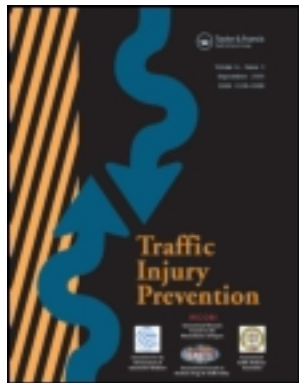


On: 16 June 2014, At: 05:17

Publisher: Taylor & Francis

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



## Traffic Injury Prevention

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/gcpi20>

### Vision and Night Driving Abilities of Elderly Drivers

Nicole Gruber<sup>a</sup>, Urs P. Mosimann<sup>a b</sup>, René M. Müri<sup>a c</sup> & Tobias Nef<sup>a d</sup>

<sup>a</sup> Gerontechnology and Rehabilitation Group, University of Bern, Bern, Switzerland

<sup>b</sup> Department of Old Age Psychiatry, University Hospital of Psychiatry, University of Bern, Bern, Switzerland

<sup>c</sup> Division of Cognitive and Restorative Neurology, Department of Neurology, Inselspital, University of Bern, Bern, Switzerland

<sup>d</sup> ARTORG Center for Biomedical Engineering Research, University of Bern, Bern, Switzerland

Accepted author version posted online: 08 Nov 2012. Published online: 17 May 2013.

To cite this article: Nicole Gruber, Urs P. Mosimann, René M. Müri & Tobias Nef (2013) Vision and Night Driving Abilities of Elderly Drivers, Traffic Injury Prevention, 14:5, 477-485, DOI: [10.1080/15389588.2012.727510](https://doi.org/10.1080/15389588.2012.727510)

To link to this article: <http://dx.doi.org/10.1080/15389588.2012.727510>

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at <http://www.tandfonline.com/page/terms-and-conditions>

# Vision and Night Driving Abilities of Elderly Drivers

NICOLE GRUBER<sup>1</sup>, URS P. MOSIMANN<sup>1,2</sup>, RENÉ M. MÜRI<sup>1,3</sup>, and TOBIAS NEF<sup>1,4</sup>

<sup>1</sup>Gerontechnology and Rehabilitation Group, University of Bern, Bern, Switzerland

<sup>2</sup>Department of Old Age Psychiatry, University Hospital of Psychiatry, University of Bern, Bern, Switzerland

<sup>3</sup>Division of Cognitive and Restorative Neurology, Department of Neurology, Inselspital, University of Bern, Bern, Switzerland

<sup>4</sup>ARTORG Center for Biomedical Engineering Research, University of Bern, Bern, Switzerland

Received 18 April 2012, Accepted 3 September 2012

**Objective:** In this article, we review the impact of vision on older people's night driving abilities. Driving is the preferred and primary mode of transport for older people. It is a complex activity where intact vision is seminal for road safety. Night driving requires mesopic rather than scotopic vision, because there is always some light available when driving at night. *Scotopic* refers to night vision, *photopic* refers to vision under well-lit conditions, and *mesopic* vision is a combination of photopic and scotopic vision in low but not quite dark lighting situations. With increasing age, mesopic vision decreases and glare sensitivity increases, even in the absence of ocular diseases. Because of the increasing number of elderly drivers, more drivers are affected by night vision difficulties. Vision tests, which accurately predict night driving ability, are therefore of great interest.

**Methods:** We reviewed existing literature on age-related influences on vision and vision tests that correlate or predict night driving ability.

**Results:** We identified several studies that investigated the relationship between vision tests and night driving. These studies found correlations between impaired mesopic vision or increased glare sensitivity and impaired night driving, but no correlation was found among other tests; for example, useful field of view or visual field. The correlation between photopic visual acuity, the most commonly used test when assessing elderly drivers, and night driving ability has not yet been fully clarified.

**Conclusions:** Photopic visual acuity alone is not a good predictor of night driving ability. Mesopic visual acuity and glare sensitivity seem relevant for night driving. Due to the small number of studies evaluating predictors for night driving ability, further research is needed.

**Keywords:** photopic and mesopic visual acuity, glare sensitivity, visual field, useful field of view, night driving

## Introduction

Driving is a preferred and primary mode of travel (Hu and Reuscher 2004) for older and younger drivers (Bundesamt für Statistik 2010; Collià et al. 2003; Engeln et al. 2001; Organisation for Economic Co-operation and Development 2001). It is a complex activity with high vision requirements (Johnson and Wilkinson 2010; Owsley and McGwin 2010), and adequate vision is seminal for road safety (Desapriya et al. 2011; Lachenmayr 2006).

