table 4.1.2). Subjects using prescribed optical aids were more than expected to: (1) have last eye examination in less than 2 years, (2) have previous eye examination before this screening and (3) pass the near visual acuity tests both monocularly and binocularly.

The average age of subjects who joined the vision tests was 53 years of age; this was used as a cut-off point to form younger and older age groups. Significant associations were found between age groups and previous eye examination (phi = 0.144; χ^2 = 7.400; p = 0.007); age groups and visual acuity outcomes (Table 4.1.3); age groups and glare complaints (phi = 0.138; χ^2 = 6.849; p = 0.009); age groups and use of sunglasses (phi = -0.126; χ^2 = 5.684; p = 0.017). Older drivers were more likely to have had an eye examination. However, more older drivers failed the distance and near visual acuity tests than expected, while younger drivers were more likely to have glare complaints and to wear sunglasses. Drivers who used sunglasses were also associated significantly with glare problems (phi = -0.145; χ^2 = 7.548; p = 0.006). Sunglasses users were facing more glare-related problems. Associations were also revealed between drivers with self-reported blurred vision and all distance visual acuity outcomes (Table 4.1.4). Drivers who perceived blur were more than expected to fail the distance visual acuity tests.

Table 4.1.2. Associations between the use of prescribed optical aids and near visual acuity outcomes.

	phi	χ^2	p
Use of prescribed optical aids * Near OD VA	0.228	18.778	< 0.0001
Use of prescribed optical aids * Near OS VA	0.165	9.821	0.002
Use of prescribed optical aids * Near OU VA	0.150	8.103	0.004

Table 4.1.3. Associations between age groups and visual acuity outcomes.

	phi	χ^2	p
Age group * Distance OD VA ($6/18^{+2}$)	-0.197	14.033	< 0.0001
Age group * Distance OS VA ($6/18^{+2}$)	-0.167	10.058	0.002
Age group * Distance OU VA ($6/18^{+2}$)	-0.130	6.116	0.013
Age group * Distance OD VA ($6/12^{+2}$)	-0.254	23.177	< 0.0001
Age group * Distance OS VA ($6/12^{+2}$)	-0.175	11.059	0.001
Age group * Distance OU VA ($6/12^{+2}$)	-0.232	19.294	< 0.0001
Age group * Near OD VA	-0.172	10.670	0.001
Age group * Near OS VA	-0.166	9.918	0.002
Age group * Near OU VA	-0.221	17.570	< 0.0001

Table 4.1.4. Associations between the self-reported blurred vision and distance visual acuity outcomes.

	phi	χ^2	p
Self-reported blurred vision * Distance OD VA ($6/18^{+2}$)	-0.145	7.562	0.006
Self-reported blurred vision * Distance OS VA ($6/18^{+2}$)	-0.177	11.281	0.001
Self-reported blurred vision * Distance OU VA ($6/18^{+2}$)	-0.160	9.188	0.002
Self-reported blurred vision * Distance OD VA ($6/12^{+2}$)	-0.109	4.263	0.039
Self-reported blurred vision * Distance OS VA ($6/12^{+2}$)	-0.109	4.259	0.039
Self-reported blurred vision * Distance OU VA ($6/12^{+2}$)	-0.117	4.935	0.026

4.1.4 Discussion

Our data show that less than 40% of these participants have had an eye examination conducted within the last two years whereas the figure is over 60% out of 301 randomly sampled drivers aged from 17 to 60 years or over in the United Kingdom (Anuradha et al 2007). Apparently, the commercial vehicle drivers in Hong Kong have less awareness of the importance of eye care and personal responsibility to meet the legal vision standard for driving. Road safety is a global public health and economical issue. In the United States, motor vehicle accidents are the leading cause of death in the workplace and accounted for 35% of workplace fatalities between 1992 and 2001 (National Center for Statistics and Analysis 2002). The annual damage due to road accidents has been estimated to 2% of the gross national product in highly-motorised countries, such as Australia, Germany and Japan (Jacobs et al 2000).

The Hong Kong transport authority conducts a vision test (currently a number plate test) for drivers on their first licence application but no further evaluations are mandated in the subsequent renewals until they are 70 years of age (Transport Department 2005a). In this sample, only 18.6% have been mandated by the authority to use corrective optical aids when they obtained the first driving licence. However, our findings show that a higher portion of subjects (approximately 28%) wear optical prescriptions at work, that is, spectacles, contact lenses or prescription sunglasses. Nevertheless, about 14% of the sample, including both non-optical and optical aid users, still cannot meet the distance visual acuity criterion. The results suggest that the vision test of the current licensing system does not effectively identify commercial drivers on the road with sub-standard visual performance; either a driver with sub-standard vision manages to pass the visual test at the entry point or the visual performance of a driver with competent vision has deteriorated over time.

The holders of a Hong Kong driving licence are responsible to inform the Transport Department when their vision falls below the necessary standard (Transport Department 2005b) but this recommendation is not strictly adhered to. Once an individual is granted a driving licence, the visual performance is not a driver's primary concern and the drivers do not necessarily believe that good vision is essential for safe driving (Humphriss 1987). Compensatory strategies are adopted by those individuals with reduced visual acuity who restrict their driving speeds (Szlyk et al 1995) rather than risking a licence suspension. Ignorance of the importance of vision is a serious problem in the commercial driver population in Hong Kong.

Even though a driver has passed the visual evaluation at the entry point, it does not warrant a lifetime competency. The current licence policy ignores the fact that vision will change with age and it may eventually fall below the legislated criterion.

Our analysis showed that drivers with perceived blur, who failed the distance visual acuity test, were still driving. It suggests that subjective blur is a sensitive indicator of failing the visual standard, although not all drivers seek professional help proactively. For example, more than 40% Nigerian drivers with significant refractive errors do not use spectacles while driving (Bekibele et al 2007). It follows that some drivers are aware of their visual defects but they do not realise the importance of vision in driving: even the detection of brake lights onset is reported to be delayed (Lamble et al 2002). Educational programs may need to be implemented to change this mindset.

Although there is no clear association between crash rate and drivers' visual acuity (Sims et al 2000, Owsley et al 2001, Bohensky et al 2008), standard visual acuity assessment is universally adopted in most land transport licensing systems to ensure that the drivers must have a minimum vision standard before obtaining their driving licence. Intuitively, commercial vehicle drivers are expected to meet more stringent vision standards than private vehicle drivers because they have a higher responsibility for passengers and goods when on the job. Apart from distance vision, more than 60% of the commercial vehicle drivers failed the near visual acuity test. It is interesting to note that these drivers (90% are aged 40 years or more) do not wear near optical prescription for near work although completing paper work is a common requirement in land transportation.

Tiredness of eyes is a symptom frequently reported in this study. Itching eyes, tearing and dry eyes are also commonly reported. These anterior ocular symptoms may be attributed to the ages, long working hours of our sample and also the polluted environment (Saxena et al 2003). The average age of this sample is above 50 years. Tear quality deteriorates with increasing age and long hours of concentration in general. It has been shown that visual acuity, taken after 10 to 20 seconds without blinks, deteriorates significantly in dry eye subjects (Toda et al 2009). This anterior eye problem may be precipitated by increased driving speeds, when blinking rates are further decreased (Goto et al 2002). In addition, age-related visual impairments, such as cataract and glaucoma, are known to decrease driving performance, for example, sign detection and recognition, peripheral reaction time and driving time may be impaired (Wood 1999). Older drivers with reduced useful field of view are more likely to be involved in crashes (Ball et al 1993, Owsley et al 1998a). A reduced temporal visual field may indicate emerging age-related visual impairments.

The working hours of these drivers vary greatly (from 3.2 to 119.0 hours per week). Serious and fatal accidents involving buses in Hong Kong happen more often toward the end of long shifts (Evans and Courtney 1985).

Significantly longer visual reaction times are also reported by tired night-time cab drivers (Corfitsen 1993) and sleep deprivation reduces the useful visual field (Roge et al 2003). In addition, prolonged working hours may also contribute to the symptoms reported in this study. An occupational guideline could be developed to control the working hours of commercial vehicle drivers with regular time breaks advised for drivers with extended work schedules.

Colour vision difficulties were found in about 10% of our male-dominated sample. The finding is comparable to other epidemiological studies (Modarres et al 1996, Al-Aqtum and Al-Qawasmeh 2001). A disagreement is noted between the self-reported colour vision conditions and the colour vision test results. Some drivers reported no colour vision difficulties but they demonstrated deficiency in colour vision. It was also worthwhile to note that as the testing carried out was only a colour vision screening, a high false positive rate may result. Although colour vision defects are predominately congenital in nature, drivers may acquire colour deficiency due to ocular pathology over time. This suggests that the local drivers receive inadequate levels of eye care and they may overlook the significance of colour vision in driving safety. Colour defective deutans have reduced chromatic sensitivity to road signs and signals (O'Brien et al 2002) and thus have increased response time to red lights and poor identification of rear signal lights (Atchison et al 2003, Tagarelli et al 2004). On the other hand, colour defective protans have been reported to demonstrate significantly higher rear-end collision rates (Vingrys and Cole 1988). Even drivers with very mild colour defects of both types, would have difficulties in detecting low luminance coloured objects (Cole and Lian 2006). Since most colour-related visual problems are experienced at night (Tagarelli et al 2004), colour defective drivers may restrict themselves to daytime driving; however, commercial vehicle drivers do not have the flexibility to choose their working hours.

Difficulty in recognising road-side signage is a common problem reported by the drivers. Road signs were recognised by one-third of the subjects as having too much information. Unlike the road sign systems in United States and United Kingdom, Hong Kong adopts a bilingual system - Chinese and English. As more information is packed onto road signs, visual crowding may compromise the ability to recognise the components of a visual task (Chung et al 2001) and peripheral awareness is also reduced (Wood and Troutbeck 1992). Driving performance was reported to be affected adversely in a United Kingdom bilingual road sign system (Jamson et al 2005). Due to the complexity of contents on the road signs, drivers have to spend more time to resolve the information, which may distract their attention from detecting vehicles or persons on the road.

In addition, unclear information of road surface signage is another issue experienced by the subjects. The contrast on the road surface is reduced by water, dirt and wear. This problem may be exacerbated when the drivers have reduced contrast sensitivity (Wood and Carberry 2006). Hence, a driver may attribute more difficulties to the road-side and road surface signage systems if he has a sub-standard vision.

Glare-related problems are very common. About 90% of the participants reported at least one form of glare affecting their driving performance. The discomfort and disability glare of oncoming vehicle headlights make it difficult for drivers to concentrate, especially at night and during twilight (Anderson and Holliday 1995). This may result in compromised object detection, direction control, sign reading and critical decision making. Significantly more collisions and reduction in the safety margin are reported under the effects of glare (Gray and Regan 2007). Our data show that around 60% of the participants wear sunglasses to avoid or minimise the glare during driving. Sunglasses will certainly help in daytime driving but not at night. Moreover, older drivers tend to have more driving complaints of glare at night (Anderson and Holliday 1995). There are no effective means to alleviate night-time glare. Further investigation on the driving performance under the effects of glare is indicated.

Our results clearly illustrate that there is room for improvement in the current land transport system in Hong Kong. For example, a simplified design of signage and a good maintenance of road signs would create a better driving environment. Trained visual screening operators in the licensing system for visual assessment would benefit all drivers, especially the commercial drivers. If there are any doubts in the assessment outcomes, qualified eye care practitioners should be consulted to obtain a thorough examination. The examination process should also include standardised equipment and protocols. Updated ocular health statistics to the government can also be collected on a regular basis in order to obtain the current information on the vision competence of the drivers. Colour vision screening should also be introduced into the test. In the consulting rooms, eye care practitioners should remind the colour defectives of the potential driving problems (Cole 2007) and they should be given a full diagnostic assessment and consultation before a career decision is made (Siu and Yap 2003).

Since poor VA would affect road sign recognition (Wood 1999), eye care practitioners are advised to play an active role in educating drivers on the importance of competent vision and road safety. Routine eye examinations help to detect and remediate un-noticed visual problems. Optometrists provide optical corrections and teach the drivers to use their spectacles (such as distance prescription, progressive lenses or reading glasses) correctly at work. In addition, appropriate optometric care can manage dry eye symptoms effectively. It is also the duty of optometrists to inform their patients if they cannot fulfil the visual related legal requirements for driving. All drivers must be informed of potential age-related visual problems. Other health care providers should be involved in the consultation if significant physical symptoms exist, such as headache. The eye care professions in Hong Kong should involve promoting the importance of regular eye examinations of drivers and explaining the consequences of driving-related visual impairment. Occupational health education on vision and public health is also required. The eye care practitioners and the government should take pro-active roles to improve the visual status of all road users, particularly that of commercial drivers. Mandatory regular vision testing would help to maintain adequate visual competency for driving.

To summarize, the low prevalence of regular eye checks among Hong Kong commercial vehicle drivers indicates that they do not recognize the importance of maintaining good vision. The licensing system conducts a visual acuity test at the entry point as the primary gate-keeping vision assessment tool. This study shows that many drivers, who are in their mid-50s, are operating the commercial vehicles with sub-standard visual status. There is a need to understand the relationship among vision, driving performance and age. Tiredness, dry eye, glare intolerance, inadequate road lighting and crowded road signage are the most commonly encountered visual symptoms / difficulties reported by the commercial vehicle drivers at work. Many symptoms are related to the road design and working hours whereas glare intolerance is a well-established nuisance factor in vision research. In the following experiments, the effects of glare on the visual performance in the aged population will be quantified.

4.2 Experiment II – The effects of age and glare on the contrast sensitivity functions

4.2.1 Introduction

The visual acuity test, which reflects the integrity of the macula, is the most common test adopted in vision screening and clinical practice. It assesses the ability to read the smallest high-contrast optotypes. Licensing agencies also adopt it as a compulsory test for assessing driving fitness though there is only a weak association between visual acuity and road accident rates (Owsley and McGwin 1999). Furthermore, visual acuity test cannot evaluate the level of visual deficits in certain situations, such as central serous retinopathy (Plainis et al 2007) or posterior subcapsular cataract (Bal et al 2010). Individuals with such conditions would have normal or slightly sub-normal visual acuity such that they can still pass the driving-related licensing test despite having compromised contrast sensitivity. Such conditions not only reflect the limitations of the visual acuity test, but should also alert licensing agencies that this test may not identify potentially unfit drivers. It follows that visual acuity test is not a reliable assessment tool for the evaluation of vision and driving.

However, the contrast sensitivity test can be a supplementary test for assessing the complete picture of spatial vision because it can evaluate both the resolution and contrast of the targets at the same time. In clinical practice, contrast sensitivity is only measured at the macula. However, peripheral vision and hence the peripheral contrast sensitivity are as important as central vision in driving. Although the environment is actively scanned by the driver, sudden events, such as a cat appearing suddenly from the curb, may happen out of the driver’s expectation. These events can trigger a driver to immediately direct their gaze to the point of interest. Detection of emerging peripheral objects relies heavily on the function of peripheral contrast sensitivity. Rovamo and co-workers (1992) showed that contrast sensitivity was independent of eccentricity up to 2-4 degrees. At greater eccentricities, contrast sensitivity was reduced. It decreased with increasing eccentricity at all spatial frequencies and the rates of decrease were faster at higher spatial frequencies (Rovamo et al 1984). There were overall depressions in contrast sensitivity, a reduction in the cut-off spatial frequency and a shift of peak sensitivity towards the lower spatial frequencies (Thomas 1978).

Age also plays an important role in contrast sensitivity (Korth et al 1989). Older subjects have significantly lower central contrast sensitivity than younger subjects at medium and high spatial frequencies due to neural and optical clarity changes with age (Evans and Ginsburg 1985, Elliott 1987, Crassini et al 1988). Better performance was also found from younger subjects in detecting a sharp edge in peripheral viewing conditions (Crassini et al 1988). As the population is ageing all around the world, older drivers may still drive, especially those living in rural areas and the commercial drivers. Worse contrast sensitivity had been associated with reduced driving exposure, e.g. reduced annual miles (Stutts 1998). A correlation between contrast sensitivity and highway-sign discrimination distance has also been revealed. Older subjects who had significantly lower contrast sensitivity than younger subjects were found to require a significantly larger sign symbol, i.e. a closer distance, for differentiation (Evans and Ginsburg 1985). Another study also demonstrated the relationship between contrast sensitivity impairments and unsafe driving behaviour. Subjects with a Pelli-Robson contrast sensitivity test score of 1.25 or lower were 8 times more likely to have a history of crash involvement within 5 years prior to the study (Owsley et al 2001). The contrast sensitivity test has been proposed for inclusion in the assessment of European drivers (van Rijn et al 2009).

As reported in Experiment I, more than 90% of subjects had problems related to glare which may affect their driving performance. Glare is a source of visual disturbance associated with bright light and it can be classified into two types: (1) Discomfort glare refers to the subjective perception of annoyance and discomfort without the impairment of vision. (2) Disability glare is defined as a glare source causing a reduction of visual performance. The effect of glare is more prominent in people with cataracts

(Hard et al 1990), corneal oedema (Dovie and Gurwood 2006), LASIK (Tahzib et al 2005) and wearing tinted or soft bifocal contact lens (Rajagopalan et al 2006, Hiraoka et al 2009). A veiling luminance, which is produced by intraocular scattering, superimposes on the retinal image and causes the reduction in visual performance, such as a decline in contrast sensitivity (Steen et al 1993).

The problem of glare is found to interact with increasing age. No 20-30 year old subjects suffered from the problem of glare, but increased glare sensitivity was found in 4.7% of subjects in the group of aged 55-64 years. Sensitivity to glare increased to 29.5% for the group older than 74 years (van Rijn et al 2009). In the presence of glare, contrast sensitivity at low and medium frequencies decreased (Paulsson and Sjostrand 1980).

Another prospective study revealed that increased glare sensitivity was associated with increased crash risk for those drivers with worse vision (Rubin et al 2007). It has been reported that older drivers always complain about night driving difficulties (Owsley 1994) and restricted night-time driving (Ball and Owsley 1991). The most common reason for restricting night driving is related to the discomfort and disability glare of oncoming vehicle headlights which reduces visibility at night and under twilight conditions (Owsley 1994). Glare can reduce the retinal image contrast substantially. Under a simulated low-positioned sun level, a significant reduction in the safety margin used by drivers and significantly higher mean number of collisions were also found (Gray and Regan 2007). The glare sources come from different directions and the effect may be extended to the peripheral retina. The ability of driving is further compromised in detecting objects, controlling vehicle direction, reading signs and making critical decisions. While the worldwide population ages, problems related to glare will become more important in the next few decades. Due to the scarcity of literatures on task detection in the conditions of glare and fixation eccentricity, it was the aim of this study to quantify the influence of glare on the peripheral vision in older individuals. The glare position was also varied in the experiment to understand the effects of eccentricity on visual performance.

