

# Vision measurability and its impact on safe driving – a literature review

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Received November 20, 2015, accepted May 27, 2016

Keywords: Vision test, Safe driving, Visual capabilities, Useful field of view, Contrast sensitivity, Visual acuity

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## Abstract

Knowledge of measurability of vision and its impact on safe driving have been proven to be important to secure a safe traffic system. Several different approaches to measuring visual function in order to improve road safety have been identified around the world. A trend seen in the literature is that traditional vision tests are increasingly supplemented by cognitive tests. The purpose of this study was to provide an overview of visual capabilities that are important for safe driving. The study answered questions about the visual capabilities that are essential for safe driving; which tests are available and how they are used; and existing evidence for these tests. The literature review was based on database searches of TRID, Web of Science and PubMed. In total 128 scientific publications were included in the overview. The results provided an overview of international standards of vision required for driving a car. Moreover, the results were structured according to the different visual capabilities and a corresponding account of the diseases that may affect these capabilities; available tests and corroborating evidence for the test; and the manner in which these capabilities are important for safe driving. Two tests were highlighted based on the review: contrast sensitivity, and Useful Field of View. It was also concluded that 1) testing of vision should consist of several complementary tests, 2) good visual acuity is not alone sufficient for safe driving, and 3) tests including cognitive aspects can complement vision testing and improve the assessment of safe driving.

## Sammanfattning

Kunskap om synförmågens mätbarhet och inverkan på bilkörning har visat sig vara av vikt för att trygga ett säkert trafiksystem. Flera olika ansatser till att mäta synförmågan i syfte att förbättra trafiksäkerheten har identifierats runt om i världen. En trend som setts är att traditionella syntester alltmer kompletterats med kognitiva tester. Syftet med den här studien var att ge en översikt över synförmågor som är viktiga för säker bilkörning. Studien besvarade frågor om egenskaper i synen, viktiga för säker bilkörning, vilka tester som finns och hur dessa används, samt vilken evidens som finns för olika tester. Litteraturoversikten vilade på resultat från sökningar gjorda i databaserna TRID, Web of Science och PubMed. Totalt inkluderades 128 vetenskapliga publiceringar i översikten. Resultaten bereder en översyn av internationella krav på synförmågan som ställs för privata bilförare. Vidare presenteras resultat uppdelat utifrån olika synförmågor där dessa beskrivs tillsammans med en översikt av sjukdomar som kan påverka förmågan, vilka tester som finns och dess evidens, samt hur förmågan inverkar på säker bilkörning. Två tester lyftes fram utifrån dessa starka stöd i litteraturen och dessa var (1) kontrastkänslighet och (2) Useful Field of View. Utifrån resultatet drogs slutsatsen att testning av synförmåga bör bestå av kompletterande tester, att de mest förekommande måtten på synskärpa inte är tillräckligt för att säkerställa säker bilkörning, samt att tester som inrymmer kognitiva aspekter kan komplettera bedömningen av synförmågan.

## Introduction

There are a number of different approaches related to vision that target improved road safety. These approaches may include several methods such as driving simulators or driving with an instructor on a test track, combined with visual and cognitive tests. Methods and tests that are used to secure that a country's requirements are met differ between different countries, and sometimes even within one country (Desapriya, Subzwari, Fujjwara, & Pike, 2008). A commonly used measure to determine that drivers meet the requirements at hand is that of visual acuity. Drivers with vision-related problems undertake testing and may then continue to drive as before or with corrected vision if needed to meet the requirements. A literature review of vision-related policies for the renewal of licences in the United States shows that there is a link to improved road safety, especially for groups with elevated risks (McGwin, Sarrels, Griffin, Owsley, & Rue, 2008; Shipp et al., 2000). In Sweden there are medical requirements for holding a driving licence, such that, for example, loss of vision and difficulty seeing at night can be an obstacle for the licence. However, there is the possibility of conditional approval and in some cases also exemptions (Transportstyrelsen, 2015) (Swedish Transport Agency). Medical requirements exemplified above notwithstanding, a European study found that a large percentage of people were driving without meeting the requirements of vision (Levecq, De Potter, & Jarmart, 2013). These results illustrate how important mobility is in enabling people to live a good and functional life, therefore it is vital that mobility is ensured. Focusing on mobility instead of a unilateral focus on limiting driving can hinder unnecessary suffering and risk-taking that could affect not only the person driving but also fellow road users. In this context it is also of importance to mention drivers' ability to adapt their driving in relation to specific impairments (e.g. Kotecha, Spratt, & Viswanathan, 2008), such as hearing loss (Thorslund, 2014), indicating that the assessment of driving ability should rely on more than a simple, traditional vision test.