Older drivers often report visual difficulties while driving at night, even in the absence of ocular diseases (Emsbach and Friedel 1999; Mortimer and Fell 1989; Werber 2003). Visual acuity (VA) decreases at night in younger and older drivers (Mortimer and Fell 1989). The decrease is more pronounced in older drivers, who also experience more glare sensitivity

from oncoming headlights, than younger drivers (Mortimer and Fell 1989). Because of demographic changes related to aging and the increasing number of older drivers, the number of drivers with vision-related difficulties at night is increasing (Organisation for Economic Co-operation and Development 2001).

The risk of being involved in a fatal crash is higher at night than during the daytime, as measured by distance driven (Massie et al. 1995; Niemann et al. 2009; Werber 2003; Williams 2003). Reasons for the higher nighttime crash risk are speed, alcohol, fatigue, and decreased night vision (Massie et al. 1995; Niemann et al. 2009; Plainis and Murray 2002). Alcohol and excessive speed account for the largest number of fatal nighttime crashes, and they are usually caused by younger drivers (Owsley and McGwin 1999). The risk related to age-related decreased night vision is not clear, but the fact that better road lighting decreases nighttime accidents emphasizes the important role of good night vision ability (Plainis and Murray 2002). Poor visibility in low-light conditions is associated with pedestrian and bicyclist collisions (Owens and Sivak 1996) and with diminished road sign recognition (Chrysler et al. 1996; Owens et al. 2007; Sivak et al. 1981). Poor lighting decreases the distance to read traffic signs and consequently leaves less

---

Address correspondence to Tobias Nef, PhD, Assistant Professor, Gerontechnology and Rehabilitation Group, ARTORG Center for Biomedical Engineering Research, University of Bern, Murtenstrasse 50, 3010 Bern, Switzerland. E-mail: tobias.nef@artorg.unibe.ch

time to react upon their information. This effect is most pronounced in older drivers when driving at night (Chrysler et al. 1996; Sivak et al. 1981). Compared to younger drivers, older drivers also show a greater degradation of steering accuracy in low luminance (Owens and Tyrrell 1999). Despite this knowledge, in most countries current laws for obtaining or renewing driver's licenses do not include an assessment of night vision. The present study reviews the existing literature on age-related decline of vision at night and its impact on night driving.

### *Age-Related Changes in Vision*

As people age, they suffer anatomical and functional changes in vision, some of which are age-related and others of which are disease-related. With increasing age, a loss in elasticity in the lens and changes in the ciliary muscles occur (Atchison 1995; Holland 2001), and both lead to an age-dependent decline in accommodative power to focus on near objects, also known as *presbyopia*.

Another aging or disease-related process is the opacification of the normally clear lens (Michael and Bron 2011), or *cataract*. As a result, increased light scattering leads to a reduction in the retinal image contrast (de Waard et al. 1992). Cataracts can seriously decrease VA and contrast sensitivity and increase disability glare (Jefferis et al. 2011) and thus lead to a higher risk of being involved in at-fault crashes (Owsley et al. 1999). Cataract surgery can improve VA and contrast sensitivity and reduce disability glare (Elliott et al. 1997; Rubin et al. 1993) and thus might also reduce the rate of crash involvement (Owsley et al. 2002).

The diameter of the pupil for a given value of illumination tends to become smaller. This is known as *pupillary miosis* (Schieber 2006). The greatest age-related changes in pupil diameter occur at low illumination (Winn et al. 1994), which may reduce retinal illumination in extreme situations (Archibald et al. 2009) and may also impair dark adaptation. Other causes for impaired dark adaptations have been suggested on a neural basis (rhodopsin regeneration; Jackson et al. 1999).

Aging is also associated with other age-related eye disease, including glaucoma, macular degeneration, and diabetic retinopathy (National Advisory Eye Council 1999). They can all impair either VA or visual fields. They develop slowly and may not be apparent to the older driver. In case of age-related macular degeneration, laser photocoagulation and photodynamic therapy showed visual stabilization but no vision gain (Lim et al. 2012). However, the newer pharmacological treatments can have positive effects on VA (Lim et al. 2012; Rosenfeld et al. 2006), which might also improve driving performance (Williams and Blyth 2011). For glaucoma, medical and surgical treatments can prevent visual field loss (Boland et al. 2012) and thus might have a positive effect on driving performance. In the case of diabetic retinopathy, tight control of systemic factors, laser photocoagulation, vitrectomy, and, as of recently, pharmacological therapies are the main strategies to prevent or prolong progression of the disease (López et al. 2007).