4.2.2 Methods

Subjects

In this experiment, forty subjects (gender matched – 20 male and 20 female subjects) were recruited from the Optometry Clinic, The Hong Kong Polytechnic University for this study. They were divided equally into 2 groups, the younger group (20-29 years old) with a mean age of 21.8±1.2 (SD) years and the older group (50-59 years old) with a mean age of 54.2±2.2 (SD) years. All subjects had visual acuity of 6/6 or better with spherical equivalent refractive error less than -3.00 D and cylindrical power less than -1.00 D in their right eyes. They were free from ocular structure abnormalities and any history of ocular injury or surgery. After the details of the experiment were explained, written informed consent was obtained from each subject. The study was approved by the University Human Subjects Ethics Sub-committee.

Apparatus

A Visual Stimulus Generator VSG2/3 and the software Psycho for Windows (Cambridge Research Systems, U.K.) were used to generate and control the stimuli. The vertical sinusoidally modulated gratings were displayed on a 20-inch flat profile CRT monitor (Brilliance 202P7, Philips, The Netherlands) with a viewing distance of 2 m. The brightness of the monitor was calibrated using the spectro-radiometer SR3 (Topcon, Japan). The mean luminance of the gratings and the background was 100 cdm^{-2}. Five spatial frequencies, i.e. 1.5, 2.9, 5.8, 12.5 and 18.8 cycles per degree, were tested with 20 sequences per spatial frequency. A "yes / no" psychophysical staircase paradigm was used to determine the detection threshold. The staircase was set to 2 downs and 1 up. The step-down and step-up sizes were 2.5 dB and 4.5 dB, respectively. The step-down to step-up ratio (0.56) was close to the recommended value of 0.55 (Garcia-Perez 1998). Each screen shot of the grating was displayed for 3 seconds including a 1-second "attack time" (time for the mean luminance of the target to reach the test level) and a 1-second "decay time" (time for the mean luminance of the target to return to screen luminance).

Subjective responses were recorded using a handheld responder, the CB3 Response Box (Cambridge Research System, U.K.). It had 3 buttons, namely A, B and C. The subject was asked to push button A when he could detect the target and button C if he could not. There was a beep signal when a new grating was displayed and another beep was produced when the input signal from the subject was received.

Two fluorescent tubes (Colour temperature: 6500 K) were placed at 2.5°, 5.0° or 7.5° above and below the centre of gratings to test the effect of glare eccentricities on central contrast sensitivity (Figure 4.2.1). The effect of glare on peripheral contrast sensitivity was measured with the two fluorescent tubes placed 2.5° away from the gratings. The luminance of each fluorescent tube was 10,000 cdm^{-2}. Subjects were asked to fixate a cross to be placed at 5.0°, 10.0° or 15.0° away from the centre of the target temporally, while the peripheral contrast sensitivity was measured. Measurements of central contrast sensitivity without glare acted as control.

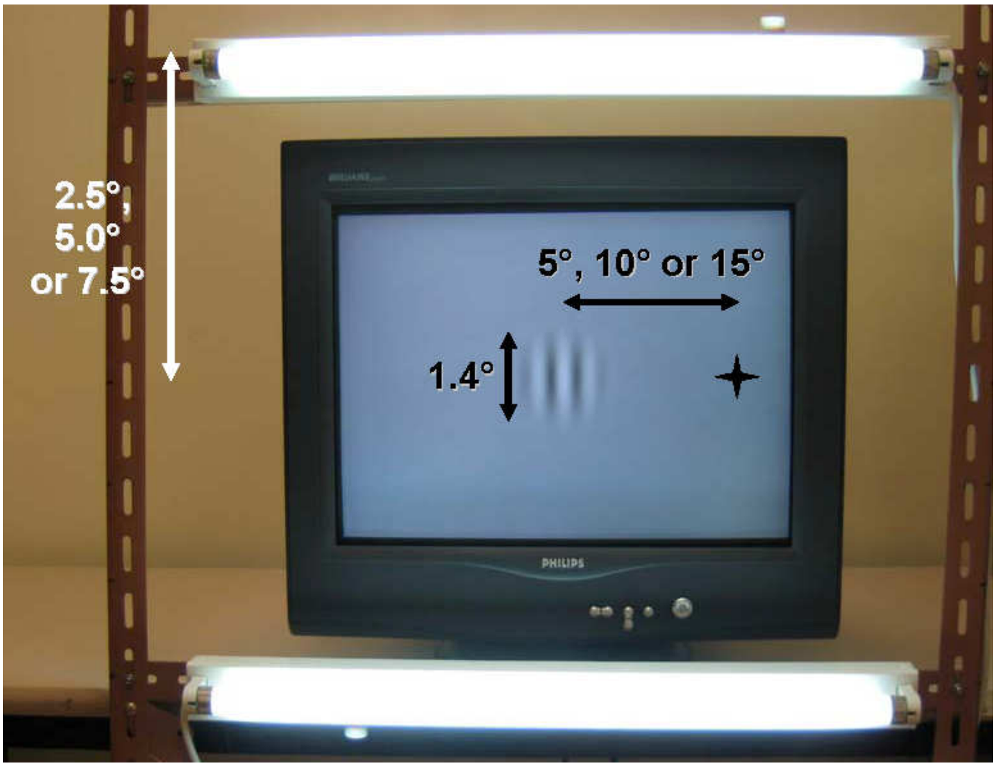

Figure 4.2.1. Experimental setup (Exp. II) showing the size of the target, glare eccentricities and fixation eccentricities.

Procedure

Before the commencement of experiment, subjects underwent a thorough eye examination. One drop of Tropicamide 1.0% was instilled into the subject's right eye to dilate the pupil and relax accommodation. The right eye was then optically corrected for the viewing distance. A 4 mm diameter artificial pupil was placed in front of the right eye to control the retinal illumination and the left eye was covered throughout the measurement. The measurements were carried out in a completely dark room. The subjects sat at 2 m from the screen. At this viewing distance the grating had a diameter of 1.4°. A 5-minute training session was given prior to the actual testing. Measurements of the central contrast sensitivity preceded all those of peripheral contrast sensitivity. The presentation sequences for different conditions were randomized. Subjects had a break of 2 minutes between conditions.

Statistical Analysis

The statistical analysis was performed using SPSS for Windows (version 16.0). The area under the log contrast sensitivity function (AULCSF) was calculated to quantify the overall visual performance (Applegate et al 1997). A two-way repeated-measures ANOVA was performed to test the effects of glare eccentricity and age on central AULCSF while the effects of glare, fixation eccentricity and age on peripheral AULCSF was tested by a three-way repeated-measures ANOVA. Post-hoc comparisons were conducted with Bonferroni tests to examine the significance. Interaction effects were further examined by one-way repeated-measured ANOVA and independent sample t-tests. An alpha level of 0.05 was used for all statistical analyses. According to the power analysis using conventional effect size of 0.4 and power of 0.8, at least 18 subjects were required in each age group.

4.2.3 Results

Figures 4.2.2 and 4.2.3 show the central contrast sensitivity functions under no glare and different glare eccentricities of the younger group and older group, respectively. Contrast sensitivity functions of a typical inverted U shape were found with peak sensitivity at 2.9 cycles per degree. Younger subjects had almost the same sensitivity under the control condition and glare sources at 7.5°. Lower sensitivities were found under glare sources at 2.5° and 5.0° for all spatial frequencies. For the older group, sensitivities without glare were better than sensitivities of the other glare conditions for all spatial frequencies. Glare caused more sensitivity reduction at the low to medium spatial frequencies. The effect of glare on contrast sensitivity for high spatial frequency was not obvious for both age groups. This could be attributed to a floor effect as the performance of subjects for high spatial frequency was already lower than that for other spatial frequencies.

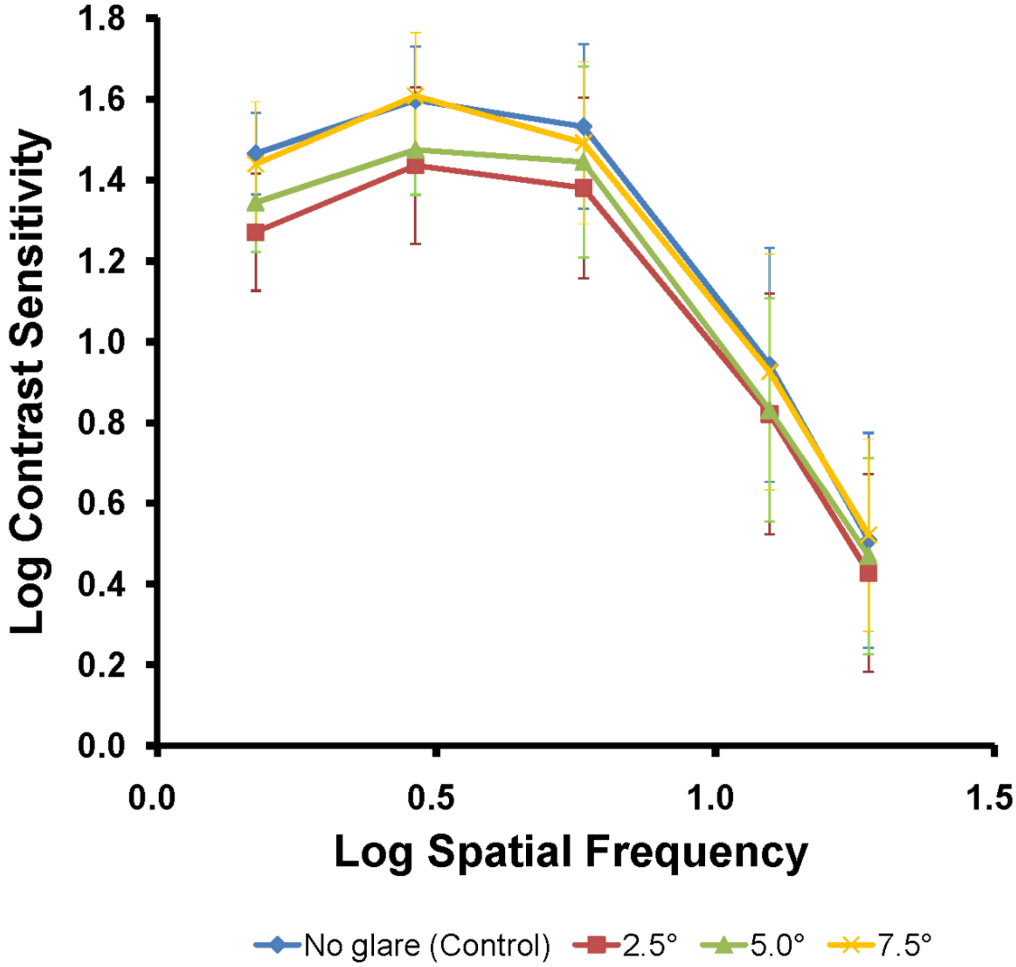

Figure 4.2.2. Central contrast sensitivity functions with different glare eccentricities of the younger group. Error bars indicate 1 SD.

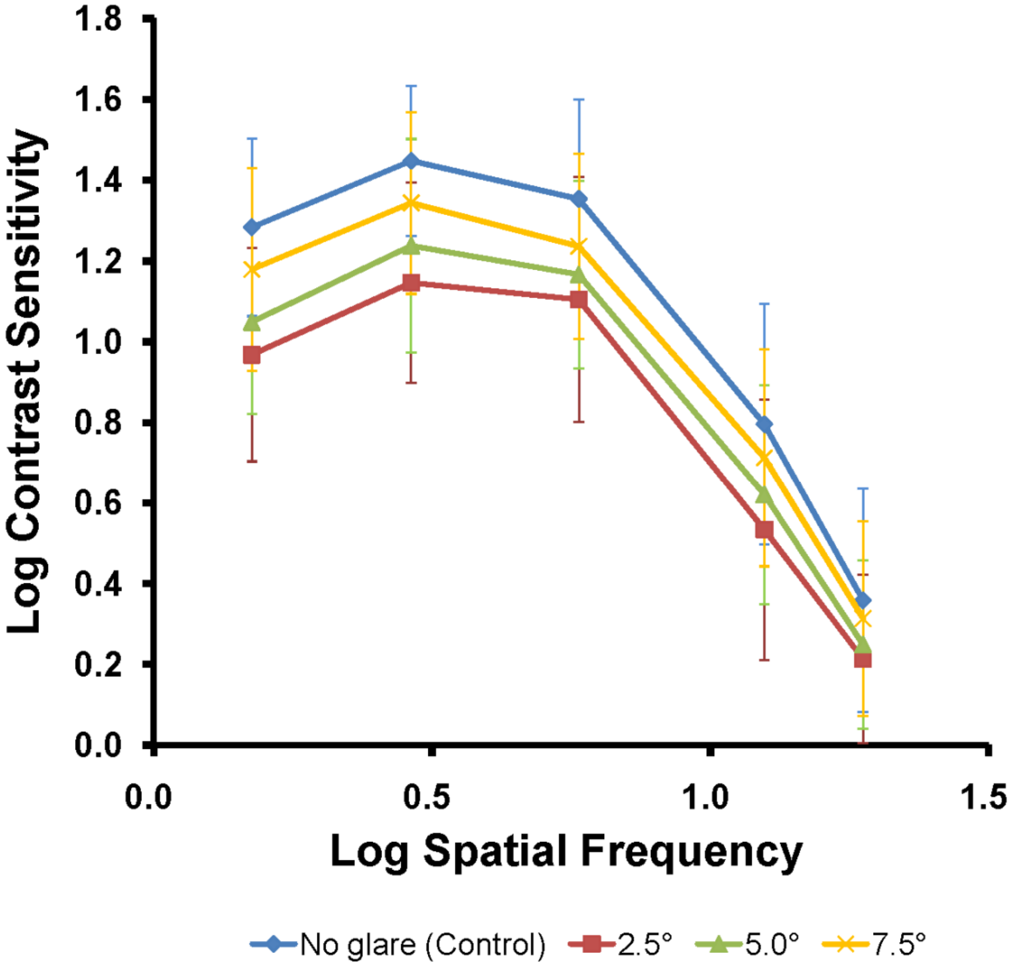

Figure 4.2.3. Central contrast sensitivity functions with different glare eccentricities of the older group. Error bars indicate 1 SD.

The contrast sensitivity functions for different fixation eccentricities with and without glare of the two age groups are shown in Figures 4.2.4 – 4.2.7. Regardless of the glare conditions and age, general depressions were revealed with increasing fixation eccentricities. The decrease in sensitivity was more dramatic at higher than at lower spatial frequencies resulting in a reduction of the cut-off frequency. A shift of peak sensitivity towards the lower spatial frequency with increasing fixation eccentricities was also observed for all conditions. At 15° fixation eccentricity, all the peak sensitivities were shifted to 1.5 cycles per degree. The contrast sensitivity was further reduced at all spatial frequencies with the presence of glare sources at 2.5°.

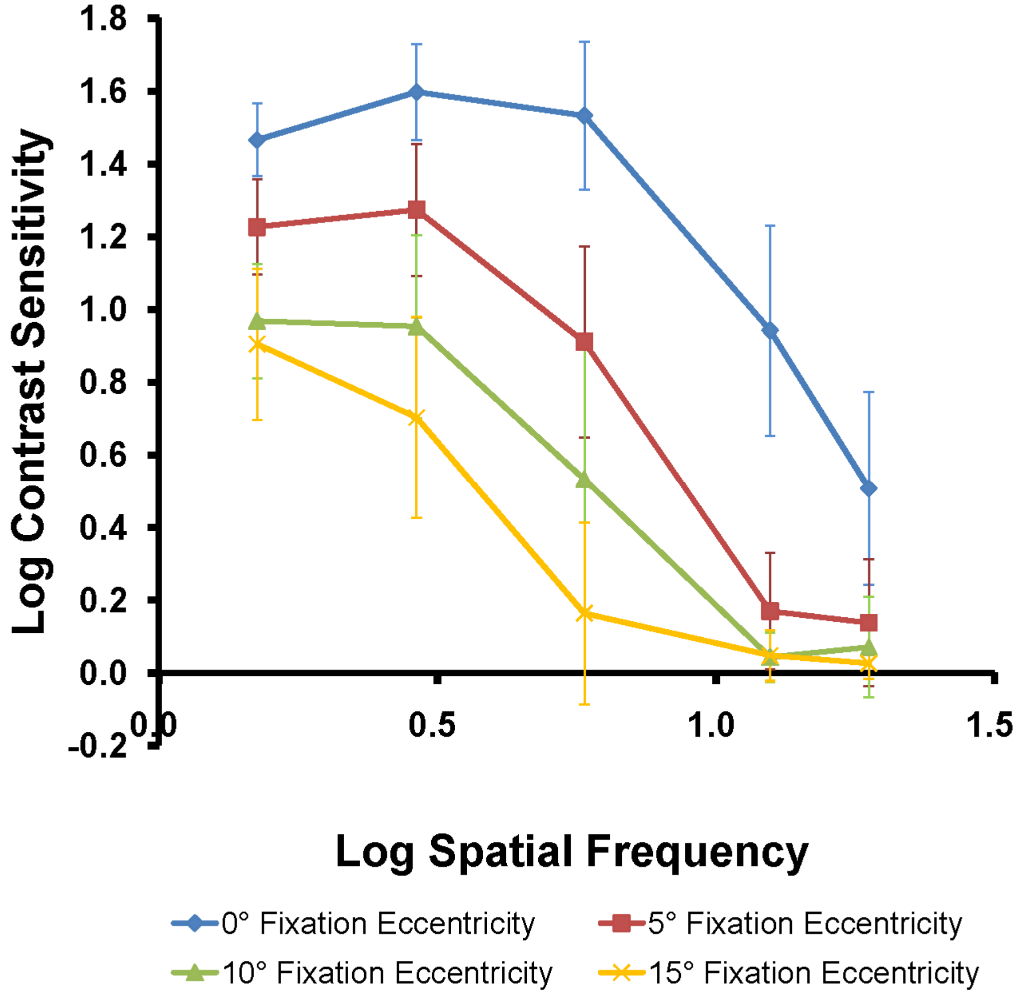

Figure 4.2.4. Contrast sensitivity functions at different fixation eccentricities of the younger group without glare. Error bars indicate 1 SD.