Vision related problems that may affect driving often occur as a consequence of a natural aging process, but they may also follow from a variety of medical conditions. The results from the review were divided into the following capabilities: (1) visual acuity (the eyes' resolution), (2) visual field (the entire field of vision seen at one moment), (3) contrast vision (ability to distinguish differences in colour and brightness), (4) colour vision, (5) diplopia (double vision), and (6) adaptation (ability to adapt to different lightning conditions). These different capabilities can be measured in order to predict if a driver is likely to drive a vehicle in a safe manner or not. In addition to vision, cognitive impairment following natural aging is also important to consider because driving is one of the most complex and safety-critical tasks in today's society (Groeger, 2000). There is now a trend where traditional vision tests such as contrast sensitivity and visual acuity are increasingly being combined with tests that also capture cognitive aspects. An example of such a test is the Useful Field of View (UFOV) which is good at predicting safe driving (Johnson & Wilkinson, 2010).

Both visual impairment and cognitive impairment may develop gradually and can take a long period of time to become discernible. As a consequence, affected individuals seldom perceive that their driving skills have deteriorated. This is a central question to address and an important reason to advocate regular testing of drivers. The main purpose of the present study was to investigate visual capabilities that are important for safe driving. This study focuses on measurable aspects of vision that are relevant for safe driving and answers the following ques-

- tions: 1) Which visual capabilities are essential for safe driving?  
 2) Which tests are available to assess these visual capabilities?  
 3) What is the evidence-base for the identified tests?

### Material and methods

A literature review was conducted based on searches in databases TRID, Web of Science and PubMed for the years between 2000 and 2014. The literature search was done with truncation in order to capture all words of the selected word stem, as well as different endings of the words. For searches in TRID and Web of Science, the following keywords were included in combination with driver, driving, and drive: contrast sensitivity, Pelli Robson, colour deficiency, dark adaptation, peripheral vision, visual acuity, vision, field of view, visual field, sight defect, vision disorder, visual impairment, visually impaired, vision test, glaucoma, useful field of view, cross/cockeyed, squint, cataract, and hemianopia. Furthermore, the following words were combined with driver, driving, drive, visual, and vision: aptitude, portability, performance, defect, fitness, impaired, disability, disabled, diabetes, disorder, illness, disease, dysfunction, testing, screening, and mobility. In PubMed searches were done with Medical Subject Headings (MeSH), which resulted in searches that combined vision disorders with (1) automobile driving, and (2) accidents, traffic. Principally English-language peer-reviewed articles from scientific journals published from 2000 until 2014 were included in the literature review.

In addition to results from the database searches, relevant references were motivated from the resulting articles, which meant that a number of conference contributions were also included in the overview. In total the literature search rendered 267 database posts of which 139 were excluded due to lack of relevance and the most relevant 128 references were included in the literature review. These are presented thematically according to the six different visual capabilities that are concerned with an addition of cognitive aspects of vision.

### Results

A summary of the results for each capability are presented in Table 1. The following subsequent chapters describe each capability specifically with background, tests used and support for traffic safety relevance.

Table 1: Result summary of results categorized into capability, tests used and support to predict safe driving.

Capability	Support for traffic safety	Tests
Visual acuity	e.g. Logmar, ETDRS, Snellen	Correlated, but insufficient on their own
Visual field	e.g. IVF, EVFT, DVF, PMP	Supported along with individual assessment
Contrast vision	Mainly Pelli Robson	Strong support
Colour vision	Farnsworth, Farnsworth-Munsell, Nagel	Not specified
Diplopia	Binocular single vision scores	No
Adaptation	Contrast sensitivity Motion sensitivity	Subjectively and objectively Detection of pedestrians at night
Cognitive aspects	UFOV, CB, MVPT, CDT, TMT	Yes, especially UFOV

### Visual acuity

Visual acuity is a measurement of the eye's resolution power and is dependent on several components, such as the optical system, the receptors on the retina and the brain. Visual acuity can be defined and measured in multiple ways but it is usually a measurement of the eye's ability to recognize certain characters

like letters or numbers (Cline, Hofstetter, & Griffin, 1997). Myopia or near-sightedness is characterised by good visual acuity close up and worse visual acuity in the distance. Hyperopia is the opposite with difficulty seeing close up while distance vision is better.

Several diseases may affect visual acuity. Cataracts, where the intraocular lens is clouded, may impair driving performance (Wood, Chaparro, & Hickson, 2009; Wood, Chaparro, Carberry, & Chu, 2010; Wood, Chaparro, & Carberry, 2007; Wood & Mallon, 2001) due to late detection of pedestrians and other risk factors (Marrington, Horswill, & Wood, 2008; Wood et al., 2012). Cataracts are also associated with a higher risk of accident involvement (Owsley, Stalvey, Wells, Sloane, & McGwin Jr, 2001). Several studies have shown clear improvements in driving performance after cataract surgery (Wood & Carberry, 2004; Owsley et al., 2002).