## **Methods**

PubMed, ISI Web of Knowledge, and Google Scholar were used to search for relevant papers using the following search algorithm: (driving OR driver) AND (night OR mesopic OR twilight OR low light OR illumination OR luminance) AND (visual acuity OR glare sensitivity OR visual field OR useful field of view) AND (age OR old OR elderly) LIMIT English, French, and German language. In addition, we screened the references of papers found in the database for further relevant literature. Papers published between 1920 and 2011 were included in the review. Case-control studies with fewer than 8 subjects were not included in this review to avoid reporting results that are based on very small numbers of subjects only. Four hundred fifty articles were identified through electronic database search and their abstracts were screened independently by 2 authors (N.G., T.N.) for correlations between 6 visual functions (photopic/mesopic/scotopic VA, glare sensitivity, visual field, and useful field of view) and night driving. Disagreements between the 2 authors were resolved by reading the full-text article and by discussing to reach a consensus. Ten papers met these inclusion criteria and were included in this review. The same search strategy was used to search for the definition and age-related changes of these 6 visual functions.

## **Vision and Night Driving**

In research on driving, vision tests are investigated with regards to 2 major outcomes: driving safety and driving performance (Owsley and McGwin 2010). According to Owsley and McGwin (2010), driving safety refers to motor vehicle collision involvement. These data are typically provided by the state's crash records or are self-reported. *Driving performance* refers to driving behavior and can be measured in 2 ways: physically (e.g., speed, lane position, scanning behavior) or by ratings from a trained evaluator (Owsley and McGwin 2010).

Lighting conditions are divided into 3 categories. Photopic vision during daylight is the lighting condition brighter than 1.0 cd/m<sup>2</sup>, whereas night vision (scotopic vision) is defined as the lighting condition darker than 0.01 cd/m<sup>2</sup>. The area between photopic and scotopic vision is called *mesopic* vision (0.01–1.0 cd/m<sup>2</sup>; Schieffer et al. 2005). As a result of modern street lighting and car headlights, driving at night takes place in a mesopic rather than in a photopic or scotopic range (Aulhorn and Harms 1970; Eloholma et al. 2006; Lachenmayr 2003).

Specific visual functions and their correlations with night driving ability are summarized in Table 1.

### *Photopic Visual Acuity*

Photopic VA measures the eye's ability to resolve fine detail at high contrast (Rubin et al. 2001) to perceive 2 closely located points as 2 separate points (Werber 2003). It is measured with optimal lighting and high contrast at near or far distance with Snellen VA charts or Landolt rings. In a driving situation, photopic VA is required to perceive other road users, road signs, and road signals for overtaking maneuvers in interurban