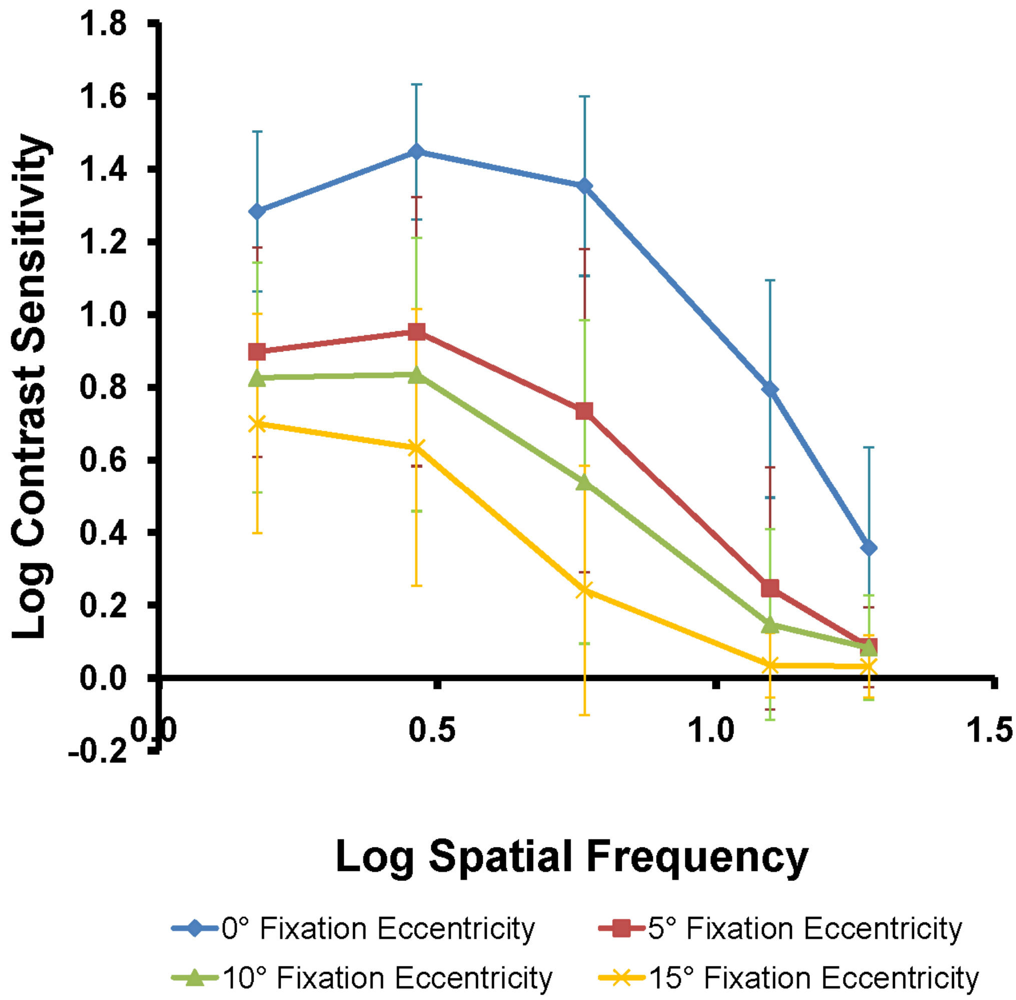

Figure 4.2.5. Contrast sensitivity functions at different fixation eccentricities of the older group without glare. Error bars indicate 1 SD.

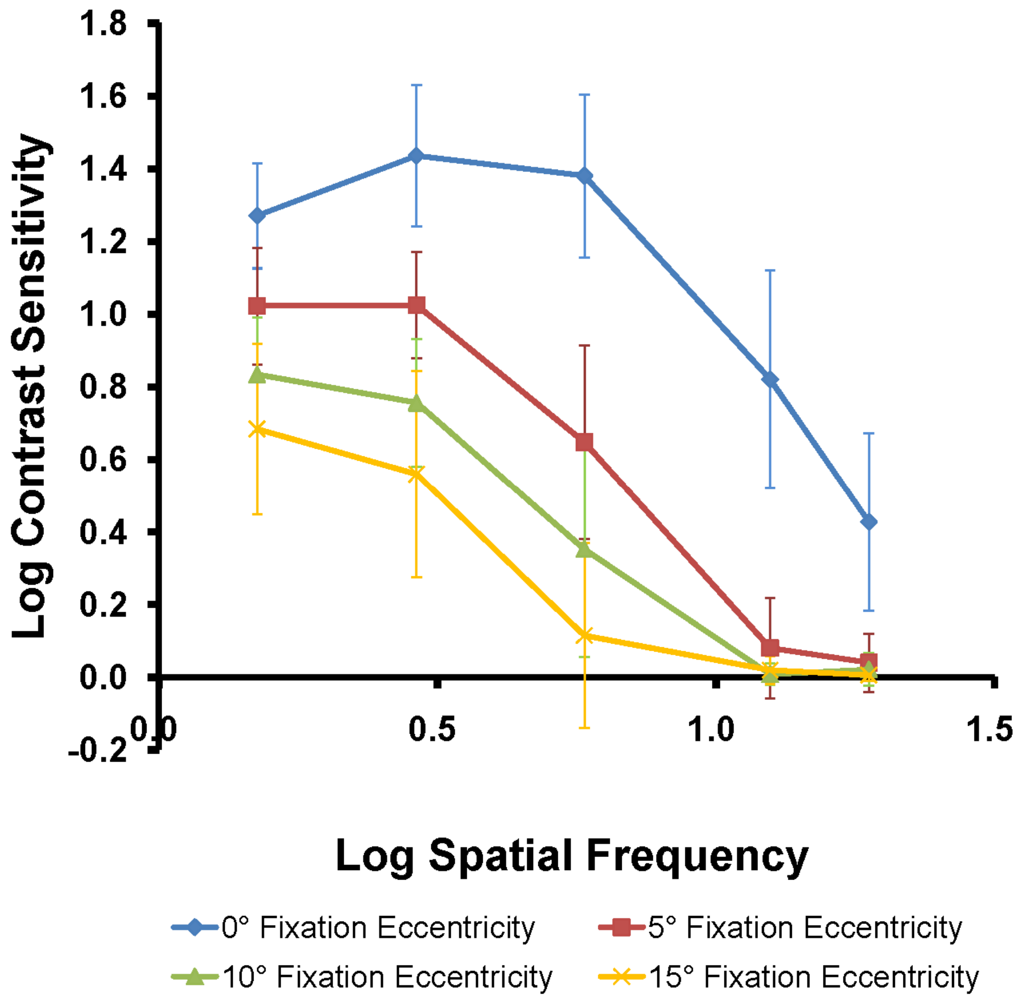

Figure 4.2.6. Contrast sensitivity functions at different fixation eccentricities of the younger group with glare sources at 2.5°. Error bars indicate 1 SD.

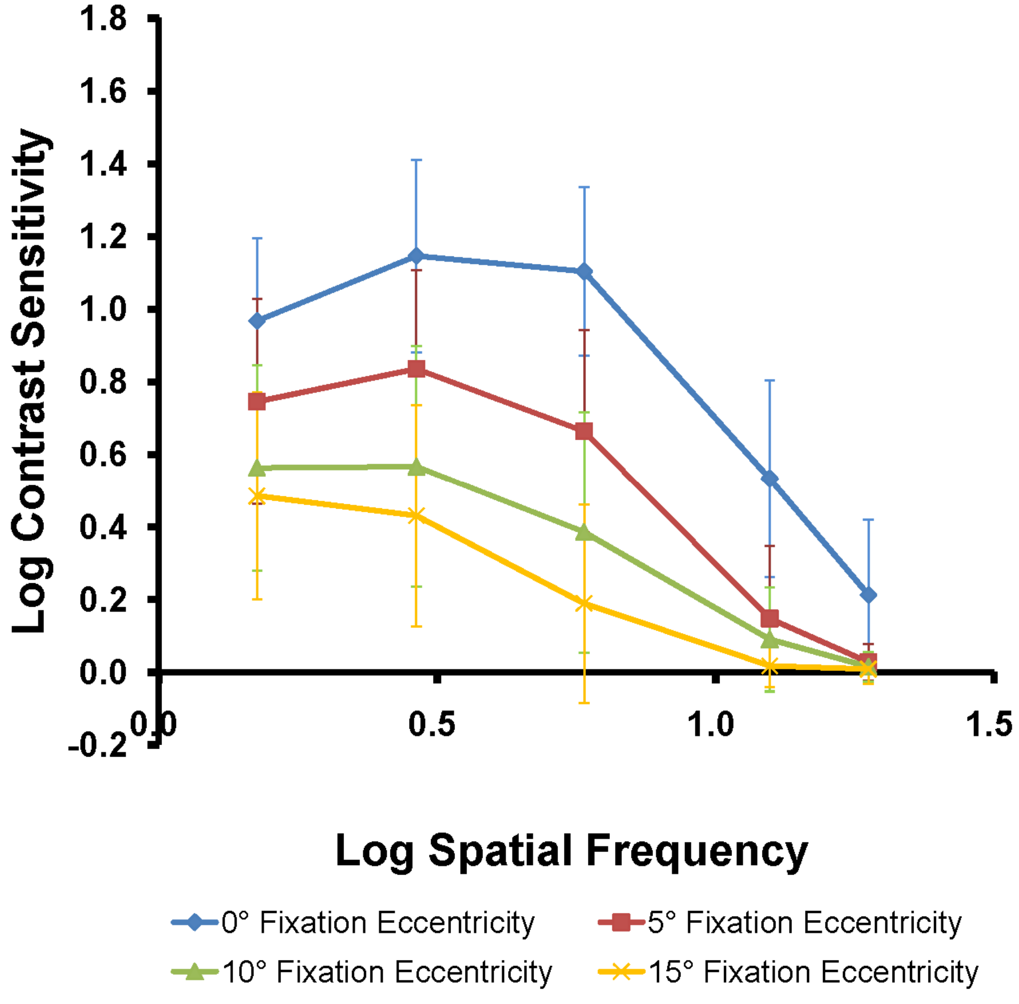

Figure 4.2.7. Contrast sensitivity functions at different fixation eccentricities of the older group with glare sources at 2.5°. Error bars indicate 1 SD.

Figure 4.2.8 shows the central AULCSF for each group under different glare eccentricities. AULCSF were significantly different under glare ($F = 59.713$, $p < 0.001$). For both age groups, the influence of glare on contrast sensitivity gradually decreased with increasing eccentricity with the central target. The younger group had significantly better AULCSF than the older group ($F = 14.786$, $p < 0.001$). The contrast sensitivities of the two age groups were affected differently by different glare eccentricities, as shown by an interaction effect ($F = 4.586$, $p = 0.005$). Using post-hoc comparisons, the AULCSF of the control conditions were compared with the AULCSF values of various glare eccentricities in the two age groups. AULCSF was decreased significantly when the glare sources were placed at 2.5° (Younger group: 1.28±0.20, $p < 0.001$; Older group: 0.98±0.29, $p < 0.001$) and 5.0° (Younger group: 1.33±0.18, $p < 0.001$; Older group: 1.06±0.24, $p < 0.001$), compared with no glare in both groups (Younger group: 1.44±0.18; Older group: 1.27±0.24). For the younger group, there were no significant differences in AULCSF between glare sources at 7.5° (1.43±0.19) and no glare ($p > 0.05$). On the other hand, glare sources at 7.5° (1.16±0.24) caused a significant reduction in AULCSF for the older group ($p = 0.004$). The younger age group had significantly better AULCSF than the older age group at all glare eccentricities and no glare (Control: $p = 0.044$; Glare sources at 2.5°: $p < 0.001$; Glare sources at 5.0°: $p < 0.001$; Glare sources at 7.5°: $p < 0.001$).

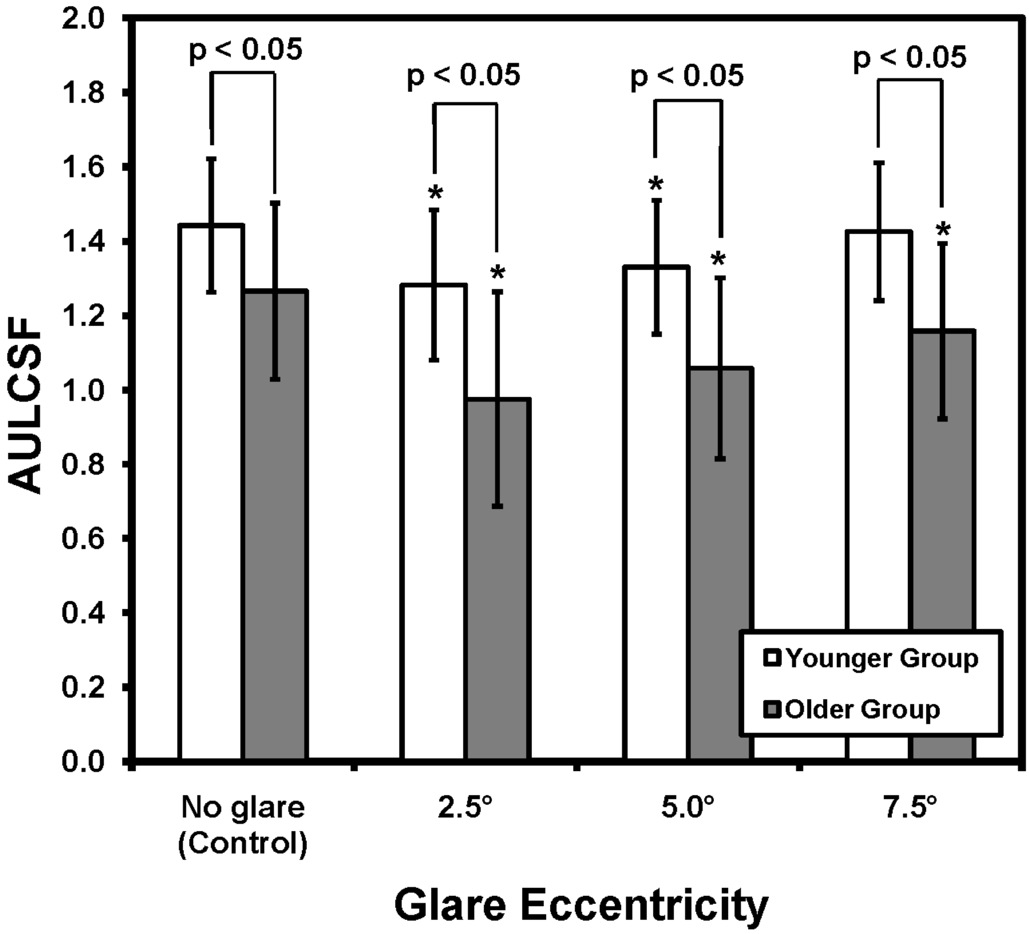

Figure 4.2.8. Central AULCSF under different glare eccentricities between the younger and older groups. * denotes $p < 0.05$ compared to control value for younger or older groups. Error bars indicate 1 SD.

There were no significant differences in central and peripheral AULCSF between the age groups under both control and glare conditions ($F = 3.443$, $p = 0.071$). As a result, the central and peripheral AULCSF under the effect of glare sources at 2.5° and without glare of the two groups were analysed together. These data are presented in Figure 4.2.9. The AULCSF decreased significantly with increasing fixation eccentricities ($F = 374.791$, $p < 0.001$). With the presence of glare, the AULCSF further decreased and the differences were statistically significant ($F = 80.778$, $p < 0.001$). A significant interaction between the effect of glare and fixation eccentricity was also found ($F = 3.992$, $p = 0.01$). Post-hoc comparisons showed that central AULCSF (1.35±0.23) was significantly better than AULCSF at other eccentric points, both with glare (5° fixation eccentricity: 0.64±0.20; 10°fixation eccentricity: 0.42±0.21; 15°fixation eccentricity: 0.28±0.19) and without glare (5° fixation eccentricity: 0.80±0.29; 10°fixation eccentricity: 0.59±0.28; 15°fixation eccentricity: 0.38±0.22) ($p < 0.001$). Glare also significantly reduced the AULCSF at all fixation eccentricities ($p < 0.001$).

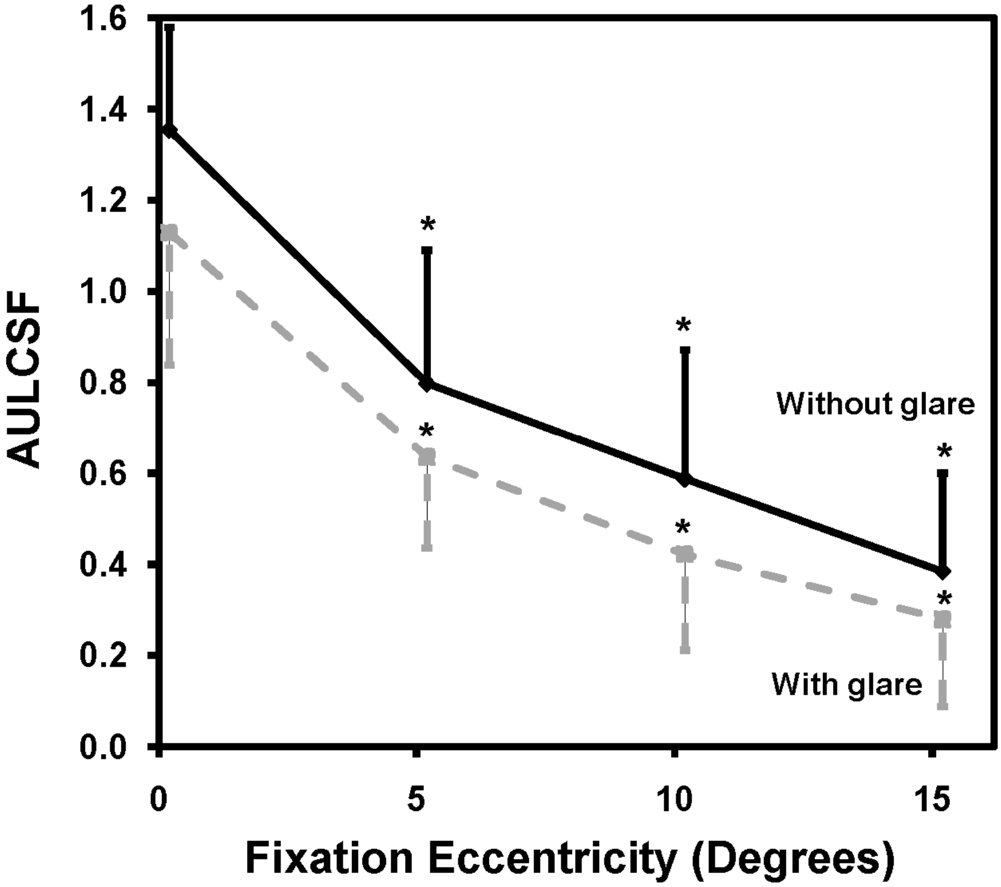

Figure 4.2.9. AULCSF at different fixation eccentricities with and without glare. * denotes $p < 0.05$ compared to control value for both with glare and without glare. Error bars indicate 1 SD.