### Testing visual acuity

Several studies have demonstrated that the traditional tests of visual acuity (e.g. Logmar, ETDRS, Snellen), performed at high contrast, on their own, are not appropriate to identify unsafe drivers (Currie, Bhan, & Pepper, 2000; Horton & Chakman, 2002; Kiel, Butler, & Alwitry, 2003; Morrisey & Grabowski, 2005; Owsley et al., 2001; Rubin et al., 2007; Schultheis et al., 2010; Wood, Chaparro, Carberry, & Hickson, 2006; Wood & Owens, 2005). Ball, Wadley, Edwards, and Ball (2001) suggest only a weak correlation between visual acuity and accident risk while other studies have shown a significant correlation between driving performance and both visual acuity and contrast sensitivity (Carberry, Wood, Watson, & King, 2006; McGwin Jr, Chapman, & Owsley, 2000).

A review by Owsley and McGwin Jr (2010) concluded that visual acuity is, at best, weakly correlated with safe driving and unsuitable for identifying drivers who have an increased risk of being involved in future accidents. According to them, visual acuity testing used as a screening of visual function should be accompanied by further tests such as contrast sensitivity, visual field, processing speed, and tests of divided attention, which have been shown to have great relevance to safe driving. This is in line with Higgins and Wood (2005) who also suggested a contrast sensitivity test to supplement visual acuity tests in order to better identify vision related problems caused by cataracts.

### Visual field

The visual field is the entire field of vision that can be observed at a specific moment. The maximum static visual field is approximately 180 degrees horizontally and 130 degrees vertically. Peripheral vision is the part of field of view beyond the part that the eye can focus sharply on. It is equivalent to about 95% of the entire field of view. The peripheral vision registers and reacts to movement and attracts the eyes to things that move within the gaze range (Martin, 2010).

Visual field loss may be the result of pathology affecting the optic nerve or the brain, which may be caused by a stroke. The most common causes for visual field loss are glaucoma, retinal disorders, and cataracts (Johnson & Keltner, 1983). A driver with visual field loss cannot see the whole field of view, which means that important information may be missed. Studies have shown decreased driving performance (Wood & Troutbeck, 1995) and also higher risk of accident as a result of this (Johnson & Keltner, 1983; McGwin Jr et al., 2005; Tanabe et al., 2011).

Difficulties described for people with visual field loss include speed matching when changing lanes (Bowers & Peli, 2005), lane positioning, especially in curves (Lockhart, Boyle, & Wilkinson, 2009; Bowers & Peli, 2005; Bowers, Peli, Elgin, McGwin, & Owsley, 2005; Elgin et al., 2010), and increased reaction times to unexpected developments in the periphery (Lockhart

et al., 2009; Haymes, LeBlanc, Nicolela, Chiasson, & Chauhan, 2008). Numerous studies have presented results suggesting that drivers with visual field loss detect significantly fewer pedestrians and that it takes longer time for them to detect them (Alberti, Peli, & Bowers, 2013; Bowers, Mandel, Goldstein, & Peli, 2007; 2009; L. Zhang et al., 2007).

The effects of decreased field of vision on driving performance is far from conclusive and several researchers argue that it does not by necessity involve any danger in traffic (Elgin et al., 2010; Yuki, Asaoka, & Tsubota, 2014). One study reports poorer driving performance among subjects with central visual field loss, whilst at the same time they were found to have fewer traffic-related convictions (Owsley & McGwin Jr, 2008). Several studies suggest that the degree of visual field loss has no significant effect on driving performance and that compensatory behaviour varies, resulting in the conclusion that individual assessments should be favoured (Bowers et al., 2007; Elgin et al., 2010; Racette & Casson, 2005; Wood, McGwin Jr, et al., 2009; Yuki et al., 2014).

Several studies have shown that drivers compensate for their decreased field of view by eye and head movements (e.g. Bahnemann et al., 2014; Bowers et al., 2007) or through speed reduction (Rogé, Pébayle, Campagne, & Muzet, 2005). Bowers, Mandel, Goldstein, and Peli (2010) showed that drivers with homonymous hemianopia thus choose the position that increases the margin of the affected side. Bohensky et al. (2007) suggested that research in this area is unclear, referring to the fact that methods for assessing safe driving skills for those who have decreased field of view are not properly validated (Wood, 2002; Higgins & Wood, 2005). This is in line with Horton and Chakman (2002) who argued that limited field of vision may be a risk factor when driving, but the evidence is vague.