**Table 1.** Overview of studies that assessed the association between vision and night driving

Variable	Study design	Study population	Driving outcome	Correlation between vision and night driving	Reference
Photopic VA	Case-control	261 night accident perpetrators (56.1 ± 11.5 years) 250 control persons (57.7 ± 10.2 years)	State's crash records	Photopic VA was significantly reduced in night accident perpetrators compared to the control group ( $P < .001$ )	Lachenmayr et al. (1998)
	Prospective comparative study	279 patients with cataracts (71 ± 6 years) 67 controls without cataracts (67 ± 6 years)	Driving habits questionnaire	Decreased photopic VA was associated with difficulty driving at night (for trend $P = .0003$ )	McGwin et al. (2000)
	Prospective case series	93 subjects (≥50 years)	Perceived driving disability questionnaire	No correlation between subjective perceived driving disability at night and photopic VA ( $P = .426$ )	van Rijn et al. (2002)
	Prospective comparative study	8 young drivers (21.5 ± 2.8 years); 8 middle-aged drivers (46.6 ± 4.2 years); 8 older drivers (71.9 ± 2.6 years)	On-the-road test	Photopic VA does not predict recognition performance ( $r^2 = 0.01-0.06$ )	Wood and Owens (2005)
	Prospective comparative study	12 young subjects (20.3 ± 2.5 years) 12 older subjects (70.1 ± 3.8 years)	Legibility distance on the road	Photopic VA does not account for the age-related differences in legibility distances ( $r = -0.02$ )	Sivak et al. (1981)
Mesopic VA	Case-control	261 night accident perpetrators (56.1 ± 11.5 years) 250 control persons (57.7 ± 10.2 years)	State's crash records	Mesopic VA was significantly reduced in night accident perpetrators compared to the control group ( $P < .001$ ).	Lachenmayr et al. (1998)
	Prospective case series	93 subjects (≥50 years)	Perceived driving disability questionnaire	Subjective perceived driving disability at night is significantly correlated with the Mesotest without glare (= mesopic VA; $P = .018$ ) but is not correlated with the Nyktotest without glare (= mesopic VA; $P = .164$ ) Background illumination: Mesotest: 0.0316 cd/m <sup>2</sup> ; Nyktotest: 0.1 cd/m <sup>2</sup>	van Rijn et al. (2002)
	Case-control	432 night accident perpetrators (30–59 years), photopic VA > 0.7 432 control persons (30–59 years), photopic VA > 0.7	Road accidents	Almost 20 percent of professional drivers involved in nighttime collisions with other road users have severely diminished twilight vision ( $P \leq .01$ )	von Hebenstreit (1984)
	Prospective comparative study	6 young subjects (23.3 ± 4.1 years) 6 older subjects (67.5 ± 6.0 years)	Legibility distance on the road	Good low-luminance/high-contrast acuity assured good performance in legibility distance	Sivak and Olson (1982)
Glare sensitivity	Case-control	261 night accident perpetrators (56.1 ± 11.5 years) 250 control persons (57.7 ± 10.2 years)	State's crash records	Glare sensitivity was significantly increased in night accident perpetrators ( $P < .01$ )	Lachenmayr et al. (1998)
	Case-control	432 night accident perpetrators (30–59 years), photopic VA > 0.7 432 control persons (30–59 years), photopic VA > 0.7	Road accidents	25 percent of professional drivers involved in nighttime collisions with other road users have increased susceptibility to glare ( $P \leq .01$ )	von Hebenstreit (1984)
	Prospective case series	8 subjects (47.3 ± 8.97 years)	Truck simulator	Target detection in the presence of glare was slower than in the absence of glare (pedestrian detection $P = .0006$ )	Ranney et al. (1996)
	Prospective comparative study	8 young Dutch subjects (28.3 years) 8 young Americans (24.4 years) 8 older Dutch subjects (62.3 years)	On-the-road test	Glare caused a significant drop in detecting simulated pedestrians along the roadside. There was a trend that older participants showed the largest drop ( $P = .063$ )	Theeuwes et al. (2002)
	Prospective comparative study	279 patients with cataracts (71 ± 6 years) 67 controls without cataracts (67 ± 6 years)	Driving habits questionnaire	No correlation between disability glare and difficulty driving at night (no $P$ -value specified)	McGwin et al. (2000)

(Continued on next page)

**Table 1.** Overview of studies that assessed the association between vision and night driving (*Continued*)

Variable	Study design	Study population	Driving outcome	Correlation between vision and night driving	Reference
Visual field	Case-control	261 night accident perpetrators (56.1 ± 11.5 years) 250 control persons (57.7 ± 10.2 years)	State's crash record	No significant correlation between visual field and night accident perpetrators (no <i>P</i> -value specified)	Lachenmayr et al. (1998)
Functional field of vision	Prospective case series	93 subjects (≥50 years)	Perceived driving disability questionnaire	No correlation between subjective perceived driving disability at night and UFOV ( <i>P</i> = .85)	van Rijn et al. (2002)
	Prospective comparative study	279 patients with cataracts (71 ± 6 years) 67 controls without cataracts (67 ± 6 years)	Driving habits questionnaire	No correlation between UFOV and difficulty driving at night (no <i>P</i> -value specified)	McGwin et al. (2000)

traffic to evaluate the speed of oncoming vehicles (Lachenmayr 2006). Reduced VA leads to a shorter recognition distance and thus to reduced time for an adequate reaction (Lachenmayr 2003, 2006).