4.2.4 Discussion

Central contrast sensitivity functions of a typical inverted U shape was found which was similar to previous study (De Valois et al 1974). It was shown that the poor contrast sensitivity in low spatial frequency of a single ganglion cell of cats was caused by the lateral inhibitory effect of the periphery of a cell’s receptive field (Enroth-Cugell and Robson 1966). Similar finding measured psychologically in human was confirmed to show that the effects of an antagonistic surround in the receptive field of cells caused the low spatial frequency sensitivity decrease (Daitch and Green 1969). Our data showed that younger subjects had significantly better central contrast sensitivity than older subjects for all glare eccentricities and the control conditions. This agrees with the findings of another study, that under daylight conditions with and without glare, contrast sensitivity decreased with age in normal subjects and this desensitization mainly increased for high-frequency optotypes (Sakamoto et al 2002). It was also reported that central contrast sensitivity decreased significantly with increasing age at all spatial frequencies. The main sensitivity loss happens in the group over 50 years of age at all spatial frequencies (Korth et al 1989). Age-related sparing of contrast sensitivity to gratings of low spatial frequency has also been reported (Crassini et al 1988). The present study is also consistent with the finding that there are no significant differences in contrast sensitivity as a function of age in the presence or absence of glare for a group of normal subjects aged 20 – 50 years (Harrison et al 1993). The age-related reduction of contrast sensitivity may be explained by the increasing yellowing of the crystalline lens as age increases (Korth et al 1989). Such a lens would lower the retinal luminance and increase the scattering inside the eye, thus the central contrast sensitivity is compromised. It was further proposed that the age-related changes at medium and high spatial frequencies was mainly due to the neural changes with age and the optical factors only had a minor effect at the high spatial frequency (Elliott 1987).

Central contrast sensitivity was significantly decreased when the glare sources were presented at 2.5° and 5.0° for the younger group and at 2.5°, 5.0° and 7.5° for the older group. The reduction might be accounted for by the forward scattering of light at angles away from the visual axis; this scattered light reduces the contrast of the retinal image (Abrahamsson and Sjostrand 1986). The strength of this veiling light depends on the angular distance of the glare from the object being viewed and the strength of light falling in the plane of the eye (Vos 2003). It has been found that the veiling luminance increases proportionally to the reciprocal of the squared angular distance of the glare from the object being viewed. This implies that as the incident angle of the glare source approaches the visual axis, the veiling luminance will increase dramatically and reduce the contrast of the target (Aslam et al 2007). This explains why there was no significant reduction in contrast sensitivity found for the younger group when the glare sources were presented at 7.5° because the veiling luminance was not strong enough to cause any significant contrast reduction of the image. On the other hand, more forward light scattering resulting from the degraded crystalline lens of the older subjects may cause contrast sensitivity reduction even when the glare sources were placed at 7.5°.

Our results showed that contrast sensitivity decreased significantly with increasing fixation eccentricities which agrees with the findings of Pointer and Hess (1989). Higher contrast sensitivity at the fovea was found for all frequencies and the sensitivities reduced progressively as eccentricity increased (Regan and Beverley 1983, Garcia-Perez and Peli 1999). For gratings of 2 and 6 cycles per degree, contrast sensitivity declined linearly with eccentricity. This decline was greater at 6 than at 2 cycles per degree (Wright and Johnston 1983). Retinal-eccentricity-related sparing of contrast sensitivity to gratings of low spatial frequency were also revealed (Crassini et al 1988). Similar observations could be found in Figures 4.2.3 – 4.2.6. As consistent with the previous findings (Kelly 1984), the contrast sensitivity functions from different eccentricities are similar in shape but as the eccentricity increases, the peak of curves shift towards lower spatial frequencies. This can be explained by the size variation of the receptive fields of retinal ganglion cells with increasing eccentricity (Fischer 1973, Rovamo and Virsu 1979). This finding was also supported by another study which proposed that peripheral spatial resolution for achromatic stimuli was limited by post-receptoral mechanisms which might be related to the density of human retinal ganglion cells (Anderson et al 1991).

Comparing the central and peripheral contrast sensitivity from the two age groups, there were no significant differences detected. However, younger observers had better detection than older observers for lower contrast values (Crassini et al 1988). Moreover, with the presence of glare, contrast sensitivities at different fixation eccentricities were further impaired. The reduction can also be accounted for by the forward scattering of bright light source (Abrahamsson and Sjostrand 1986).

Glare worsens peripheral vision which contributes greatly to driving performance. Glare may cause individuals having poor detection of objects and to drive significantly slower on dark and winding roads. The visibility of objects and roadways may be influenced under glare and the drivers will drive slower to compensate for this adverse condition (Theeuwes et al 2002). Also, Gray and Regan (2007) found that glare has a larger effect for low contrast than for high contrast objects. It causes a significant reduction of safety margins in executing turns. We should note that the objects in the real world are mostly below 100% contrast level. Under the effects of glare, the visibility of road signs and obstacles on the road will be affected and the deterioration will be more severe in the periphery as suggested by our findings. To summarize, peripheral vision is less sensitive than central vision. Contrast sensitivity decreases with age. Glare further deteriorates the peripheral vision and the effect of age on performance under glare can only be found in central vision.

4.3 Experiment III – The effects of age and glare on the useful field of view

4.3.1 Introduction

The results of Experiment II show that glare affects contrast sensitivity at different retinal eccentricities. Overall contrast sensitivity was reduced dramatically in the peripheral retina. The findings suggest that peripheral visual function should be investigated to understand the relationship of visual deterioration and driving performance under the effect of glare. Useful field of view (UFOV) is a measure of the functional peripheral vision under cognitive loaded conditions, where information can be located and extracted. It is also known as a measure of visual attention. Its size is smaller than the static peripheral visual field (Ball et al 1993). The UFOV is measured when central and peripheral tasks are performed simultaneously. The speed of visual processing of the 2 tasks is measured in msec and which is used to express as the size of the UFOV.

Performance of on-road driving was reported to be predicted by the UFOV (Wood 2002a). Simulated driving speed and the UFOV deteriorated significantly with increasing age (Roge et al 2005). Older drivers detected significantly fewer peripheral signals than younger drivers and this difference was increased as eccentricity increased (Roge et al 2004). Older drivers with shrinkage of the UFOV were reported to be six times more likely to be involved in one or more crashes in a retrospective study (Ball et al 1993). Furthermore, older drivers with a 40% or greater reduction in the UFOV were two-fold more likely to have an accident in the following 3 years (Owsley et al 1998a). Hence, the UFOV test seems to be a predictor of drivers at-risk.

The extent of the UFOV is reduced under visual distraction (Wood et al 2006). Glare is a common visual disturbance in driving. Experiment I showed that more than 90% of commercial vehicle drivers reported that various forms of glare adversely affected their driving. Glare also influences the central and peripheral spatial components of driving which have been investigated in Experiment II. Driving is a multifactorial task in which vision provides drivers with significant perceptual information. Driving problems relating to glare will become more important in the next few decades while the worldwide population ages. Since the UFOV is a good predictor of driving performance, understanding the effect of glare on the aged is valuable for day as well as night driving. The lack of knowledge on the UFOV under the influence of glare among drivers of different ages in the literature suggests that it would be worthwhile to conduct such a study. In the current experimental setting, the effect of glare as a visual distracter on the UFOV was studied in two age groups under controlled laboratory conditions.

4.3.2 Methods

Subjects

Based on a previous study (Wood et al 2006), 30 subjects were required in each group with a similar design to test the statistical significance. Sixty gender matched subjects were recruited from the Optometry Clinic, The Hong Kong Polytechnic University for this study. They were divided equally into two groups, the younger group (20-29 years old) with a mean age of 23.0±2.5 (SD) years and the older group (50-59 years old) with a mean age of 53.5±2.8 (SD) years. All subjects had monocular visual acuity at least 6/6 or better with intact central visual field in both eyes. They were free from ocular structural abnormalities and any history of ocular and brain injury or surgery. The cognitive function of each subject was also screened by going through the digit symbol, block design, digit span and symbol search subtests of Wechsler Adult Intelligence Scale (3rd Edition) and the "Trail making test A and B". After the project was explained, written informed consent was obtained from each subject. The study was approved by the University Human Subjects Ethics Sub-committee.

Apparatus

The UFOV was assessed using the commercially available computer software (UFOV software, Version 6.0.7, Visual Awareness, Inc.). The software was run on an IBM-compatible personal computer with a 17-inch touch-screen monitor (Entuitive Touchmonitor ET1725C-4CWE-3-G, Elo TouchSystems, California, USA). The test was composed of three increasingly difficult subtests - processing speed, divided and selective attention were evaluated. The targets subtended a visual angle of 1.7° vertically and 2.3° horizontally while the subjects' viewing distance was fixed at 55 cm. The first subtest assessed the processing speed (Figure 4.3.1). Subjects were requested to identify a car or a truck presented in a central fixation box. Divided attention was measured by the second subtest which involved the identification of the central target, which was the same task as in subtest 1, with localization of a peripheral target presented simultaneously at one of eight locations along the cardinal and oblique axes (Figure 4.3.2). The peripheral target was a silhouette of a car at a fixed eccentricity of 10° from the centre of the central target. The two tasks in the third subtest were the same as in subtest 2 but there were additional distracters comprising of forty-seven triangles of similar sizes and same luminance as the peripheral targets. The visual distracters filled up the rest of the visual display (Figure 4.3.3). Subjects responded by using a rod to touch the monitor in choosing the correct target and the correct location of the peripheral target for the central and peripheral tasks, respectively. A "2 down and 1 up" staircase was adopted to adjust the duration of target presentation. Scores for each subtest were expressed as the display duration of the task, in msec, at which the subject had 75% accuracy of the trials. The score ranged from 17 to 500 msec with lower scores representing better performance, i.e. required information can be located and extracted in a shorter period of time.

Figure 4.3.1. UFOV screen presentation for subtest 1 (Exp. III).

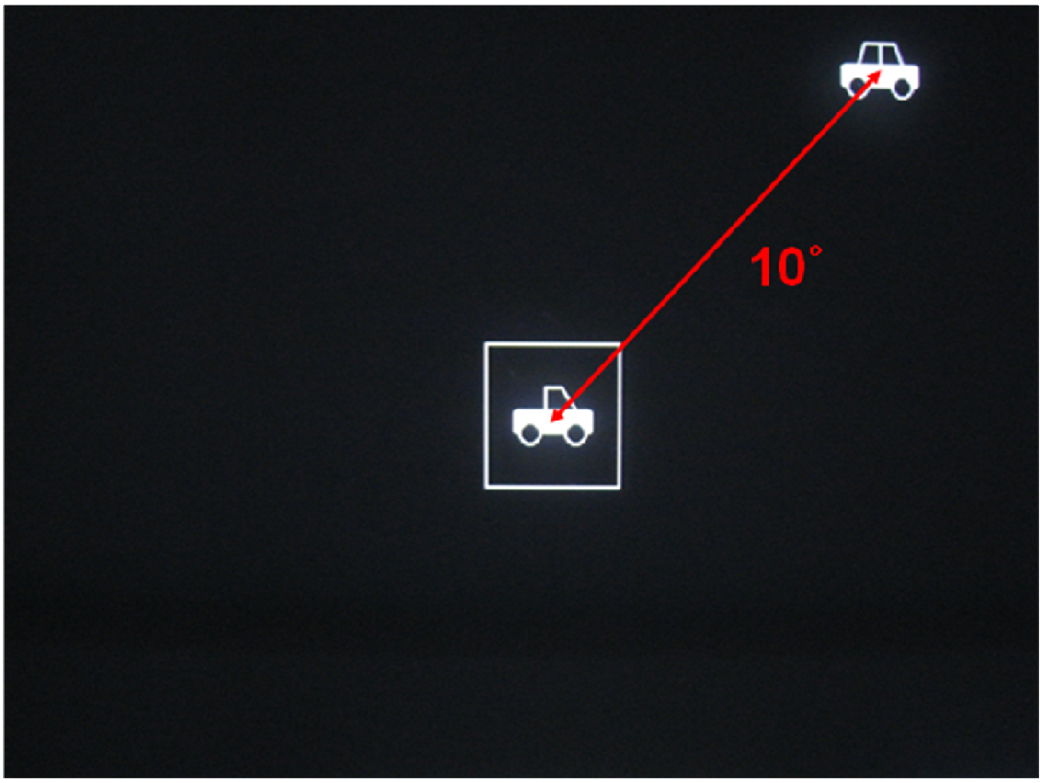

Figure 4.3.2. UFOV screen presentation for subtest 2 (Exp. III).

Figure 4.3.3. UFOV screen presentation for subtest 3 (Exp. III).

Subjects were asked to touch the screen directly using their hand or a rod to localize the peripheral target. No feedback on the response accuracy was given. For subtests 2 and 3, a correct response was counted if both the central and peripheral tasks were completed correctly.

Annular glare sources were presented at 2.5°, 5.0° or 7.5° from the centre of the display using LED projection. At each glare eccentricity, there were eight LEDs corresponding to the eight positions of the peripheral target (Figure 4.3.4). The image of the LED was projected to the designated position using the reflective property of a glass plate (3 mm thickness) (Figure 4.3.5). The luminance of each LED was around 103,000 cdm^{-2} after reflection.

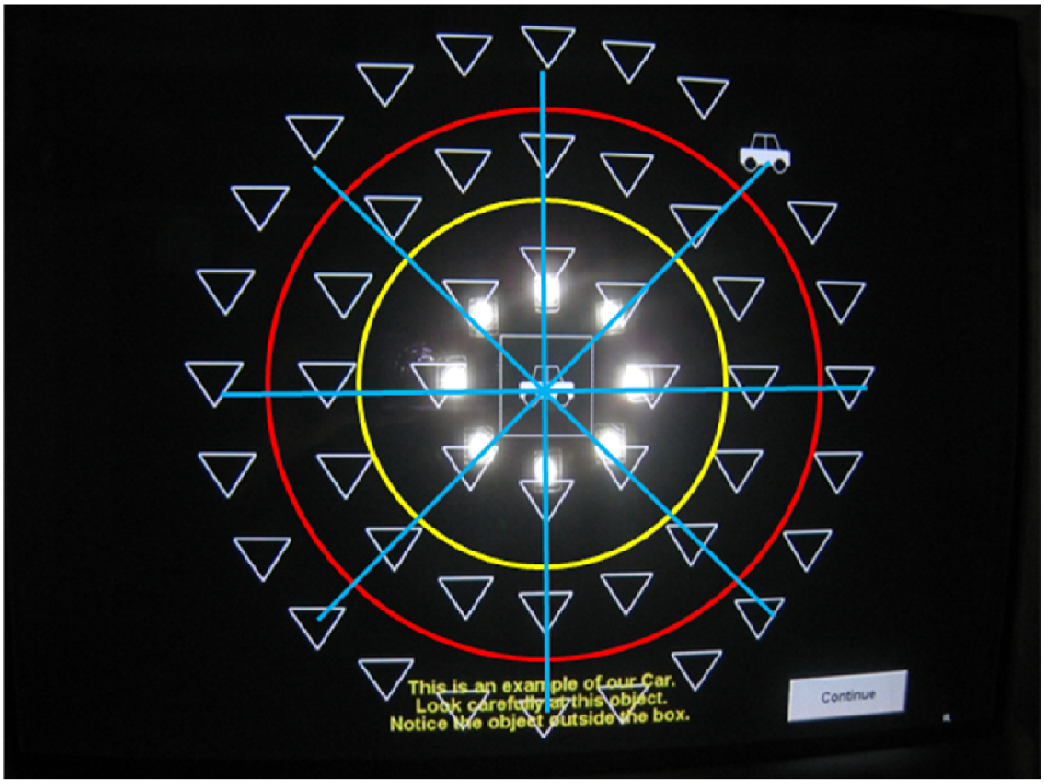

Figure 4.3.4. UFOV screen presentation for subtest 3 with glare sources at 2.5°. Yellow and red rings represent the glare eccentricities of 5° and 7.5°, respectively. Blue lines represent the 8 meridians.

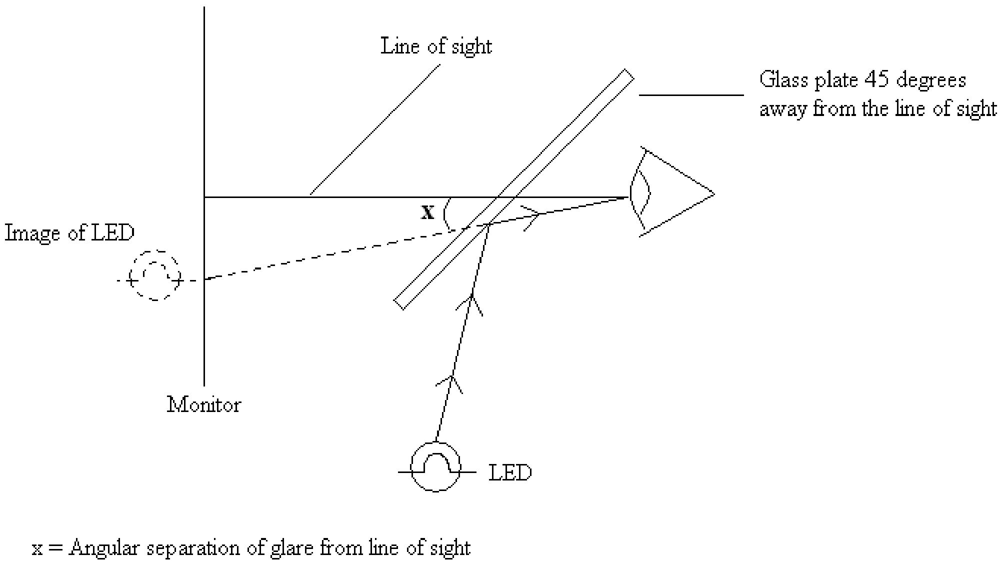

Figure 4.3.5. Experimental setup (Exp. III) for the glare condition.

Procedure

Before the experiment, subjects underwent a thorough eye examination. The subjects' working distance was fixed at 55 cm from the monitor by using a chin rest. Vision was optically corrected for the working distance. Testing was performed binocularly with natural pupils. The centre of the test monitor was aligned with the subject's dominant eye. The room was kept as dark and quiet as possible. Before the beginning of each subtest, a verbal explanation of the task was given to the subject and two practice trials were permitted. Measurements were conducted in order of increasing complexity. Subtest 1 was measured first, followed by subtests 2 and 3. The presentation sequences of different glare conditions in each subtest were randomized. Measurement of subtests without glare acted as controls. Breaks of 3 minutes were provided between subtests.

Statistical Analysis

The statistical analysis was performed using SPSS for Windows (version 16.0). A two-way repeated-measures ANOVA was performed to test the effects of glare eccentricity and age on each subtest. Post-hoc comparisons were conducted with Bonferroni tests to compare the main effects. Significant interaction effects were further examined using one-way repeated-measures ANOVAs and independent sample t-tests. An alpha level of 0.05 was considered as statistically significant for all analyses.

4.3.3. Results

Results of subtest 1 are presented in Figure 4.3.6. There were no significant effects of age ($F = 2.953$, $p = 0.092$) and eccentricity of glare source ($F = 1.492$, $p = 0.231$) on the scores of UFOV.