#### *Testing visual fields*

Different ways of measuring the field of view may be appropriate for different situations and purposes. Monocular, rather than binocular, testing has been suggested to give more specific information on the location and depth of any defect. This makes it more appropriate for measuring vision in traffic situations (Ayala, 2012). Integrated Visual Field (IVF) is a method of quantifying the central binocular visual field by merging results from monocular fields (Crabb & Viswanathan, 2004). Owen et al. (2008) argue that binocular IVF results are better than monocular visual fields at predicting whether an individual is at risk of losing their licence in the future. In a comparison between IVF and Esterman visual field test (EVFT) it was found that IVF approved drivers who should be classified as unfit (Chisholm et al., 2008).

Dynamic Visual Field (DVF) testing captures the two eyes' views and produces an enhanced perception of relative range and can improve the perceptual discrimination (Yeh & Silverstein, 1990). DVF testing is to be distinguished from Static visual field, where different locations throughout the field are tested one at a time, and from Kinetic visual field which uses a mobile test stimulus. D. Zhang et al. (2000) argue that a dynamic visual field (DVF) shows the context of accident involvement, better than the static. Furthermore, they found a high correlation between the DVF and maximum safety rate among drivers who have been or not been involved in accidents.

Some suggest combinations of Useful field of view (UFOV) (see Cognitive aspects) and other tests like contrast sensitivity (Bowers et al., 2005), Peripheral Motion Processing (PMP) (Henderson & Donderi, 2005), or Complex Figure Test Copy (Uc, Rizzo, Anderson, & Sparks, 2006) to best predict driving performance. But there are also those who question the test's suitability for assessing the risk of accidents among drivers with visual field loss (Chisholm et al., 2008). Papageorgiou et al.

(2010) argue that no vision-related parameters are suited to predict accident involvement. Instead, an individualized approach is required, that takes account of compensatory strategies in the form of eye and head movements.

Clinical evaluation of visual field loss by means of computed tomography or magnetic resonance has not been shown to predict safe drivers (Vaphiades et al., 2014). Regarding self-rated driving performance, older drivers with poorer results on several tests, mainly contrast sensitivity and visual fields, are more likely to stop driving of their own volition (Freeman, Muñoz, Turano, & West, 2005).

#### **Contrast vision**

Contrast vision is the ability to distinguish differences in colour and brightness, for example to distinguish an object from its background. Generally speaking, contrast vision and thus contrast sensitivity decrease with age (Lasa, Podgor, Datiles, Caruso, & Magno, 1993). According Puell, Palomo, Sánchez-Ramos, and Villena (2004), contrast sensitivity is stable until the age of 50 after which it decreases by 0.1 log contrast sensitivity per decade.

Age-related deterioration in contrast sensitivity has been associated with older drivers' driving cessation (Freeman et al., 2005), or self-regulation (Sandlin, McGwin, & Owsley, 2014). Contrast vision can be negatively affected by numerous pathologies, such as cataract (Owsley et al., 2001) and Parkinson's disease (Devos et al., 2007; Uc et al., 2009). The link between cataracts and impaired driving performance has been made in a number of studies (e.g. Wood & Troutbeck, 1995; Wood, McGwin Jr, et al., 2009; Wood et al., 2010), and has been explained by a decrease in contrast sensitivity.

Association between safe driving and tests for visual acuity and contrast sensitivity has been shown in several studies (e.g. Carberry et al., 2006; McGwin Jr et al., 2000). Older drivers experiencing difficulties in high risk situations has been associated with impairment in visual acuity and contrast sensitivity (McGwin Jr et al., 2000). Some studies have shown an increased risk of accidents for older drivers with reduced contrast vision (Ball & Owsley, 2003; Owsley et al., 2001; Sandlin et al., 2014) while other studies failed to find a correlation or found only a weak association (e.g. Ball et al., 2001; Rubin et al., 2007).

Decline in contrast sensitivity has been shown to impair the recognition of road signs and dangers in traffic (Wood & Owens, 2005), manoeuvring (Bowers et al., 2005), and driving at night (Freeman, Muñoz, Turano, & West, 2006; Puell et al., 2004). Again, it is important to note that drivers with impairments tend to adjust their behaviour. Deficiencies in contrast sensitivity have been shown to be related to avoidance of driving at night (Puell et al., 2004), decrease in annual mileage (Freeman et al., 2006; Sandlin et al., 2014), and fewer trips (Sandlin et al., 2014).

#### *Testing contrast vision*

To measure contrast vision, a contrast sensitivity test is often used. Generally, contrast sensitivity testing is well supported by research regarding determination of driving performance and prediction of safe driving (e.g. Amick, Grace, & Ott, 2007; Worringham, Wood, Kerr, & Silburn, 2006). However, there are several different ways of measuring contrast sensitivity, and there is no consensus in the literature on which is the most appropriate (Johnson & Wilkinson, 2010).