Photopic VA declines with increasing age (Morgan and King 1995), even in the absence of ocular disease (Klein 1991). Some studies showed a fairly stable photopic VA until age 50 to 60 (A. J. Adams et al. 1988; Johnson and Choy 1987; Mortimer and Fell 1989; Pitts 1982) or even until age 65 to 70 (Haegerstrom-Portnoy et al. 1999) with an age-related decline afterwards, whereas other studies reported a gradual decline starting at age 25 (Elliott et al. 1995; Frisen and Frisen 1981). However, despite the general age-related decrease in VA, a considerable interindividual variance was observed (Pitts 1982).

Some studies showed a correlation between photopic VA and night accident perpetrators (Lachenmayr et al. 1998) and night driving difficulty (McGwin et al. 2000). However, other studies found no significant correlation between photopic VA and subjective perceived night driving disability (van Rijn et al. 2002) and the drivers' recognition ability (e.g., road signs, pedestrians) under nighttime road driving conditions (Sivak et al. 1981; Wood and Owens 2005).

### Mesopic Visual Acuity

Mesopic VA measures the VA in twilight conditions. It decreases with decreasing illumination (Ferree and Rand 1923; Hecht 1928; Johnson and Casson 1995; Lachenmayr 2003; Mainster and Timberlake 2003; Morgan and King 1995; Mortimer and Fell 1989; Shlaer 1937; Sturgis and Osgood 1982; Wilcox 1932). In mesopic light conditions, such as during night driving, VA drops to about half of the photopic acuity (Lachenmayr 2003, 2006; Walsh 1965).

The loss in mesopic acuity is more pronounced in older drivers (Hartmann and Wehmeyer 1980; Mortimer and Fell 1989; Puell et al. 2004; Scharwey et al. 1998; Sturr et al. 1990) as the lens becomes yellower and less transparent and the pupil becomes smaller (Puell et al. 2004). Sturr et al. (1990) reported that 65 years is the critical age after which mesopic VA declines significantly, whereas Puell et al. (2004) maintained that mesopic VA is stable until age 50, with a gradual decrease from 51 years onward.

Few studies exist that have examined the correlation between mesopic VA and a specific part of night driving: In 2

studies, night accident perpetrators (according to von Hebenstreit [1984], in particular, drivers involved in nighttime collisions with another road user) showed reduced mesopic vision compared to drivers with a clean record (Lachenmayr et al. 1998; von Hebenstreit 1984). Other studies reported a correlation between mesopic vision and subjective perceived driving disability at night (van Rijn et al. 2002) and the performance in nighttime legibility distance (Sivak and Olson 1982).

### Scotopic Vision

Driving at night usually requires mesopic vision rather than scotopic vision, because most of the time there is enough light available to fall in the mesopic luminance region (e.g., headlights of the car, headlights of other cars, or street lighting; Aulhorn and Harms 1970; Eloholma et al. 2006; Lachenmayr 2003).

### Glare Sensitivity

Investigators have often distinguished 2 types of glare: discomfort and disability glare (Abrahamsson and Sjostrand 1986; Bullough et al. 2002; Mainster and Timberlake 2003; Werber 2003). Discomfort glare can be distracting but does not necessarily impair vision, whereas disability glare causes impaired vision (Abrahamsson and Sjostrand 1986; Bullough et al. 2002; Mainster and Timberlake 2003). Disability glare is the result of forward intraocular light scattering due to a nearby glare source and leads to a decreased VA and contrast sensitivity (Bichao et al. 1995; Bullough et al. 2002; Puell et al. 2004; Rubin et al. 2001).

Mesopic vision in combination with glare seems to be fairly stable until age 40 and then gradually decreases (Puell et al. 2004). Seventy-five percent of subjects older than 70 years cannot discriminate any contrast in conditions of glare (Puell et al. 2004). Mesopic vision without glare starts to decrease around ages 51 to 60, whereas mesopic vision with glare starts to decrease around ages 41 to 50 (Puell et al. 2004). Therefore, glare leads to an earlier as well as a greater age-dependent decrease in mesopic vision than in nonglare conditions (Puell et al. 2004; Scharwey et al. 1998). Several factors lead to an increased disability glare with increasing age. Age-associated lens protein changes and increased lens density cause an increase in light scattering (Morgan and King 1995). This, in

turn, increases the sensitivity to glare even in people with otherwise perfectly healthy eyes (Haegerstrom-Portnoy et al. 1999; Lachenmayr 2003; Mainster and Timberlake 2003; Puell et al. 2004; Werber 2003). On the other hand, the time required to recover from glare also increases with age (Morgan and King 1995). Factors that influence glare recovery time are crystalline lens optical density, photopigment regeneration, and aberrations (Mashige 2010; Stringham and Hammond 2007).