In subtest 2 (Figure 4.3.7), older subjects had significantly worse performance than the younger subjects ($F = 28.456$, $p < 0.001$). Glare also significantly affected these results ($F = 8.437$, $p < 0.001$) (Table 4.3.1). There was a significant interaction effect ($F = 4.839$, $p = 0.007$), with older subjects showing much worse performance than younger subjects at all glare eccentricities. For both age groups, glare sources at 7.5° compromised the performance significantly when compared with the control condition (Younger group: $p = 0.044$; Older group: $p < 0.001$). There were no significant differences between the scores under no glare condition and the other two glare eccentricities for the two age groups ($p > 0.05$).

Table 4.3.1. Mean and standard deviation of UFOV scores in subtest 2.

	Mean (standard deviation)	
	Younger group	**Older group**
Control	17.97±3.79 msec	31.00±19.99 msec
Glare sources at 2.5°	20.03±6.49 msec	44.83±37.13 msec
Glare sources at 5.0°	18.67±3.99 msec	35.23±24.53 msec
Glare sources at 7.5°	21.93±7.20 msec	59.50±43.97 msec

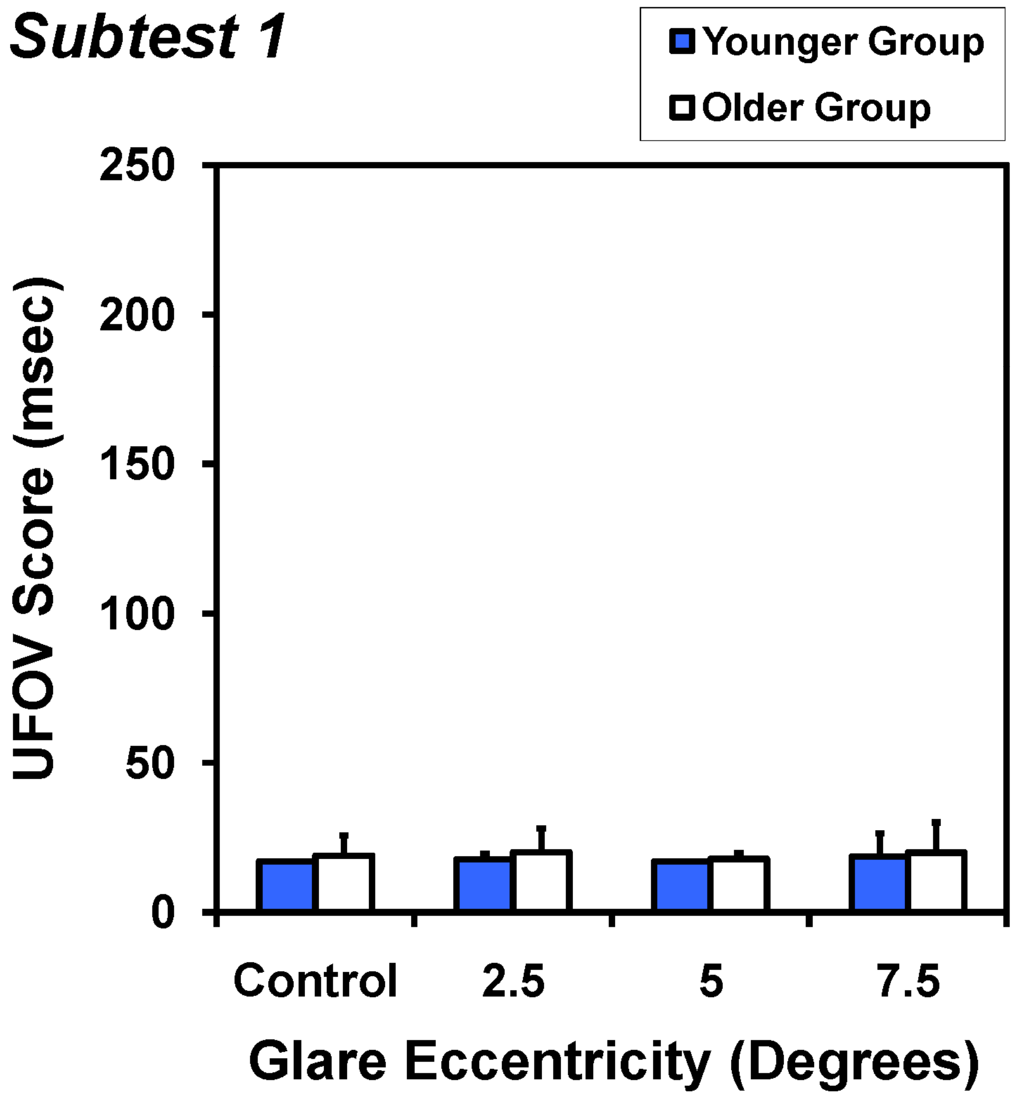

Figure 4.3.6. UFOV scores for subtest 1 at different glare eccentricities. Error bars indicate 1 SD.

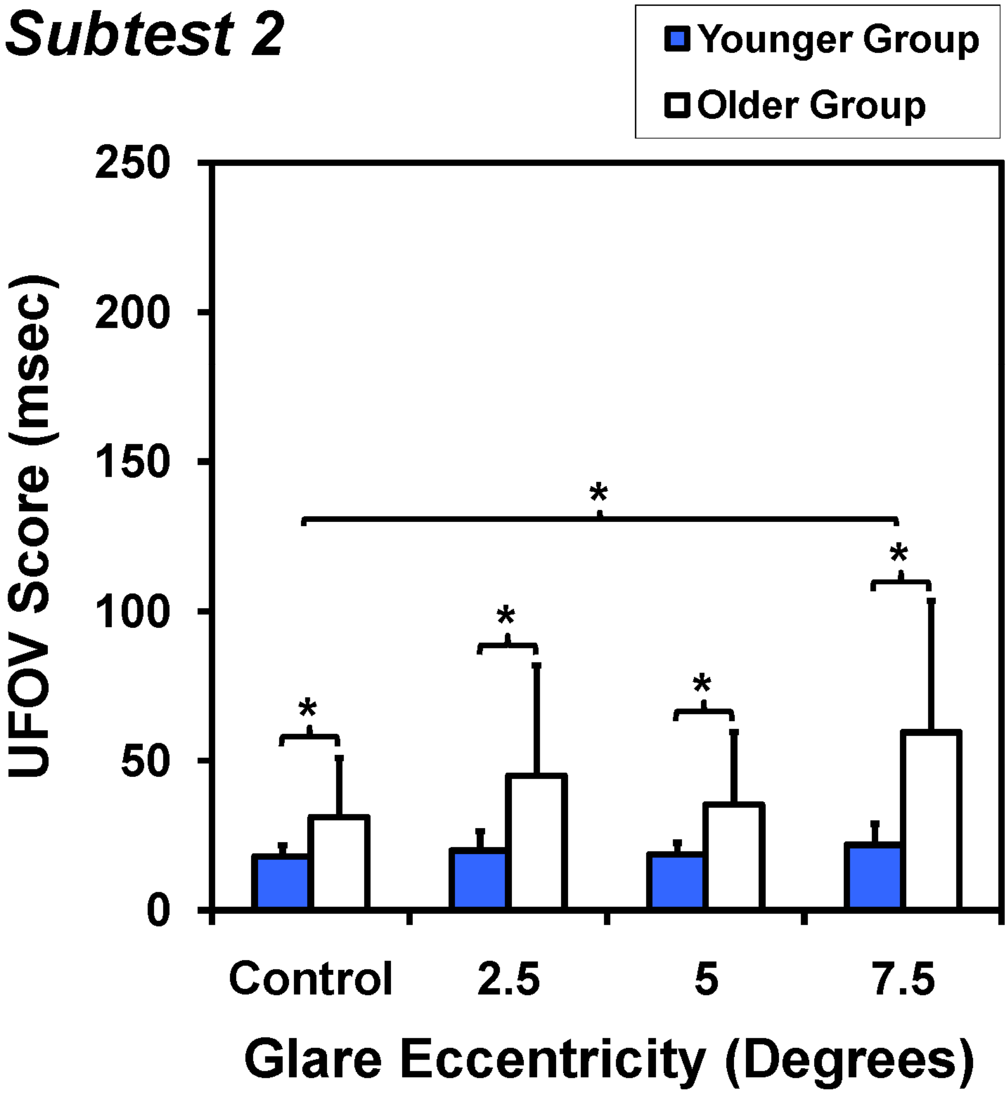

Figure 4.3.7. UFOV scores for subtest 2 at different glare eccentricities. Error bars indicate 1 SD. * denotes $p < 0.05$.

Figure 4.3.8 shows the score of subtest 3 under different conditions. At all glare eccentricities, younger subjects had significantly better performance than older subjects ($F = 86.942$, $p < 0.001$). The scores of UFOV were also significantly influenced by glare eccentricities ($F = 10.520$, $p < 0.001$) (Table 4.3.2). There were no interaction effects between age and eccentricity ($F = 2.387$, $p = 0.071$). For the younger group, significantly better scores were found at all glare eccentricities (Glare sources at 2.5°: $p = 0.004$; Glare sources at 5.0°: $p < 0.001$; Glare sources at 7.5°: $p < 0.001$) while the older subjects had significantly better performance only when the glare sources were presented at 2.5° (Glare sources at 2.5°: $p = 0.004$; Glare sources at 5.0°: $p = 0.196$; Glare sources at 7.5°: $p > 0.05$).

Table 4.3.2. Mean and standard deviation of UFOV scores in subtest 3.

	Mean (standard deviation)	
	Younger group	**Older group**
Control	81.90±32.41 msec	159.03±54.44 msec
Glare sources at 2.5°	54.97±40.61 msec	129.63±58.53 msec
Glare sources at 5.0°	50.00±35.05 msec	135.73±53.65 msec
Glare sources at 7.5°	50.07±17.79 msec	152.43±48.69 msec

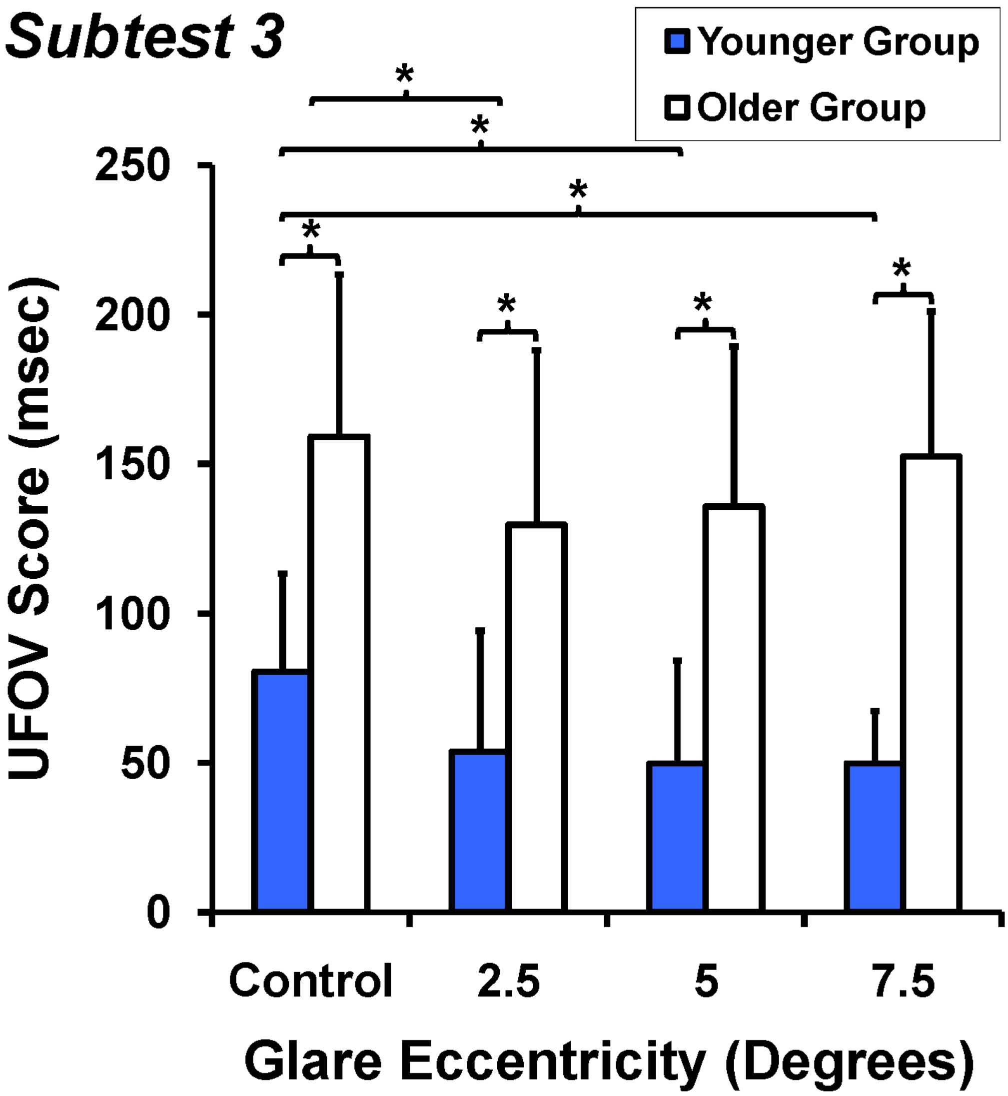

Figure 4.3.8. UFOV scores for subtest 3 at different glare eccentricities. Error bars indicate 1 SD. * denotes $p < 0.05$.

4.3.4 Discussion

Figure 4.3.6 shows that there were no differences between two age groups in the central processing performance under all glare and control conditions. However, Sekuler and co-workers (2000) reported that a group aged 15 – 44 years had better performance in the central task than a group aged 45 – 84 years. The difference in findings may come from the difference in measurement tasks between studies. Sekuler and co-authors (2000) requested the subjects to identify the letter at the centre of the screen and feedback was given if the response was incorrect.

Our result revealed that younger subjects had significantly better performance in the divided attention task than older subjects under all glare conditions. A similar finding was reported previously in that a group of 20-year-olds had significantly fewer errors of divided attention than groups of 40-year-olds and 50-year-olds. They also reported that errors in identifying the peripheral task increased linearly with age from 20 to 60 years (Sekuler et al 2000). Horswill and co-workers (2009) reported that deterioration of UFOV in a divided attention test was probably related to age-related differences in hazard perception. In the presence of glare at 7.5°, both groups showed a selective deterioration in subtest 2. As with the effect of glare on contrast sensitivity, a veiling luminance was cast on the peripheral task of subtest 2, causing the contrast of the peripheral retinal image to reduce (Abrahamsson and Sjostrand 1986). This would increase the difficulty in localizing the peripheral task and thus impair overall performance in the divided attention test. With a reduced UFOV, drivers may need more time to search for information and may need to perform more eye movements to gather information from the scene. As a result, they would have worse performance on visual search tasks and other visually oriented behaviours. It has already been reported that subjects with subtest 2 score of 353 msec or longer were 2.02 times more likely to have at-fault motor vehicle crashes (Ball et al 2006).

Younger subjects had better UFOV scores in subtest 3 than older subjects under both control and glare conditions. Interesting results were found from the selective attention test when glare sources are present. Performance of younger and older subjects was improved in the presence of glare sources at 2.5° while younger subjects also had better performance with the presence of glare sources at the other two glare eccentricities. It was originally hypothesized that glare would produce a synergistic effect with the triangular distracters to further impair the performance on the UFOV task. However, an opposite phenomenon was revealed from the results. The effect of glare may not be explained simply by the increase of veiling luminance in this situation. It should be noted that glare reduces the contrast of the retinal image but it also increases the mean luminance at the same time where the increased mean luminance was reported to improve the visibility of objects

(Aguirre et al 2008). In addition, the glare-induced reduction of retinal images' contrast would also affect the image quality of triangular distracters which may cause less distraction to the subjects. It is believed that glare sources in the selective attention test increased the mean luminance and at the same time, they masked the distracting effect of the triangular icons originally in the test by reducing the contrast of the icons' retinal images. For the older subjects, as stray light effect increased with age (Van Den Berg et al 2007), the effect of veiling luminance cast on the image of the peripheral tasks increased with glare eccentricities and the effect was more severe than that on the younger group. Therefore, unlike the younger group, the performance of older group did not improve with the presence of glare source at 5.0° and 7.5°. In general, the manufacturer advises that the UFOV test should be run in a testing room kept as dark as possible. Our result provided further experimental evidence to support this advice and all investigators and practitioners using UFOV should take it into account.

To summarize, ageing has no effects on central processing speed in this experiment. When attention is divided to analyse the central and peripheral tasks, both younger and older subjects have reduced ability to analyse the information; there is a selective deterioration when the glare is presented closer to the peripheral task. In the tests of selective attention where visual distracters were presented, the younger subjects demonstrated improved UFOV in the presence of glare; this effect was not shown in the older group except when the glare source was at 2.5°.

4.4 Experiment IV – The effects of age and glare on simulated driving performance

4.4.1 Introduction

Driving is a multi-factorial task in which vision contributes significant information to the drivers. Older drivers often complain of night driving visual difficulties (Owsley 1994) and may restrict night-time driving (Ball and Owsley 1991). An earlier study has shown that glare causes increased lane position variation and steering variation in simulated driving (Ranney et al 2000). Moreover, temporal safety margins decrease significantly in the presence of glare (Gray and Regan 2007). Pedestrian detection in on-road driving also worsens because of ageing and glare (Theeuwes et al 2002, Wood et al 2005). Probably the discomfort and disability glare of oncoming vehicle headlights makes it difficult for drivers to see at night and under twilight conditions (Owsley 1994).

To establish the link between glare and driving difficulty, Experiment I was conducted to obtain preliminary findings. In this experiment, more than 90% of the Hong Kong commercial vehicle drivers surveyed admitted that various forms of glare affected their driving performance. To understand which visual parameters were being affected by glare, Experiment II attempted to characterize the glare-induced disability on the central and peripheral contrast sensitivities. Results showed that central contrast sensitivity deteriorated significantly when glare sources were presented at 2.5° and 5.0° eccentricities for both younger and older groups. Contrast sensitivities of the older subjects were also decreased significantly under the influence of glare sources at 7.5°. Significantly reduced peripheral contrast sensitivity was also found for both age groups for glare at an eccentricity of 2.5°. The reduced contrast sensitivity observed in Experiment II suggested that reading of road sign may be compromised by sunlight or oncoming headlights. Using a UFOV test paradigm in Experiment III, it was further confirmed that glare of different viewing eccentricities caused different deteriorations of divided attention (subtest 2). With glare sources at an eccentricity of 7.5°, significantly worse divided attention performance was shown in both age groups. Since subtest 2 of UFOV has been proposed to predict the risk of crash involvement (Owsley et al 1998a), the results of Experiment III subtest 2 have highlighted a potential detrimental effect of glare on driving. Poor UFOV performance is also associated with worse on-road evaluations, motor vehicle collision statistics and driving simulator performance as evaluated by a meta-analysis (Clay et al 2005).