Contrast sensitivity (CS) is often measured with a Pelli Robson eye chart (Pelli, Robson, & Wilkins, 1988), but other letter targets and methods are also available and used. The Functional Acuity Contrast test (FACT) measures contrast sensitivity at different spatial frequencies with circular photographic plates arranged in five rows and nine columns (Ginsburg, 1996).

The Pelli Robson chart does not measure spatial frequencies, but compared to the FACT is a general, and quicker to administer, standardized tool for measuring CS. The chart consists of rows of letters that decrease in contrast. The letters are arranged in groups of three and the contrast decreases from each successive group to the next. In this task the dependent measure is the threshold derived from the lowest contrast value at which two of the three letters are correctly reported (Pelli et al., 1988).

The studies found in this review on contrast sensitivity and traffic safety all refer to Pelli Robson tests. According to Carr (2007) the contrast sensitivity is the most predictive test for determining deterioration in driving. This is in line with van Rijn et al. (2011) who suggest that contrast sensitivity should be included for driver assessments since it is more common to drive with reduced contrast vision compared to impairments in visual acuity and visual field loss, which today are often included in assessments of driving ability. Also Worringham et al. (2006) suggest that testing of contrast sensitivity adds objectivity and predictive strength that is important to independently determine and predict fitness to drive.

### Colour vision

Problems with colour vision are referred to as colour blindness or colour deficiency depending on the severity, and can occur with different colours. Approximately 8% of males and 0.5% of females in the population have congenital red-green colour-deficient vision. True colour blindness is rare (0.0005%, Pokorny, Smith, Verriest, & Pinckers, 1979). These people have reduced ability to discriminate redness-greenness throughout the full gamut of colours. Most significantly, from a safety point of view, the problem includes the red, orange, yellow, and yellow-green parts of the visible spectrum (Atchison, Pedersen, Dain, & Wood, 2003).

Red-green colour-vision deficiencies are subdivided into a number of categories (after von Kries, 1899): Dichromats, people with protanopia and deuteranopia, lack the long-wavelength ("red") receptor or the middle-wavelength ("green") receptor, respectively. Their ability to discriminate a red, yellow, and yellow green signal code on the basis of colour is absent, and they must rely on the usual brightness hierarchy that yellow is brighter than yellow green, which is brighter than red. In addition, in protanopia, red signals are seen as substantially darker and are less alerting. A red traffic signal as seen in protanopia has approximately 25% of the luminous intensity it has for a colour normal (Dain & King-Smith, 1981). Protanopia and deuteranopia each constitute about 1% of males (Atchison et al., 2003). For anomalous trichromats, people with protanomaly and deuteranomaly, the ability to discriminate a red, yellow, and yellow green signal code on the basis of colour is present but reduced. Protanomaly and deuteranomaly constitute about 1% and 5% of the male population, respectively. Deuteranopia and deuteranomaly are collectively referred to as deutan colour deficiencies, and protanopia and protanomaly are collectively referred to as protan colour deficiencies.

According to Atchison et al. (2003), most studies of colour vision in traffic accidents have limitations, usually involving low numbers, drivers' sex not being given, or not being applicable to the population of drivers and there is only some weak evidence that protans have higher road crash rates than do colour normal. Twenty percent of anomalous trichromats and 50% of dichromats admit to difficulty recognizing signal colours, and approximately 14% of protans admit to difficulty seeing red signal lights (Cole & Maddocks, 1997; Steward & Cole, 1989).

According to Odell (2005), who reported an overview of the guidance for fitness to drive in Australia, it is not relevant to test for colour blindness in order to assess driving ability. How-

ever, others suggest an elevated risk related to colour vision deficiency (e.g. Cole, 2002; Vingrys & Cole, 1988). According to Cole (2002), anyone who suffers from a protan colour deficiency has more difficulty seeing red lights and is at greater risk of being involved in accidents.

Attention conspicuity of red, orange/amber and green road signs has been shown to be inferior in individuals with green colour deficiency compared to people with normal colour vision, while there was no difference for yellow and blue colour deficiency (O'Brien, Cole, Maddocks, & Forbes, 2002). Atchison et al. (2003) point out that many licence requirements in terms of colour vision are aimed at people with protan colour deficiency. The results of their study on response to traffic signals indicates that people with deutan colour deficiency should also be scrutinized in terms of driving performance. The response time for the red lights increased with the degree of colour deficiency and deuteranopia led to worse performance than protanopia, at the same degree of reduction. Similar patterns were also seen for yellow lights, but reaction time to green lights was similar for all groups. A survey provided results indicating that individuals with defective colour vision tend to prefer driving during the day, because it is particularly difficult to identify road studs and rear signal lights of vehicles ahead at night (Tagarelli et al., 2004).