In general, the effect of glare will increase with an increasing glare source, decreasing background luminance, and decreasing angle between the line of sight and the direction of the light source (Bichao et al. 1995; Bullough et al. 2002). Sivak and Olson (1982) showed a significant disability glare effect if the angle of the glare source is very small ( $0.2^\circ$ ) or glare level is very high, whereas glare sources positioned outside the fovea ( $2^\circ$ ) might even lead to improved legibility of the sign legend. Disability glare increases further if the glare source appears suddenly and is transient (Bichao et al. 1995; Mainster and Timberlake 2003; Werber 2003) because the glare encounters a dilated pupil (Werber 2003). This enhancement during transient glare compared to stable glare increases with increased intraocular scattering (Bichao et al. 1995).

During driving, glare appears mainly from oncoming vehicles and from street lighting (Deutsche Ophthalmologische Gesellschaft 2008; Lachenmayr 2006). Several studies have shown a correlation between glare sensitivity and night driving performance, where increased glare sensitivity increases the risk of traffic accidents (Lachenmayr et al. 1998), in particular, nighttime collisions with another road user (von Hebenstreit 1984). Glare is also correlated with slower target detection (e.g., pedestrians; Ranney et al. 1996; Theeuwes et al. 2002) and slower driving speed on dark and winding roads (Theeuwes et al. 2002). Both are more pronounced in older drivers (Theeuwes et al. 2002). Furthermore, sign legibility distance is reduced in the presence of glare for older drivers but not for younger and middle-aged drivers (ages 40–55; Schieber and Kline 1994). Sivak and Olson (1982), however, found no age-related effect from glare on legibility during night driving if the participants were matched in terms of low-luminance/high-contrast VA. In addition, whereas van Rijn et al. (2002) showed a significant relationship between glare sensitivity and subjective perceived night driving disabilities, McGwin et al. (2000) found no correlation between disability glare and night driving, as assessed by the driving habits questionnaire.

### Visual Field

The visual field is defined as the area within which information can be perceived with an immobilized head and the eyes fixated in primary position (Lachenmayr 2003). A normal monocular visual field extends to about  $90\text{--}100^\circ$  temporal,  $70^\circ$  downward,  $60^\circ$  upward, and  $60^\circ$  nasal (Weijland et al. 2004). Relevant for driving is the overlay of the visual field from left and right eye, the so-called binocular visual field (Lachenmayr 2003). The most important information during driving appears within the central  $30^\circ$  of the visual field (Deutsche Ophthalmologische Gesellschaft 2008). In addition to the central visual field,

the horizontal area to left and right is also of prime importance, such as for lane change (Deutsche Ophthalmologische Gesellschaft 2008). The visual field downward and upward is often limited by vehicle parts (Lachenmayr 2003). A loss of the visual field may occur as a result of disease or trauma at the level of the eye or the brain (e.g., age-related macular degeneration, retinitis pigmentosa, glaucoma, and specific neurological disorders; Charlton et al. 2010).

Numerous studies have reported an age-related decrease in the visual field (Adams et al. 1999; Haas et al. 1986; Heijl et al. 1987; Jaffe et al. 1986; Johnson et al. 1989; Johnson and Choy 1987; Katz and Sommer 1986; Morgan and King 1995). Some studies found a more or less linear decline in the visual field with increasing age, starting around the age of 20 (Haas et al. 1986), whereas others showed a fairly linear reduction in sensitivity until ages 50 to 60 and a slightly greater reduction in sensitivity afterward (Adams et al. 1999; Johnson and Choy 1987). Visual field sensitivity also declines with increasing eccentricity (Jaffe et al. 1986; Katz and Sommer 1986). A generally accepted age-dependent effect of eccentricity on variability in the visual field has not been clarified to date. Some researchers reported a greater interpersonal variability for older persons in the peripheral visual field compared to their central visual field and compared to younger counterparts (Katz and Sommer 1986). Others revealed no age-related effect on variability (Adams et al. 1999).

To the authors' knowledge, few studies exist concerning the correlation between the visual field and night driving performance. The only study found reported no differences in the visual field sensitivity between a nighttime accident-involved group and an accident-free control group (Lachenmayr et al. 1998).