Since Experiments II and III involve laboratory-based tasks with no direct link to driving, the effects of glare on driving have not been established. To address this issue, the effects of glare on driving should be investigated using real driving tasks. Since there are a number of safety issues associated with such tasks on the roads in Hong Kong, driving simulators have been used to mimic a real driving task. Simulators are widely used in different research studies (Coeckelbergh et al 2002, Hoffman and McDowd 2010) and driving learning courses. Precise measurements of behaviours can be logged by the computer in modern simulators. Although a simulated driving environment cannot represent a real driving experience, a simulator provides a well-controlled environment in which the parameters can be altered without risking the safety of participants and other road users. A major criticism of employing simulators in driving research is that they will never reproduce the interactive driving tasks on the road. Another drawback is the (possible) experience of motion sickness induced when a driving task is simulated (Brooks et al 2010).

With the advent of improved health care technology, a longer life expectancy will result in a larger number of aged drivers on the road. The driving problems related to glare will be more prevalent in the next few decades. Since there is a lack of knowledge of driving performance under the influence of glare in middle-aged subjects, it is the aim of this study to understand the characteristics of the effects of glare on driving. The research question was tackled using a simulated driving platform developed in our laboratory.

4.4.2 Methods

Subjects

Since the driving simulator is a newly developed platform, we do not have previous performance statistics available to determine the needed subject numbers in this study. Based on similar studies (Theeuwes et al 2002, Gray and Regan 2007), fifteen subjects were tested in each age group. Thirty male subjects were recruited from the Optometry Clinic, The Hong Kong Polytechnic University for this study. They were divided equally into two groups, the younger group (20-29 years old) with a mean age of 26.5±2.5 (SD) years and the older group (50-59 years old) with a mean age of 53.3±3.1 (SD) years. All subjects had monocular visual acuity at least 6/6 with intact visual field in both eyes (Humphrey Visual Field Analyzer), normal colour vision and normal cognitive function as measured by digit symbol, block design, digit span and symbol search subtests of Wechsler Adult Intelligence Scale (3rd Edition) and the “Trail making test A and B”. Habitual monocular visual acuities of all subjects reached the minimum requirement in the worse eye for driving commercial vehicles of $6/12^{+2}$. They were free from ocular structure abnormalities and any history of ocular and brain injury or surgery. After the project details were explained, written informed consent was obtained from each subject. The study was approved by the University Human Subjects Ethics Sub-committee.

All subjects had a valid Hong Kong commercial vehicle driving licence for more than 3 years. Younger and older subjects held the licence for 5.8±2.5 (SD) years and 29.9±5.9 (SD) years, respectively. In terms of last year driving experience prior to the date of the experiment, younger subjects drove 3.6±2.2 (SD) hours and 125.3±126.6 (SD) km per week while older subjects drove 17.9±18.1 (SD) hours and 379.8±378.1 (SD) km per week.

Apparatus

A self-developed driving simulation software programme was run using an IBM-compatible personal computer with a 42-inch plasma display (Hitachi 42PD5000MA, Japan). The effective display area was 922 mm horizontally and 522 mm vertically with a maximum resolution of 1024 x 1024 and a maximum refresh rate of 75 Hz. It subtended 54.2° horizontally and 32.3° vertically when the subject was sitting 90 cm from the monitor. Audio clips of engine ignition, running of engine, braking, collision with pedestrians and collision with other objects were incorporated into the programme. Different driving scenarios had been built into this programme. The subject controlled an automatic transmission van using a steering wheel with accelerator and brake pedals connected to the simulator. A digital speedometer was installed near the bottom of the screen which provided visual feedback to the subject. To follow the road condition in Hong Kong, the van was required to stay on the left hand side of a double lane track. The subjects were reminded that cars might approach from the opposite direction in the right lane. The subjects were asked to reach a destination and name all Chinese characters displayed on the road signs en route (except for the characters of the destination). Characters were named individually whenever they appeared. Subjects were requested to complete all tasks as quickly as possible while observing a speed limit of 50 km/h. The speed, position of the car relative to the lane, number of collision, number of wrong turns, reaction time to the movement of pedestrian and time used were recorded 50 times per second on the computer. There were four types of route with different settings. Subjects completed all the routes as described below.

Practice route

As driving a real car was different from operating a driving simulator, subjects familiarised themselves with the controls of the simulator by completing 2 practice routes. The routes were formed by a loop of 3.51 km which was composed of 20 straight road segments of various lengths and 24 corners (Figure 4.4.1). Subjects were required to execute a left turn at 4 corners. At the remaining corners, subjects encountered a cross junction. At the beginning of each test, a destination location was given to each subject. The subject had to reach the destination by following the road sign indication. Directional road signs were presented on the left hand side of the road and on the pedestrian path before each cross junction. At the junctions, drivers would read the information on the signs (Figure 4.4.2) and determine which direction they should go. The number of right and left turns at the cross junction was counter-balanced. Twelve pedestrians were incorporated at the scene in the middle of the walkway. These pedestrians might start to walk across the road when the car approached at the pre-set position of 35 m away from the pedestrian. Six of them were designed to do so and the rest would stay on the walkway. At that moment, the pedestrian subtended 2.35° vertically (approximately 1.44 m high in the real world). When the drivers perceived the pedestrian crossing, they had to stop the car completely as quickly as possible and the reaction time was then measured. When the road was clear, the subject could start the van again and continue the journey when he found the situation was safe. The subjects were reminded to observe the speed limits and keep the van in the middle of the lane.

Test 1

All settings remained the same as in the practice route but there were no reaction time tasks. Subjects were required to complete the route and name all the characters on each road sign only.

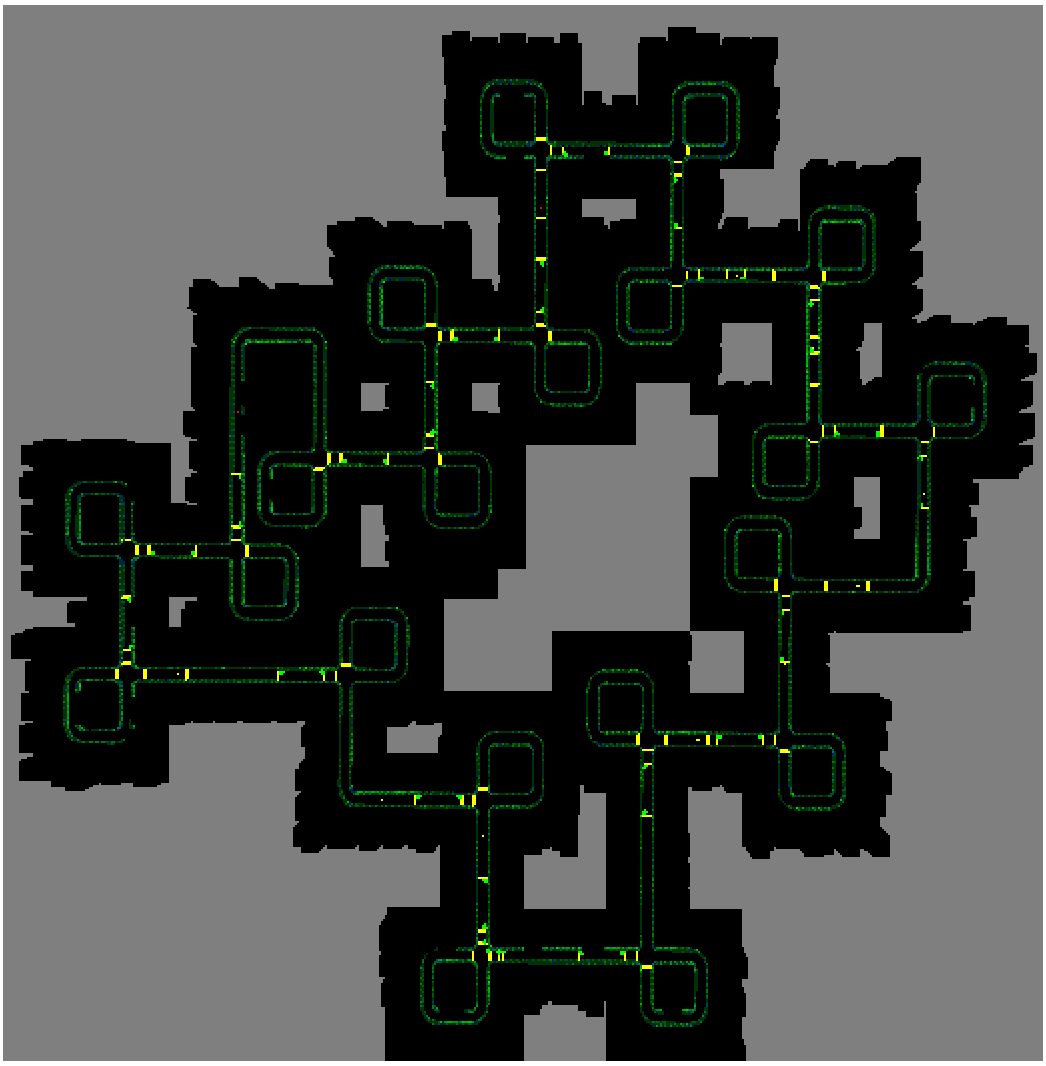

Figure 4.4.1. Circuit of practice route and test 1 (Exp. IV).

Figure 4.4.2. Bilingual road signs with directional information.

Test 2

A straight one-way route of 1.29 km was used. A grey wall was shown on the right hand side to conceal the views on the right. Five pedestrians were incorporated behind the wall at different position along the route. These pedestrians could not be seen by the subjects. These pedestrians would “walk through” the wall and cross the lane from the right hand side when the car was 35 m away (Figure 4.4.3). The pedestrian image would become visible once it started the motion. The subject had to stop the car completely when the pedestrian began to walk across the road. Reaction time was recorded when the subject stepped on the brake pedal. At the starting point, there were 90 m allocated for the subject to accelerate the van from an idle status. There were no pedestrians shown in this section. This allowed enough distance for the van to reach the 50 km/h limit. Then in the coming 150 m, a pedestrian would be randomly placed within this section to determine the reaction time. After the crossing, the subject would continue on the journey. The accelerating and testing sections were repeated for the remaining pedestrians. Pedestrians were placed randomly along the straight route in the testing session for each subject to minimise guessing during completion of the task.

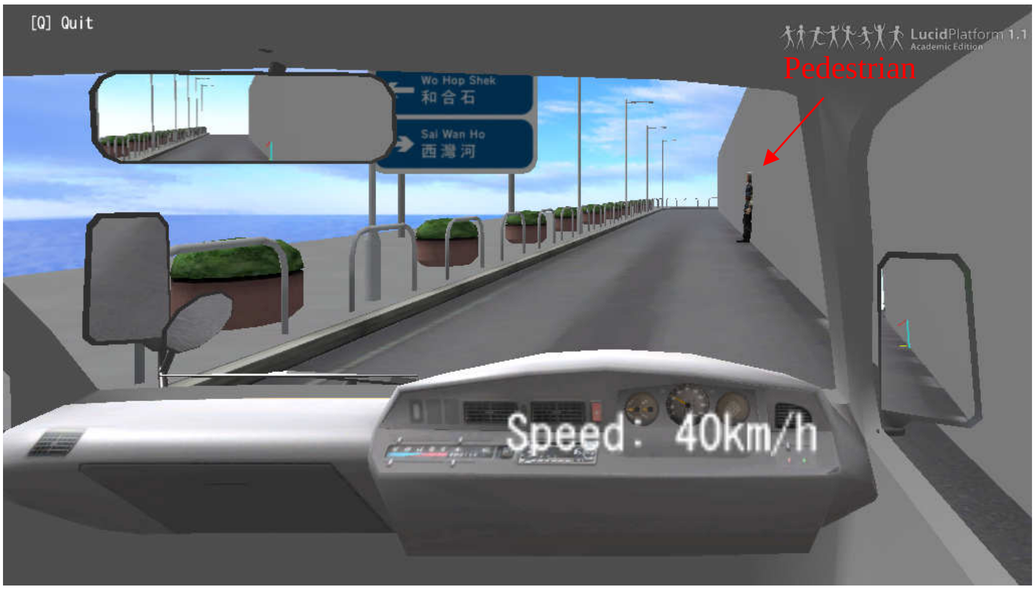

Figure 4.4.3. The pedestrian walks through the wall and crosses the road.

Test 3

A straight route of 4.98 km was used to study the character naming task and the reaction time task together. The environment and reaction time task settings were the same as described in tests 1 and 2. Ten directional road signs were presented on the left hand side of the left lane with five of them paired up with the reaction time task and placed in the same plane as the pedestrian. At the starting point of reaction time measurement, i.e. 35 m away from the pedestrian, the Chinese characters on the road sign would subtend the angular equivalent of 6/18 optotypes. The remaining five road signs were presented randomly within the testing section. The character naming and the combined reaction time tasks also appeared randomly. At the point of trigger, if the subject was viewing the centre of the road sign, the pedestrian would appear from the wall-side (right hand side of the lane) 10° from the primary line of sight. The arrangements followed the setting of the UFOV subtests 2 and 3 in Experiment III.

Parameters for outcome measures

The following parameters were measured.

Mean speed of travel (km/h)

This was the average speed of the van in the whole test, including the duration for which the van was stopped.

Area of speeding (km·sec/h)

As there was a speed limit of 50 km/h, the mathematical product of the speed higher than 50 km/h and the duration of speeding were measured. For example, if a subject drove the car at 60 km/h for 5 sec, the area of speeding would be 300 km·sec/h.

Mean speed before road sign (km/h)

The average speed of the vehicle was determined for the distance travelled from 50 m in front of the road sign until the van was past the road sign. In test 3, the measurements were taken only for the road sign reading tasks, and not paired up with any combined reaction time tasks.

Mean lateral offset (m)

This was the mean absolute lateral distance that the van deviated from the centre of the lane.

Variation of lateral offset

This was the standard deviation of the lateral distance of the van offset from the centre of the lane. This variable measured steering stability.

Area of lane crossing (m·sec)

This was the mathematical product of lateral offset in distance and duration.

Number of collision

This was the number of collisions recorded with the van and other objects, such as pedestrians, road signs and buildings.

Number of wrong turn

In practice route and test 1, subjects were provided a destination and they needed to follow the instructions on the direction signs to reach the destination. If they turned wrongly at the corner, one wrong turn was counted. Subjects would then be instructed by the examiner orally to get back on the course by making 3 or 4 extra turns.

Number of characters named correctly

This was the number of characters recognized by the subject on each road sign. There were three Hong Kong locations on each road sign and each location included three characters. All of the locations chosen had a similar number of strokes and stroke frequency which were calculated following a previous study (Zhang et al 2007).

Mean reaction time (sec)

The average reaction time in the whole test was calculated.

Number of reaction time task missed

This was the number of times that the subject gave no responses to the pedestrian's crossing.

Completion time (sec)

This was the duration used to complete the whole test.

A spot light (12 V, 50 W, 36 degrees) was used as a glare source. It projected a strong illumination on the screen. A plastic transparent protector was fixed on the plasma screen to increase the reflectance and scattering of the glare effect. The spot light was reflected and scattered by the imperfect surface of the plastic transparent protector (Figure 4.4.4). The luminance of this spot light was around 22,600 cdm^{-2} after reflection. The glare was placed at the end of the left lane (Figure 4.4.5). As a result, when the vehicle was 35 m away from the road sign and the pedestrian, with a viewing distance of 90 cm, the glare would be 7.5° and 2.5° away from the road sign and the pedestrian, respectively.

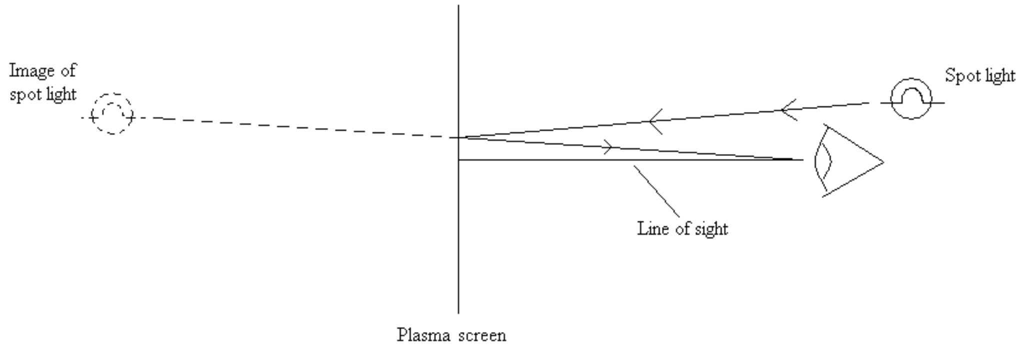

Figure 4.4.4. Experiment setup (Exp. IV) for the glare condition.

Figure 4.4.5. Position of the glare projection - the yellow star represents the location of the glare.

Procedure

Before the experiment, subjects underwent a thorough eye examination. As previously noted, the subjects' viewing distance for this simulation was around 90 cm. The sitting position of the subject was aligned with the steering wheel and also the centre of the left lane. Driving performance was measured binocularly with natural pupils, and using the drivers' habitual spectacles. The room was kept as dark and quiet as possible. Before tests 1 – 3, two practice routes were provided for the subject to familiarize them with the controls of the simulated driving system and the tasks they faced in the subsequent tests. The subjects practiced more than 10 minutes for the two routes. Test 1 was performed first, followed by tests 2 and 3. The measurement without glare served as a control. The assessment sequence of control and glare conditions in each test was randomized. A 3-minute break was given between each test.

Statistical Analysis

The statistical analysis was performed using SPSS for Windows (version 16.0). A two-way repeated-measures ANOVA was performed to test the effects of glare and age on each outcome measure. Post-hoc comparisons were conducted with Bonferroni tests to examine the significance of main effects and interactions. Significant effects were further examined by one-way repeated-measured ANOVA and independent sample t-tests. An alpha level of 0.05 was taken as statistically significant.

4.4.3. Results

Test 1

Results are summarized in Table 4.4.1 and 4.4.2. Younger drivers drove significantly faster than the older drivers by 9.18% and 7.96% under control and glare conditions, respectively. The mean speed was also significantly decreased by 2.24% and 1.16% for the younger and older groups under the influence of glare. The mean speed before road signs of younger drivers was significant lower by 1.74 km/h with the presence of glare ($t = 4.808$, $p < 0.001$) while there was no significant difference for older drivers ($t = 0.558$, $p < 0.586$). For the effects of age, younger subjects only drove faster before road sign than older subjects in the control condition by 10.6% ($t = -3.544$, $p = 0.002$) while there was no significant difference between the 2 age groups under glare ($t = -2.127$, $p > 0.05$). Under the effect of glare younger subjects deviated less significantly from the centre of the lane. Younger drivers also had significant better steering stability and used 25.60 sec and 29.06 sec less than the older subjects to complete the course for the control and glare conditions, respectively. There were no effects of glare and age on area of speeding, area of lane crossing, number of collision, number of wrong turn or number of characters named correctly.