### Testing colour vision

It has been suggested that deficiencies may lead to higher accident risk and difficulties reading signs. Therefore, various studies (Atchison et al., 2003; Cole, 2002; Vingrys & Cole, 1988) have proposed that colour vision should be tested when assessing driving ability. However, the type of test has not been specified. In their study, Atchison et al. (2003) used three different tests to categorize the degree of colour deficiency: 1) The Farnsworth lantern, which contains nine pairs of coloured lights. Colours included are green, red and white. A pass is two or fewer identification errors on two runs. 2) The Farnsworth-Munsell Panel D-15 test, which involves arranging 15 caps in order of colour. Individuals with colour deficiencies of sufficient severity make particular types of arrangement errors. 3) The Nagel anomaloscope, which requires subjects to match various red-green light mixtures with a yellow light.

### Diplopia

Diplopia or double vision results in a person seeing two objects instead of one. This may be caused by an inability to look towards a point, resulting in the image not ending up in the corresponding retinal (fusional) area. In this case double vision is only present when the person looks with both eyes. Double vision may also be due to cataracts that cause the person to get a prismatic image. In that case the double vision is present even if one eye is closed.

### Testing for diplopia

Persons suffering from cataracts can be affected with double vision. A relevant article on this subject was written by White, Marshall, Diedrich-Closson, and Burton (2001) reporting a driving simulator study where driving performance of drivers with chronic diplopia was evaluated. Diplopia was tested by using binocular single vision scores (Sullivan, Kraft, Burack, & O'Reilly, 1992). To evaluate driving performance various cues and threats, including near-accident situations, were presented; stimulus recognition and reaction times were recorded. It was noted that diplopia is not a complication that should affect whether the person is allowed to carry a driving licence, or not.

## Adaptation

Adaptation can be seen as the eye's ability to adapt to different lighting conditions. Light sensitivity or glare problems are signs of adaptation difficulties. When adapting to low light conditions, the pupil dilates, and both visual acuity and contrast sensitivity significantly decrease. This affects vision and may affect driving safety. One medical condition affecting adaptation is night myopia, or night blindness, which makes it difficult to see in half darkness. Another example is cataracts which entails increased glare sensitivity (Lasa et al., 1993). Cohen et al. (2007) examined changes in visual acuity, indicative of night myopia, in full light and in darkness in professional drivers and correlated this with accident involvement. Since drivers with night myopia were involved in more accidents during night driving, an examination for night myopia was recommended.

Self-limiting night driving depends on both visual and cognitive abilities. Reduced contrast sensitivity and visual field loss are conditions that have been found to affect drivers' own reservation from night driving (Kaleem, Munoz, Munro, Gower, & West, 2015; Puell et al., 2004). Wood, Lacherez, and Tyrrell (2014) found that motion sensitivity was the ability that could best predict the detection of pedestrians at night. Other functions involved in detecting pedestrians at night were visual acuity, contrast sensitivity, and UFOV.

Night time driving leads to many situations of glare and few studies have been conducted to investigate the effect of glare. However, a field study by Theeuwes and Alferdioc (1996) showed that even low levels of glare resulted in reduced ability to see in the distance, more powerful speed reductions, and higher steering activity. Källmark (2015) found that the average recovery time after glare was longer for older drivers. The average recovery time of 8.6 seconds for driver's aged 56 to 65 years, suggest a driving distance of 260 meter before vision recovers. Gray and Regan (2007) showed that the number of collisions increases and safety margins decrease with glare, especially for older drivers. This is in line with Babizhayev (2003) who proposed the introduction of simple tests for contrast sensitivity and glare for a driving licence requirement in order to increase traffic safety. These tests were seen as especially suitable for older drivers.

### Tests of adaptation

Tests of adaption, relevant for safe driving, include visual acuity, contrast sensitivity, motion sensitivity, and tests measuring the ability to recover from glare. Contrast sensitivity has been shown to correlate with both subjective and objective assessment of driving ability in adaptation (Kaleem et al., 2015; Babizhayev, 2003). Motion sensitivity was highlighted as a good measure of ability to detect pedestrians at night (Wood et al., 2014). Changes in visual acuity in full light and in darkness can be used to explore night myopia (Cohen et al., 2007). Furthermore, the ability to recover from glare should be explored to enhance road safety (Babizhayev, 2003; Gray & Regan, 2007; Theeuwes & Alferdioc, 1996).

## Cognitive aspects

There are several cognitive aspects relevant for driving. The scope of this study includes cognitive aspects essential for safe driving and relating to vision, such as visual attention, memory, decision making and visuo-spatial ability. A variety of medical conditions connected to changes in cognitive abilities affect driving performance and safe driving skills among persons with these conditions.