### Functional Field of Vision

The functional field of vision describes the ability to simultaneously process central and peripheral visual information. The extent of the functional field decreases as the quantity of information within the field of vision increases (Sanders 1970). One way to assess the functional field of vision is the Useful Field of View (UFOV) test.

### Useful Field of View

The UFOV was introduced by Ball et al. (1988) and is the total visual field area within which information can be acquired without eye and head movements. The computer-generated UFOV test includes both sensory and cognitive factors (A. B. Sekuler et al. 2000) because it combines a visual task with a neuropsychological task of attention (van Rijn 2005). The test consists of 3 subtests to assess the following outcomes: processing speed, divided attention, and selective attention (Ball et al. 1993). It is measured binocularly and involves detection, localization, and identification of targets against more complex visual backgrounds compared to the visual field where the stimulus is presented on a uniform background (Ball and Owsley 1993; Ball et al. 1988; Johnson and Wilkinson 2010; A. B. Sekuler et al. 2000). Therefore, the UFOV can be much smaller than the area of the visual field sensitivity (Ball et al.

1990; Ball and Owsley 1993; Scialfa et al. 1994). The extent of the UFOV is individual and can vary under different task demands (e.g., target/distractor similarity, stimulus duration; Ball and Owsley 1993). Even a person with normal functional vision (e.g., acuity, visual field sensitivity) may have a restricted UFOV (Ball and Owsley 1993).

The prevalence of people with UFOV restrictions increases with age (Ball et al. 1988; Ball and Owsley 1993) and the difference in the size of the UFOV between older and middle-aged (ages 40–49) or young observers further increases with increasing complexity of the task (Ball et al. 1988). Despite the general age-dependent shrinkage of the UFOV, there remain a significant number of drivers over 80 years old with an unrestricted UFOV (Ball and Owsley 1993). The interpersonal variability increases with age (Haegerstrom-Portnoy et al. 1999).

The fact that UFOV deteriorates with age is generally accepted in the literature, but the type of deterioration varies from one study to the next (Roge et al. 2004). Some researchers reported a worse performance in older adults compared to younger adults independent of the eccentricity of the peripheral signal (Seiple et al. 1996; A. B. Sekuler et al. 2000). Others noted that the difference in the UFOV between older and younger observers increases with increasing eccentricity of the peripheral signal (Ball et al. 1988; R. Sekuler and Ball 1986).

To the authors' knowledge, there exists only one study about the relation between the UFOV and night driving performance. van Rijn et al. (2002) found no significant correlation between the UFOV and subjective perceived night driving disabilities.

## Discussion

Photopic VA, the most common vision test to assess or renew driver's licenses, is not, by itself, a good predictor of night driving ability. Even the correlation with daylight driving is discussed critically (Desapriya et al. 2011). Owsley and McGwin (2010) reviewed the correlation between photopic VA and driving safety as well as driving performance during daylight. They concluded that the correlation between photopic VA and driving safety (motor vehicle collision) is, at best, weak. Conversely, they found that photopic VA is significantly correlated with specific parts of driving performance (e.g., road sign recognition and road hazard avoidance). They concluded that VA may be important for route planning, but it may not be a strong predictor for collisions because VA does not, by itself, reflect the visual complexity of the driving task. Finally, they suggested supplementing the VA test with other visual tests to improve the efficacy of vision screening even for predicting daylight driving (Owsley and McGwin 2010).

Visual field tests measure target sensitivity on a simple background without head and eye movements. This is in direct contrast to the complexity of driving, where head and eye movements are needed to scan the environment. Research has shown that patients with visual field loss may partly compensate for such limitations by enhancing eye movements and fixations within the area of the field loss (Müri et al. 2005; Pflugshaupt et al. 2009; Trauzettel-Klosinski 2010). According to Charlton et al. (2010), research regarding daylight crash

risks and visual fields is inconsistent due to ambiguous assessments and definitions of field loss. The integration of the visual field test into medical examinations seems evident for road safety, but the actual cutoff value is still unclear and further research is needed (van Rijn 2005).