Table 4.4.1. Mean and standard deviation of outcome measures in test 1.

	Mean (standard deviation)			
	Younger group		Older group	
Outcome measures	**Control**	**With glare**	**Control**	**With glare**
Mean speed (km/h)	40.10 (3.59)	39.20 (3.28)	36.73 (3.45)	36.31 (3.75)
Area of speeding (km·sec/h)	0.07 (0.08)	0.06 (0.08)	0.05 (0.06)	0.06 (0.06)
Mean speed before road sign (km/h)	42.62 (2.68)	40.88 (2.92)	38.57 (3.51)	38.30 (3.69)
Mean lateral offset (m)	0.84 (0.20)	0.82 (0.16)	1.16 (0.27)	1.08 (0.31)
Variation of lateral offset	0.45 (0.10)	0.45 (0.09)	0.61 (0.17)	0.58 (0.15)
Area of lane crossing (m·sec)	0.82 (1.61)	0.67 (1.55)	5.44 (11.80)	3.39 (6.17)
Number of collision	0	0	0	0
Number of wrong turn	0.07 (0.26)	0.07 (0.26)	0.13 (0.35)	0.20 (0.56)
Number of characters named correctly	119.20 (1.93)	119.20 (1.78)	118.27 (3.22)	117.27 (5.01)
Completion time (sec)	299.13 (29.37)	307.27 (31.44)	324.73 (31.54)	336.33 (52.54)

Table 4.4.2. Statistical analysis of outcome measures in test 1.

	Effect of glare		Effect of age		Interaction effect	
Outcome measures	**F**	**p**	**F**	**p**	**F**	**p**
Mean speed (km/h)	4.952	0.034*	6.260	0.018*	0.655	0.425
Area of speeding (km·sec/h)	0.034	0.854	0.516	0.479	0.448	0.509
Mean speed before road sign (km/h)	11.046	0.002*	8.464	0.007*	5.901	0.022*
Mean lateral offset (m)	5.100	0.032*	11.439	0.002*	1.823	0.188
Variation of lateral offset	1.534	0.226	8.964	0.006*	0.757	0.392
Area of lane crossing (m·sec)	1.262	0.271	2.631	0.116	0.947	0.339
Number of collision	-	-	-	-	-	-
Number of wrong turn	0.104	0.749	1.189	0.285	0.104	0.749
Number of characters named correctly	0.772	0.387	1.889	0.180	0.772	0.387
Completion time (sec)	3.876	0.059	4.619	0.040*	0.120	0.732

* denotes $p < 0.05$.

Test 2

Younger subjects finished the test in a significantly shorter time with a significantly higher mean speed than the older subjects. Younger subjects used 9.27 sec and 7.20 sec less than the older subjects to complete the course under the control and glare conditions while they drove 6.69% and 5.92% faster than the older subjects without and with glare, respectively. The mean lateral offset was significantly lower by 0.09 m and 0.06 m for the younger and older groups under the glare condition. Both glare and age influenced the mean reaction time significantly. Older subjects significantly increased the reaction time by 18.87% under glare conditions ($t = -3.102$, $p = 0.016$) while younger subjects had no difference in mean reaction time under both control and glare conditions ($t = -1.201$, $p > 0.05$). Younger group had quicker responses than older group by 26.98% and 16.98% with ($t = 5.159$, $p < 0.001$) and without ($t = 2.489$, $p = 0.038$) the presence of glare. The effects of glare and age were not evident on area of speeding, variability of lateral offset, area of lane crossing, number of collisions and number of reaction time targets missed. Table 4.4.3 and Table 4.4.4 show the results and the statistical analyses.

Table 4.4.3. Mean and standard deviation of outcome measures in test 2.

	Mean (standard deviation)			
	Younger group		Older group	
Outcome measures	**Control**	**With glare**	**Control**	**With glare**
Mean speed (km/h)	35.70 (1.46)	35.42 (1.62)	33.46 (2.32)	33.45 (2.25)
Area of speeding (km·sec/h)	0.07 (0.10)	0.06 (0.06)	0.04 (0.04)	0.07 (0.07)
Mean lateral offset (m)	0.59 (0.15)	0.50 (0.15)	0.61 (0.17)	0.55 (0.18)
Variation of lateral offset	0.34 (0.08)	0.30 (0.06)	0.35 (0.09)	0.35 (0.10)
Area of lane crossing (m·sec)	0	0	0.11 (0.39)	0
Number of collision	0	0	0.07 (0.26)	0
Mean reaction time (sec)	0.88 (0.16)	0.92 (0.15)	1.06 (0.23)	1.26 (0.20)
Number of reaction time missed	0	0	0	0
Completion time (sec)	125.40 (4.50)	126.87 (5.79)	134.67 (10.03)	134.07 (9.41)

Table 4.4.4. Statistical analysis of outcome measures in test 2.

	Effect of glare		Effect of age		Interaction effect	
Outcome measures	**F**	**p**	**F**	**p**	**F**	**p**
Mean speed (km/h)	0.383	0.541	9.757	0.004*	0.355	0.556
Area of speeding (km·sec/h)	0.406	0.529	0.077	0.784	3.202	0.084
Mean lateral offset (m)	7.630	0.010*	0.530	0.473	0.431	0.517
Variation of lateral offset	3.497	0.072	0.687	0.414	2.879	0.101
Area of lane crossing (m·sec)	1.085	0.306	1.085	0.306	1.085	0.306
Number of collision	1.000	0.326	1.000	0.326	1.000	0.326
Mean reaction time (sec)	10.850	0.003*	18.734	< 0.001*	4.501	0.043*
Number of reaction time missed	-	-	-	-	-	-
Completion time (sec)	0.188	0.668	9.548	0.004*	1.069	0.310

* denotes $p < 0.05$.

Test 3

As with test 2, younger subjects significantly finished the test by 12.06 sec and 10.93 sec faster than the older subjects in both control and glare conditions. Younger subjects drove 5.70% and 5.01% faster than the older subjects without and with glare, respectively. Glare also caused the subjects to drive significantly slower by 3.14% and 2.51% and to use significant 3.29% and 2.63% more time to complete the course for the younger and older groups, respectively. With the presence of glare, all drivers had significant 10.42% and 7.84% less deviation from the centre of the lane, significant 9.38% and 6.25% better steering stability and drove significantly slower by 1.26 km/h and 0.95 km/h before the road sign for the younger and older drivers, respectively. For the reaction time task, the mean reaction time was significantly longer with the presence of glare in both groups, especially for the older subjects ($F = 30.808$, $p < 0.001$). Under the glare condition, the reaction time of younger and older subjects increased by 28% and 25%, respectively. On the other hand, older subjects were slower than the younger subjects by 46.00% and 48.78% in mean reaction time under the control and glare conditions, respectively. There were no effects of glare and age on area of speeding, area of lane crossing, number of collision, number of characters named correctly and number of reaction time task missed. A summary of results is given in Table 4.4.5 and Table 4.4.6.

Table 4.4.5. Mean and standard deviation of outcome measures in test 3.

	Mean (standard deviation)			
	Younger group		**Older group**	
Outcome measures	**Control**	**With glare**	**Control**	**With glare**
Mean speed (km/h)	40.07 (1.77)	38.81 (2.40)	37.91 (2.21)	36.96 (2.41)
Area of speeding (km·sec/h)	0.09 (0.11)	0.10 (0.11)	0.09 (0.09)	0.13 (0.11)
Mean speed before road sign (km/h)	45.31 (2.84)	41.35 (4.33)	42.56 (2.69)	40.39 (4.69)
Mean lateral offset (m)	0.48 (0.12)	0.42 (0.11)	0.51 (0.12)	0.47 (0.12)
Variation of lateral offset	0.32 (0.05)	0.29 (0.05)	0.32 (0.06)	0.30 (0.08)
Area of lane crossing (m·sec)	0	0.30 (1.13)	0	0
Number of collision	0	0	0	0
Number of characters named correctly	90.00 (0.00)	89.47 (1.36)	89.33 (1.63)	89.13 (1.60)
Mean reaction time (sec)	1.00 (0.19)	1.28 (0.27)	1.46 (0.34)	1.83 (0.36)
Number of reaction time task missed	0	0.07 (0.26)	0	0
Completion time (sec)	219.07 (9.85)	226.27 (14.84)	231.13 (15.22)	237.20 (16.16)

Table 4.4.6. Statistical analysis of outcome measures in test 3.

	Effect of glare		Effect of age		Interaction effect	
Outcome measures	**F**	**p**	**F**	**p**	**F**	**p**
Mean speed (km/h)	36.404	< 0.001*	6.525	0.016*	0.678	0.417
Area of speeding (km·sec/h)	2.037	0.165	0.189	0.667	0.459	0.504
Mean speed before road sign (km/h)	33.364	< 0.001*	2.170	0.152	2.798	0.106
Mean lateral offset (m)	11.232	0.002*	0.995	0.327	0.173	0.681
Variation of lateral offset	5.402	0.028*	0.072	0.791	0.021	0.886
Area of lane crossing (m·sec)	1.062	0.312	1.062	0.312	1.062	0.312
Number of collision	-	-	-	-	-	-
Number of characters named correctly	0.972	0.333	2.578	0.120	0.201	0.657
Mean reaction time (sec)	29.613	< 0.001*	30.808	< 0.001*	0.589	0.449
Number of reaction time task missed	1.000	0.326	1.000	0.326	1.000	0.326
Completion time (sec)	21.201	< 0.001*	5.307	0.029*	0.155	0.697

* denotes p <0.05

4.4.4 Discussion

Younger drivers drove significantly faster than older drivers in all tests and this resulted in using less time to complete the whole course. A similar finding was reported by Wood and co-authors (2009), that older drivers needed significantly longer time to complete the tasks than younger drivers in a closed-road circuit. While under the effect of glare, the mean speed of both groups was reduced significantly in tests 1 and 3 but not in test 2. Both groups also required significantly longer time to complete test 3. The main difference between test 2 and the other two tests was that the subjects had to name the characters on each road sign. The glare may compromise the contrast of the characters (Abrahamsson and Sjostrand 1986). The findings agreed well with the results of Experiment II in which both central and peripheral contrast sensitivity functions were severely reduced under the glare conditions. Therefore, the subjects had to reduce speed before the road signs under glare in simulated driving. Since the speed was lowered, subjects had more time to read the contrast-compromised characters on the road sign and thus no significant difference was found in naming the characters between the 2 testing conditions. A previous study also reported that older drivers compensate for visual impairments by modifying their driving behaviour (Ball et al 1998). We have also shown that this compensation strategy also occurs in younger drivers under adverse conditions, for example, glare. Glare may also cause individuals to drive significantly slower on dark and winding roads (Theeuwes et al 2002).

The position of the vehicle relative to the centre of the lane was evaluated by the mean lateral offset. The results were quite consistent in the mean lateral offset of all three tests: significantly lower values were shown in the presence of glare for both age groups. The results revealed that the drivers were more cautious in driving under glare and hence showed less deviation from the centre of the road under adverse conditions. Moreover, under the glare condition, the driving speed was generally slower which may be a factor which makes it easier for drivers to control the vehicles. In test 3, steering stability was also found to be better in the presence of glare. This may be explained by the lower driving speed, the increased level of driver's attention and caution. Since this glare is static, it also gives an additional reference point for the subjects to track their position in the lane. As under adverse driving conditions, drivers would drive much slower to allow compensation (Theeuwes et al 2002) and this results in better control of the vehicle. This further illustrates that the control of the vehicle is speed related. Moreover, older subjects had more deviated in driving and larger variation of lateral offset than younger subjects either with or without glare in test 1. These findings imply that older drivers have worse handling techniques than young drivers in this driving simulator. Similar stability findings were not revealed from tests 2 and 3 because only a straight road was used in both tests while more turnings were necessary from test 1.

In tests 2 and 3, a reaction time task was included. Older subjects were found to have significantly longer reaction time under glare in test 2 while it was also the case for both groups in test 3. Similar findings were revealed from subtests 2 and 3 of Experiment III where younger subjects had better performance of UFOV in all testing conditions. Taking the most serious case as an example, older drivers had a 0.55 sec delay in responding to the task when compared with the younger drivers with the presence of glare in test 3. If it is assumed that the vehicle is moving at 50 km/h which is the speed limit set for this road, the delay in response would result in lengthening the braking distance by 7.6 m and the vehicle may pose considerable risk to other road users. Similarly, older subjects have worse performance on sign detection than younger drivers (Wood et al 2009) and have problems with situation awareness in the peripheral visual field (Kline et al 1992). This can be explained by the prolonged reaction time from our finding and slowing of information processing which occurs with increasing age (Wood and Troutbeck 1995). Older drivers might have anticipated these deficits and have already reduced their driving speed to compensate; this supposition is supported by their reduced mean speed in these experiments.

While being affected by glare, older drivers had significantly increased reaction time in test 2, while both groups had increased reaction time in test 3. These findings agreed with another study using a driving simulator to investigate the effect of glare which reported that the detection of low-contrast pedestrians was poor under the glare condition (Ranney et al 2000). A similar finding was also reported in a study using a closed-road circuit where introduction of glare sources caused reduced pedestrian detection distances and more targets to be missed (Theeuwes et al 2002). It was also concluded that glare caused a significant reduction in the safety margin and a significant increase in the number of collisions. The effect of glare was even more severe on the low contrast oncoming vehicles (Gray and Regan 2007). As with Experiments II and III, a veiling luminance that reduced the contrast of peripheral targets resulted from a bright glare source (Abrahamsson and Sjostrand 1986) which lowered the sensitivity of peripheral detection and increased reaction time. It was suggested that poor driving simulator performance might be useful in predicting accidents in the real world within the subsequent 5-year follow-up period (Hoffman and McDowd 2010).

To summarize, strategies for compensating for adverse driving conditions were found in older drivers, and also in younger drivers. Moreover, glare has significant influence on the reaction times of younger drivers even though they are free from ocular abnormalities. This indicates that the situation would be more complicated in older drivers, drivers with impaired vision (e.g. uncorrected refractive errors, corneal surgery, corneal oedema, cataract, diabetes and other eye diseases) and drivers in physiological states (e.g. poor contact lens wearing, tired, headache and tearing eye, etc).

Chapter 5 Summary of key findings

The significant findings of this study are summarized as in the followings:

Experiment I – Survey of visual attributes for commercial drivers in Hong Kong

- About 80% of commercial vehicle drivers experienced vision-related symptoms at work – 50% were glare related;
- Over 60% of all subjects had not had an eye examination in the previous 2 years; older drivers were more likely to have a previous eye examination;
- More than 90% of all subjects experienced glare-induced problems during driving while younger drivers were more likely to report problems with glare;
- With reference to the local licensing requirements, around 6-14% of all subjects had sub-standard visual acuity depending on which criterion was adopted while more older drivers failed the tests than expected;

Experiment II – The effects of age and glare on the contrast sensitivity functions

- Glare reduced the central contrast sensitivity;
- For central contrast sensitivity, the influence of glare on contrast sensitivity gradually decreased with increasing eccentricity of the glare source for both age groups;
- The younger group had significantly better central contrast sensitivity than the older group with no glare and with glare at all tested eccentricities;
- No age differences were found for peripheral contrast sensitivity under both no glare and glare conditions;
- Contrast sensitivity decreased significantly with increasing eccentricity;
- With the presence of glare, the peripheral contrast sensitivity further decreased;

Experiment III – The effects of age and glare on the useful field of view

- For subtests 2 (central recognition with peripheral localization) and 3 (central recognition with peripheral localization embedded with distracters) of UFOV, younger subjects had better performance than older subjects for all conditions;

- In subtest 2, glare sources at 7.5° compromised the performance when compared with the control condition for both age groups;
- In subtest 3, better scores in UFOV were found under all glare eccentricities for the younger group while the older subjects had significantly better performance only when the glare sources were presented at 2.5°;

Experiment IV – The effects of age and glare on simulated driving performance

- Both groups drove significantly slower under the influence of glare;
- Younger subjects drove faster than older subjects in both control and glare conditions;
- The mean speed before road signs of younger drivers was lower with the presence of glare;
- Younger subjects only drove faster before road sign than older subjects in the control condition;
- Under the effect of glare, subjects in the younger group deviated less significantly from the centre of the lane in test 1 (loop course), while the mean lateral offset was lower under the glare condition for both age groups in tests 2 (straight course with reaction time task) and 3 (straight course with reaction time task and naming of characters);
- Younger drivers also had significantly better steering stability and used

less time to complete the course than older drivers;

- Older subjects had significant longer reaction time under glare;
- Younger group had quicker response than older group with and without the presence of glare;
- In test 3, glare also caused the subjects to drive slower and to use more time to complete the course;
- The steering stability was better and the speed before road sign was lower under the glare condition for both age groups in test 3;
- In test 3, the mean reaction time was significantly longer for both age groups with the presence of glare especially for the older subjects.

Chapter 6 Conclusions

6.1 Overview

Commercial vehicle drivers represent a key user group of the land transport system. Many spend long hours on the road and their daily experience reflects the principal problems encountered by most road users. At the beginning, I have surveyed a sample of commercial vehicle drivers (predominately those of middle age) and most of them expressed glare intolerance as one of the commonly encountered visual difficulties at work. Glare is a common phenomenon associated with outdoor activities and this finding indicates that more details are needed to understand the relationship between glare and driving performance in the aging population. The information gathered from this survey leads to the development of 3 further experiments in this thesis. The effects of glare and age on vision and related driving performance have been investigated. Collectively, the hypotheses have been tested in 3 more studies. In all laboratory studies, older subjects were limited to ages 50-59 years in order to match with the sample of commercial vehicle drivers in Experiment I (around 53 years old).

6.2 Critical reviews of experimental designs

Experiment I is the first-ever study conducted on commercial vehicle drivers collecting the vision status and their views on driving-related environment in Hong Kong. Although these drivers were recruited from 12 locations, the diversity might not be sufficient to represent all commercial vehicle drivers, as nearly 80% of participants were franchised public bus and taxi drivers. The remaining subjects operated public and private light buses, light, medium and heavy-sized vehicles, private buses, special purpose vehicles and articulated vehicles. The subjects had the right to join or not to join the survey and / or the vision tests. Those drivers who had questionable visual performance might not have been willing to participate because they did not want their driving license challenged due to possible unfavourable visual outcomes; this is despite the fact that the purpose and confidentiality of this study were explained beforehand. On the other hand, those with knowledge of good vision might find that the study would not be useful to them, and thus would have little interest in participation. Both conditions may have affected the study results.

If collaboration with the Transport Department could be achieved, current commercial vehicle drivers should be randomly invited to join the study as a requirement of license renewal. Moreover, if their traffic accident and ticketing records could be retrieved, further analysis could be conducted to correlate with their vision status.