### Tests of cognitive aspects

The most common test covering cognitive aspects of vision is Useful field of view (UFOV). For an overview of the test and how it is performed see Edwards et al. (2005). According to Rao,

Munoz, Turano, Munro, and West (2013) Useful field of view (UFOV) as a concept is often used synonymously with visual attention. The test contains three elements, namely: (1) processing speed, (2) divided attention, and (3) selective attention. It can be used either separately or as part of a test battery for screening at-risk groups in order to determine their ability to drive (e.g. Bentley, LeBlanc, Nicoleta, & Chauhan, 2012; Devos et al., 2007). The reviewed literature provided strong support for the test's ability to predict driving performance (e.g. Cushman, 1996; Hoffmann, McDowd, Atchley, & Dubinsky, 2015; Johnson & Wilkinson, 2010; Myers, Ball, Kalina, Roth, & Goode, 2000; Whelihan, DiCarlo, & Paula, 2004). In addition to the connection to attention the test is also related to memory, decision making and visuo-spatial ability (Lee, Lee, & Boyle, 2007). A considerable amount of the test's strength is its ability to capture both visual sensory memory and higher order attention abilities (Desapriya et al., 2008).

Examples of medical conditions where UFOV is adversely affected and for which UFOV can be used to predict safe driving are Parkinson's disease (e.g. Classen et al., 2009; Devos et al., 2007; Uc et al., 2006), Alzheimer's disease (Rizzo, Reinach, McGehee, & Dawson, 1997), cognitive impairments at an early stage (Whelihan et al., 2004), and Multiple sclerosis (Akinwuntan et al., 2012). Besides medical conditions, visual attention as measured by UFOV is also affected by natural aging (Anstey & Wood, 2011). Several studies have shown that UFOV is significantly correlated with driving performance (Bowers et al., 2005; Rogé et al., 2005) and accidents with injuries (Owsley et al., 1998) for people with visual field loss.

In studies by for example Owsley et al. (1998), and Sims, McGwin Jr, Allman, Ball, and Owsley (2000) a reduction of 40% in UFOV has been linked to a twofold increase of collision risk for older drivers. The connection between reduced UFOV and collisions has also been made in other studies (e.g. Haymes, LeBlanc, Nicoleta, Chiasson, & Chauhan, 2007; Rizzo et al., 1997; Rubin et al., 2007), and it can be assumed to apply not only to older drivers. Despite the evidence supporting UFOV and its ability to predict accidents and safe driving, it should also be noted that there is evidence showing that in specific contexts it has not been able to predict safe driving. One example is a Canadian study which evaluated a test battery called Road Wise Review, where UFOV is an important part along with contrast acuity. From this study Scialfa, Ference, Boone, Tay, and Hudson (2010) presented results showing that the test battery could not predict self-reported difficulties and drive history.

Besides UFOV there are other tests and methods relevant for safe driving. According to Henderson and Donderi (2005) peripheral contrast sensitivity, UFOV and peripheral motion processing may be viewed as complementary methods. Another test that measures aspects of visual attention is change blindness (CB), a phenomenon that occurs when a change in a visual stimulus is introduced and the observer does not notice it (Rensink, O'Regan, & Clark, 1997). While UFOV relates to memory, decision-making, attention, and visual spatial ability, CB relates to vision and attention (Lee et al., 2007). The type of images used in a CB task influence how the task relates to driving performance measures. Researchers should take care when selecting images to be included in CB tasks to maximize insight into real-world driving as described by Lee et al. (2007). Other visual perception tests have been proposed that are appropriate for identifying drivers who are at risk of accidents, for example Motor Free Visual Perceptual Test (MVPT) and Clock Drawing Test (CDT) (Oswanski et al., 2007). MVPT is a widely used, standardized test of visual perception designed to assess visual perception independently of motor ability (Colarusso & Hammill, 1996). CDT is performed by letting a person draw numbers on a pre-drawn circle, and also to draw the hands to show

a specific time. The Trail Making Test (TMT) assesses visual search, processing speed and mental flexibility (Reitan, 1986) and has shown strong association with driving ability (Reger et al., 2004). TMT part A consists of targets marked with numbers, which are connected in numerical order. Part B has targets marked with both numbers and letters, which are connected in a combined numerical and alphabetical order and the result is the time needed to complete the task.

## Discussion

The present study has provided an overview of visual capabilities that are essential for safe driving and available tests for these capabilities, and has also provided an evidence base for the identified tests.

The results from this literature study are in line with other authors (e.g. Bohensky, Charlton, Odell, & Keefe, 2008) by suggesting that tests currently used to assess driving ability and decide on the right to retain a driving licence, are insufficient. Many studies have carried out traditional tests of visual acuity, however according to the results of this review, none have found a strong correlation with road safety. The fact that visual acuity is essential for safe driving is rarely doubted, but tests for visual acuity alone are considered inadequate. It is often suggested that visual acuity testing should be accompanied by a test for contrast sensitivity. We share this view, and find it reasonable given that visual acuity is measured under very optimal conditions rarely seen in traffic. A vision examination is conducted under optimal light conditions and with high contrast black letters on a white background. This may explain why contrast perception has proved to have greater relevance for safe driving. Even self-reported contrast sensitivity has been suggested to have better predicting power than visual acuity (Fraser, Meuleners, Lee, Ng, & Morlet, 2012).