Although visual acuity was measured in this study, the causes of impairment were unknown. To investigate the cause, a visual acuity test with pin hole and an ocular health check with hand-held slit lamp and ophthalmoscope could be helpful to understand if the visual impairments of the commercial vehicle drivers were optically correctable. If the visual acuity of the subject can be improved by placing a pin hole in front of the eye and severe ocular health abnormality has been ruled out, the drivers are most likely suffering from uncorrected refractive error only. A simple pair of spectacles may help them to improve their vision to reach the required levels in Hong Kong. As a result, an estimation of the proportion of subjects who could achieve better vision with suitable optical corrections could be made.

Experiment II is a basic perceptual study to quantify the effects of age and glare on contrast sensitivity. Detection of objects under glare is compromised as shown in the results. Since a “yes / no” psychological staircase paradigm has been used, the target is always shown in each presentation. Therefore, the observer’s expectation can be maintained at the same level, although it is not criterion-free. To monitor the accuracy of the contrast sensitivity measurement, a series of blank presentations without the target could be randomly inserted between the target sequence to track the false positive rate in the response. A temporal forced choice paradigm could also be incorporated into the study to give a criterion-free procedure. To make the result more applicable in the real driving environment, market available headlamps could be used to replace the two fluorescent tubes as the luminance of the glare resembles the real situation but the test distance would need to be increased considerably.

In Experiment III, the commercially available software does not provide statistical data on the correctness of the central and peripheral tasks in subtests 2 and 3. It limits the analysis on the effect of glare eccentricity in these subtests which, if available, can confidently confirm whether the glare closer to the peripheral task causes more incorrect responses. The targets used in the UFOV test have been fixed at close to 100% contrast. If the contrast of the targets could be adjusted to lower levels, more information could be collected to represent the real environment as the objects outside the laboratory test are mostly below 100% contrast.

In Experiment IV, I have developed a computerized driving simulator to test the visual effects on the motor skills. This is an original development in collaboration with the Multimedia Innovation Centre at The Hong Kong Polytechnic University. The simulator incorporates a set of road signs using Chinese characters and is not available commercially. This device is expected to be useful for the implementation of future driving studies in Chinese-speaking communities. Other languages can be loaded into the programme to increase the versatility of the application elsewhere. The test course can also be tailor-made to meet the needs of experimenters. In the reaction time task, a simulated pedestrian has been used as the target to test a response from the driver. From the psychological point of view, this unrealistic presentation might raise additional questions in the subjects when they perceive the pedestrian walking out through the wall. A simple figure, such as a circle emerging from the wall, can solve this discrepancy among the subjects. But a pedestrian target was chosen in this experiment because of the proximity to the real situation. As the results are taken with a driving simulator, it is understood that the result may not be directly applied to the daily driving situation. However, the simulator offers a great flexibility in the experimental design and also well-controlled experimental conditions. The complexity of the course can be increased, such as by increasing the traffic flow, adding traffic lights, involving overtaking and by putting more pedestrians on the footpath. It is recognised that the control of a vehicle and a simulator are fundamentally different. Similar experiments can be repeated by using a real vehicle on a closed circuit although the closed circuit still shares the characteristics of an artificial environment, e.g. controlled traffic density and controlled ‘emergency’ events. Although an open circuit can reflect the real situation, there is little or no control over stimulus and response events which, in the present context, define the effects of glare on driver behaviour.

Since the luminance of the sun is extremely high, it has not been simulated in the laboratory tests as such high luminance will pose a potential hazard to the subjects. The glare simulation in these experiments has been designed to mimic the situation with the sun on the horizon. The sun on the horizon at dawn or dusk has a luminance of around 600,000 cdm^{-2} (Mischler 2004). The position of the glare source in Experiment IV resembles that dawn or dusk when the sun is closest to the horizon. When a driver is driving on a road, the light shines directly into the eyes even though the luminance of the sun is not at its peak at this moment. In Hong Kong, the letter size and the placement of different road signs are regulated (Transport Department 2009d). For the signs used in Experiment IV, the centre of the letter is around 0.41º-0.46 º and 1.32 º-1.47 º away from the upper and lateral edges, respectively. Therefore, the glare eccentricities have been selected at 2.5º, 5.0º and 7.5º to mimic the conditions when the sun is approaching the edge of the road sign. Similarly, the glare eccentricity arrangement has been adopted in Experiments III and IV as glare sources at 2.5º cause significant deterioration in contrast sensitivity.

In Experiment I, commercial drivers were identified to have glare-related problem in driving. Although the subjects in Experiments II and III were not commercial drivers, the findings could also be generalised to the commercial drivers and other drivers. It was because Experiments II and III were only laboratory experiments not related to the driving experience and characteristics of commercial drivers. Hence, the characteristics of a commercial driver would have no effect on the performance in these two experiments. For Experiment IV, if commercial drivers were recruited for the driving simulation test, they should have better driving experience which may affect the driving performance measured. However, the effect of glare was a major confounding factor for all drivers including both commercial and private drivers. Therefore, the outcomes measured in Experiment IV should be very similar between these two groups of drivers.

6.3 Implications and significance of findings

6.3.1 Effects of ageing are evident in individuals aged 50–59 years

Older individuals have demonstrated significantly worse visual performance than the younger subjects in most testing conditions. The mean ages of my subjects (range 50-59 years old) recruited in Experiments II to IV approach the general retiring age of the working population in Hong Kong. My findings suggest that the effect of ageing on driving-related performance is evident in individuals younger than those reported previously in the literature which are dealing with drivers aged 65 years or older (Horswill et al 2008, Wood et al 2009). Ignorance of the effects of ageing on drivers may compromise the safety aspects of all road users. There are a number of ways to create a safe driving environment for this group of individuals. For example, older drivers could be informed of this effect through education. They may adopt a ‘slow down’ strategy as a precaution. Older drivers should also consider not operating vehicles in conditions with low visibility, such as extreme lighting levels and rainy weather. From the perspective of the government, it may well be time to review the licensing requirements for the ageing population, especially for those drivers engaged in commercial activities.

6.3.2 Effects of glare on visual perception and driving-related visual performance

Nearly 80% of subjects surveyed in Experiment I experienced glare-induced problems related to sunlight. Glare is found to compromise adversely the reaction time of both younger and older drivers. In general, glare is a visual disturbance that affects the performance of drivers. Glare reduces visual contrast by projecting a veil of scattered light onto the retinal image of interest. Thus, object detection or resolution will be compromised. The detection of peripheral targets is selectively impaired by glare and the related reaction time will be increased. In the context of driving, the detection of peripheral objects is a key factor in safety because impaired UFOV is positively associated with overall and at-fault motor vehicle collisions (Cross et al 2009). Driving instructors are six times more likely to intervene in performance of individuals with slight to moderate visual field impairment, in part because of failure to detect peripheral obstacles and hazards and response to unexpected events (Haymes et al 2008). Although active visual scanning is involved in driving (which primarily involves central vision), there are unexpected events happening all the time. Drivers will direct their gaze towards these unexpected events after detection in their peripheral field. As a result, if the visibility of peripheral targets is compromised by glare, drivers may not be aware of the peripheral targets. This may lead to an accident if there is a dog or a child, for example, appearing suddenly at the roadside. In the presence of glare, drivers have adopted compensatory strategies in the driving simulator experiment to cope with this adverse condition. A number of measures including mean speed, mean speed before road signs, mean lateral offset, variation of lateral offset and completion time are affected by glare. It follows that the control of glare may enhance driving performance on the road. This is a good sign because drivers have already anticipated the problems arising from glare and they actively take measures, such as wearing sunglasses and decreasing the driving speed. In this context, it may be noted that 58.6% of our sample from Experiment 1 wore sunglasses while driving on some occasions. More studies are indicated in the future to minimize the impacts of glare on the drivers, e.g. glare control and ergonomic road designs.

6.3.3 Interaction effects

It was found that contrast sensitivity decreased with age, fixation eccentricity and the presence of glare. The effects of age on susceptibility to the effects of glare are only found in central vision. This study confirms and quantifies the effect of glare on peripheral vision which collects substantial information for driving. Based on the findings in Experiments I and II, Experiment III was conducted to understand the effects on the simultaneous perception in the UFOV assessment. Detections of central and peripheral objects are impaired in the presence of glare in Experiment II. Moreover, glare decreases the subjects' performance in subtest 2 of the UFOV (Experiment III) when the glare is closer to the peripheral target.

The central processing speed is not related to ageing in this task. When there are central and peripheral tasks simultaneously, the divided attention deteriorates selectively if the glare is placed closer to the peripheral task whereas younger subjects and older subjects in particular situations (glare sources at 2.5°) have improved UFOV in the presence of glare in the selective attention test where visual distracters are added to the divided attention test. Glare was reported as one of the visual difficulties at work in Experiment I. Here the distracting and disturbing effects from glare are demonstrated. The result shows that glare is a critical problem of middle-aged and even younger subjects in certain situations. This implies that the problem of glare could be more obvious in older drivers and / or drivers with impaired vision. Moreover, my findings from subtest 3 in the UFOV showed that there was interaction between the glare and the distracters; it may not totally reflect the real situation in driving. Driving is a dynamic activity and all the stimuli in the environment are in relative motion. Driving involves continuous cognitive processing to manage different dynamic visual information at the same time. The amount of information being processed is believed to be far more than that in the presentation in the UFOV test. Hence, the design of UFOV only partially fulfils the condition of real driving. If glare and other moving objects were located in the peripheral field in driving, it is expected that a worse effect in selective attention, rather than suppression between each other, would be found. Since driving is an interactive activity with moving objects, the dynamic visual function may be compromised in the case of glare sources and distracters together. This is an important issue for further studies.

6.3.4 Selective functional loss in the low / medium region of the spatial frequency contrast sensitivity function

There is selective visual loss in the low / medium region of the spatial frequency contrast sensitivity function with increasing fixation eccentricity under the effects of glare for both younger and older subjects. The contrast sensitivity function measures the overall visual performance of an individual whereas the visual acuity test measures the visual resolution limits at 100% contrast. These findings strongly indicate that the visual acuity test does not provide a complete assessment of the drivers' visual performance. Additional tests, such as low contrast visual acuity assessment with and without glare, should be considered to enhance the efficacy of visual screening for drivers.

6.3.5 Discrepancy in visual status and legal driving requirements

The data also show that most drivers in the sample have poor awareness of the importance of having a regular eye check. More public education is required to remind drivers of the importance of maintaining good vision on the road. Educational intervention with high-risk older drivers has been found to be successful in increased avoidance of visually challenging driving situations and reduced driving exposure. The drivers who received educational intervention are also more likely to admit to problems with their eyesight (Owsley et al 2003). In the present study, a significant percentage of commercial vehicle drivers who did not habitually wear optical correction, or who had licences with no mandatory corrective optical requirement failed the visual acuity test. It follows that either the initial visual screening procedure is not effective or the licensing system does not update the visual status with time. Policy makers should review the current licensing system based on these statistics. The incorporation of regular visual screenings in the licence renewal process is a potential solution. From the perspective of an optometrist, the low awareness of regular eye checks is also a major issue. Having an eye check not only helps drivers to maintain best possible vision by providing suitable corrections to comply with legal requirements, but also it is a good opportunity to detect any ocular pathology. It also allows the optometrist to explain to the drivers the visual-related driving problems. For example, a salt-covered windshield is found to lower the contrast sensitivity and increase the reaction time (Bachman et al 2006). This information can be shared with all drivers as they may not realize the importance of cleanliness of the windshield in driving. Sunglasses can also be prescribed if drivers are having problems with glare. A tri-blocker filter, which absorbs three spectral wavelengths and is transparent for other light of other wavelengths, can improve the contrast sensitivity of elderly subjects under daylight in the presence of glare (Sakamoto et al 2002). The prescription of light filters for night driving must be taken with care as it may reduce the overall luminance levels and only alleviate the problem of discomfort glare (Leguire and Suh 1993). In addition, currently there is a kind of photochromic lens which can become tinted in sunlight. The photochromic lens is coated with organic photochromic molecules that darken depending on the amount of ultraviolet light. This transient change of tinting can help to reduce discomfort glare as well as disability glare. However, the windscreen of the vehicle can block the ultraviolet light which triggers the change of tinting of the spectacles. In order to minimize glare problems, it may be possible to produce windscreens which incorporate this photochromic technology.

6.3.6 Development of a new driving simulator for Chinese communities

There are many driving simulators available on the market but none have incorporated Chinese characters into the system. Road sign detection is an important requirement in the study of vision and driving performance. The driving simulator here is a newly developed prototype, and still in need of validation. Such a study should be conducted before the research findings can be applied. With reference to a previous validation study (Shechtman et al 2009), a group of drivers should be recruited, and they should undergo a comprehensive eye examination to rule out any ocular abnormalities before starting the validation study. To determine the sample size, the dependent variables that having the largest variance and the smallest effect size should be used to perform the power analysis. Subjects should perform an on road driving assessment on one day and the driving simulator assessment on another day. The course of the simulator should be designed to be similar to the course of the on road driving assessment. During the assessments, the mean speed of travel, area of speeding, mean speed before road sign, mean lateral offset, variation of lateral offset, area of lane crossing, number of collision, number of wrong turns, number of characters named correctly, mean reaction time and completion time should be recorded. These parameters will be useful to determine the correlation between simulated and real driving performance. If some of the measures are found to be valid and some are not, we must confirm that those important measures in subsequent experiment, such as mean speed of travel and mean reaction time, are valid before we can apply the research findings. It is also anticipated that collisions will be rare in both testing conditions. Validation of this variable is not vital in determining the validity of the whole simulator as other driving performance measures can help to validate the simulator. It is envisaged that the newly-developed driving simulator will trigger more research interests in China.

6.3.7 Future studies

More studies are indicated to characterize the glare and ageing effects on driving in the future. For example, reaction time can be measured on those drivers with different severity of cataract. The performance of driving simulator under the effects of glare can also be compared for drivers before and after cataract extraction or LASIK surgeries. Drivers undergone these surgeries may have compromised contrast sensitivity and have glare complaint especially in dim environment, therefore, driving performances after the cataract surgery and various LASIK protocols can also be compared and evaluated using the driving simulator. As found from Experiment II, glare sources at 2.5º can already cause significant deterioration in contrast sensitivity. Studies on the width of the border surrounding the characters on the real road signs of Hong Kong are indicated. A thick border should be beneficial to block the influence of glare.

Moreover, as drivers also complain of glare from oncoming vehicles, the use of directional headlamps can also be investigated to see if there is really an improvement on-road. In all the laboratory tests, static glare sources have been used. However, in the real situation, glare always appears in a transient fashion which is a more complicated and hazardous situation as light adaptation and dark adaptation are involved. A study of dynamic glare presentation will be interesting.

6.4 Summary

To summarise, almost all subjects experienced glare-induced problems during driving. This study has demonstrated the effects of age and glare on static target resolution, simultaneous perception and simulated complex driving tasks in a well-controlled laboratory setting. Overall, older subjects performed worse than younger subjects (control) in most parts of the study. Glare reduced the central and peripheral contrast sensitivity. The UFOV (divided attention) was also selectively compromised when glare sources were located near the peripheral target. In the simulated driving experiment, drivers drove slower and had longer reaction times under glare. Compensatory strategy under adverse condition was shown from the result while the lengthened reaction time poses a threat in real driving. Further studies are warrant to control the effects of glare and ageing on driving.

Appendix

Appendix A

Sample of questionnaire for Experiment I

The Hong Kong Polytechnic University

Department of Optometry and Radiography

Vision and driving in Hong Kong

Questionnaire

Bibliography

Date		/ /
Code		
Gender		M / F
A1. Year of birth	A1.	19

A2. Type of commercial vehicles operated: A2. ____________________

A3. How long have you got the commercial vehicle licence? A3. ____________________

A4. Are you required by the law to wear optical corrections? A4. ☐ 1. Yes ☐ 2. No

A5. How many days per week do you drive? A5. ____________________

A6. How many hours per day do you drive? A6. ____________________

A7. Do you drive in the night shift? A7. Never Sometimes Often

1 — 2 — 3

Vision and health

B1. When was the previous eye examination?

B1.
- ☐ 1. Within 1 year
- ☐ 2. 1 – 2 years before
- ☐ 3. Over two years
- ☐ 4. Never have any eye examination before
- ☐ 5. Don’t know

B2. Do you have any colour vision difficulty?

B2.
- ☐ 1. Yes
- ☐ 2. No
- ☐ 3. Don’t know

B3. Which of the following visual aids do you use in driving?
(Can tick more than one answer.)

B3.
- ☐ 1. Prescription glasses
- ☐ 2. Sunglasses
- ☐ 3. Prescription sunglasses
- ☐ 4. Contact lenses
- ☐ 5. Not applicable

B4. Do you have any of following refractive problems?
(Can tick more than one answer.)

B4.
- ☐ 1. Myopia
- ☐ 2. Astigmatism
- ☐ 3. Presbyopia
- ☐ 4. Hyperopia
- ☐ 5. No refractive problem
- ☐ 6. Don’t know
- ☐ 7. Others, please specify:

  ____

B5. Do you have any of following symptoms at work?
(Can tick more than one answer.)

B5.
- ☐ 1. Blurred vision
- ☐ 2. Tiredness of eyes
- ☐ 3. Double vision
- ☐ 4. Tearing
- ☐ 5. Dry eyes
- ☐ 6. Itching eyes
- ☐ 7. Redness of eyes
- ☐ 8. Painful eyes
- ☐ 9. Loss of appetite
- ☐ 10. Headache
- ☐ 11. Migraine
- ☐ 12. No
- ☐ 13. Others, please specify: ____________

Driving Environment

Do you have any of following difficulties or problems related to ……?

C1. Recognition of road side signage (Can tick more than one answer.)

C1.
- ☐ 1. Inappropriate location
- ☐ 2. Insufficient quantity
- ☐ 3. Unclear information
- ☐ 4. Inappropriate colour
- ☐ 5. Insufficient lighting
- ☐ 6. Too many information
- ☐ 7. No problem
- ☐ 8. Others, please specify: ____________________

C2. Recognition of road surface signage (Can tick more than one answer.)

C2.
- ☐ 1. Inappropriate location
- ☐ 2. Insufficient quantity
- ☐ 3. Unclear information
- ☐ 4. Inappropriate colour
- ☐ 5. No problem
- ☐ 6. Others, please specify: ____________________

C3. Public lighting system (Can tick more than one answer. * Please delete as appropriate.)	C3. ☐ 1. Insufficient quantity ☐ 2. Too bright / Too dim* ☐ 3. Tunnel: Too bright / Too dim* ☐ 4. Highway: Too bright / Too dim* ☐ 5. Fluctuation of brightness ☐ 6. No problem ☐ 7. Others, please specify: ______________________________
C4. Glare light (Can tick more than one answer.)	C4. ☐ 1. Sunlight ☐ 2. Forthcoming headlight ☐ 3. Street light ☐ 4. Traffic light ☐ 5. Advertisement board ☐ 6. No problem ☐ 7. Others, please specify: ______________________________

The End

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