Based on the findings of this review, there are a number of vision tests that have external validity in the scientific literature, and therefore are reasonable candidates for inclusion in an assessment to ensure safe mobility and decide the eligibility of a driver's fitness to hold a licence. This view is by no means unique, it is shared by, among others, Jolly, Blanchette, Major, and Heard (2006). The results suggest a combination of different tests according to individual conditions for a fair assessment of the driving ability. This standpoint is in line with previous research (Green, McGwin Jr, & Owsley, 2013; Stav, Justiss, McCarthy, Mann, & Lanford, 2008).

The tests for visual acuity (e.g. different letter boards) that are available and in use today are not sufficient to ensure safe driving, but need to be combined with other tests. Based on the literature, contrast sensitivity and UFOV (Useful Field of View) are suggested as being the best measures of visual capabilities that are essential for safe driving and are suitable candidates to complement the already required visual acuity test. This is in line with previous research suggesting contrast sensitivity's importance for the assessment of driving ability (e.g. Bal, Coeckelbergh, Van Looveren, Rozema, & Tassignon, 2011; Fraser et al., 2012). The fact that the UFOV is highlighted shows that there is potential to complement classic vision test with tests containing cognitive aspects. According to Worringham et al. (2006) testing of cognitive functions is an easy way to provide increased objectivity in the assessment of driving ability.

Several impairments are associated with normal aging, whereas others follow medical conditions. Driving and mobility is important for many individuals' independence and well-being. It is important to have a holistic approach to ensure continued good mobility for these individuals and still increase traffic safety. Having one's vision tested may be experienced as a constraint and a threat to mobility, however, it can also act as a catalyst for continued driving. Individuals who previously

doubted their performance in traffic can, with the help of testing, gain self-confidence to continue driving. This reasoning is supported by Shipp et al. (2000), who showed that mandatory vision testing was not associated with a lower proportion of older drivers. This was explained by the fact that although some need to give up driving, others may resume driving after testing. Having said this, it is important that testing is carried out in such a manner that people view it as a way to ensure that their continued mobility is safe.

Visual scanning is a capacity outside the scope of this study. However, as it is closely related to vision capacities, it is worth mentioning. Cognitive and visual deficiencies associated with Parkinson's disease have been shown to result in impaired visual scanning and impaired driving performance including significantly fewer detected landmarks and road signs, as well as violations of other traffic rules (Uc et al., 2006). Furthermore, drivers with Alzheimer's disease have been shown to have impaired visual scanning with an inferior driving performance as a result (Duchek, Hunt, Ball, Buckles, & Morris, 1998). Also, drivers involved in collisions have shown significantly poorer scanning behaviour and steering (Mills, Hubal, & Wall, 2003). This is in line with the suggestions for individual assessment of visual field.

## Conclusions

Firstly, available and broadly used tests of visual acuity are not alone sufficient to ensure safe driving and need to be combined with other tests. Secondly, several vision tests have found support in the scientific literature and it is reasonable to further investigate how these could complement visual acuity testing in order to acquire better predictability of safe driving. From this literature study, contrast sensitivity, UFOV, and glare sensitivity emerge as strong candidates to complement visual acuity. The literature suggests that the UFOV method is also the test that best predicts driving performance. Thirdly, different tests should be combined with regards to individual case conditions in order to achieve a fair judgement of the whole driving ability.

## Research outlooks

With the results of this study in mind, further research is relevant in several areas. Given the existing support of UFOV, a target study which applies and evaluates this test in conjunction with other vision tests is suggested. Such a study should put particular emphasis on a holistic approach in which all relevant actors are involved. This could be achieved through collaboration between, for example optometrists, occupational therapists, behavioural scientists, and others. In addition to the need for research into how UFOV and other tests predict safe driving, research is needed into the combined effect of these tests in assessing driving ability. This should include different test methods, such as driving simulators and on-road evaluations. There are already approaches moving in this direction, both nationally and internationally, but there is both a need and a rationale for extending research in this area.

A complement to this literature study could include a qualitative survey containing interviews with professional drivers/driving instructors/traffic police who may have practical experience about different driver needs, but also with people from transport agencies who often retain a traffic medical board with knowledge about the basis of today's requirements. A literature review focused on professional drivers would be interesting since they have tougher demands in terms of requirements and testing.

## Acknowledgement

The authors would like to thank the Swedish Industry of Optometry for funding this study, the Library at VTI for great help

with the literature search and Dr Tania Willstrand for reviewing a previous version of the manuscript.

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