The UFOV test incorporates the influence of distractors and secondary task demands with simultaneously central and peripheral target detection within a visual angle of 30°. It has been shown in a meta-analysis that a poorer UFOV test performance is associated with poor daylight driving performance (including state's crash records, on-the-road tests, and driving simulator performance) in older adults, and further research is needed to determine reliable UFOV cutoff scores that might indicate the need for further assessments of fitness to drive (Classen et al. 2009; Clay et al. 2005). In addition to the UFOV test, a functional visual field test exists that embeds targets and distractors into pictures of everyday life and considers eye movements (Müri et al. 2005). The functional visual field test is therefore more realistic and may be better related to the complexity of a driving situation. Further research, including the age-dependent effect on the functional visual field and its correlation to night driving performance, will be needed to determine whether the functional visual field test is an even stronger predictor for safe night driving than the UFOV test.

For assessing night driving ability, ophthalmologists recommend including tests for mesopic VA and glare sensitivity into medical examinations to obtain or renew driver's licenses (Deutsche Ophthalmologische Gesellschaft 2009), because reduced mesopic acuity and increased glare sensitivity can lead to a complete loss of visual perception (Deutsche Ophthalmologische Gesellschaft 2008). As mentioned above, photopic VA alone is not a good predictor for night driving ability because minor lens opacities (cataract) have no effect on daylight performance but negatively affect nighttime driving performance (Deutsche Ophthalmologische Gesellschaft 2008). Restrictions in mesopic VA and glare sensitivity cannot be compensated for during driving because, for example, increased eye movements can compensate for visual field loss to some extent (Deutsche Ophthalmologische Gesellschaft 2008). Therefore, a driving restriction in twilight and night conditions is recommended for drivers with impaired night vision (Deutsche Ophthalmologische Gesellschaft 2008). In the case of severe night vision impairments, a restriction on night driving should be declared (Deutsche Ophthalmologische Gesellschaft 2008). A night driving restriction seems to be an effective strategy to lower crash rates of elderly drivers. Langford and Koppel (2011) reported a lower relative crash rate following the imposition of a night driving restriction. However, they mentioned that the difference is indicative only and not statistically significant due to the small number of older drivers with license restrictions. Many older drivers self-regulate their driving exposure when they become aware of having difficulties in specific driving situations (Charlton et al. 2006; Eberhard 1996). However, some older adults do not realize their own vision impairment and do not adequately self-regulate their driving exposure despite driving difficulties (Holland and Rabbitt 1992). It has been shown that educational interventions (self-perception of vision impairment,

how vision impairment can impact driver safety, and how to avoid challenging driving situations through self-regulation) lead visually impaired older drivers to reduce their driving exposure and avoid visually challenging driving situations (Owsley et al. 2003).

To date, in most countries, night vision tests are not required to obtain or renew a driver's license. This might be due to ambiguous correlations between night vision tests and night driving ability. There is no test that is a strong predictor for night driving ability. This lack of a strong predictor has various reasons. On the one hand, few studies exist that have examined the correlation between vision tests and night driving performance/safety. On the other hand, available studies differ in study design (case control, cross-sectional), number of study participants, dependent outcome variables (driving safety or driving performance), or driving assessment method (questionnaires, simulator, on-the-road tests, self-reported, and state crash records).

Due to the lack of scientific knowledge about strong and unambiguous predictors for night driving ability, further research is needed to analyze correlations between vision tests and night driving, especially for visual field sensitivity, UFOV, and the functional visual field. To date, no appropriate vision screening test to predict night driving ability has been found. A vision test or a battery of vision tests that can predict night driving ability needs to be developed to distinguish between good and bad night drivers.

Finally, some limitations of the present review need to be mentioned. PubMed, ISI Web of Knowledge, and Google Scholar were used to search for relevant papers. No grey literature was included. This article is not a systematical review because there was no classification scheme to rate the level of evidence (Wright et al. 2007).

## Acknowledgment

This work was supported in part by the Haag-Streit Foundation.

## References

- Abrahamsson M, Sjostrand J. Impairment of contrast sensitivity function (CSF) as a measure of disability glare. *Invest Ophthalmol Vis Sci.* 1986;27:1131–1136.
- Adams AJ, Wong LS, Wong L, Gould B. Visual acuity changes with age: some new perspectives. *Am J Optom Physiol Opt.* 1988;65:403–406.
- Adams CW, Bullimore MA, Wall M, Fingeret M, Johnson CA. Normal aging effects for frequency doubling technology perimetry. *Optom Vis Sci.* 1999;76:582–587.
- Archibald NK, Clarke MP, Mosimann UP, Burn DJ. The retina in Parkinson's disease. *Brain.* 2009;132(pt 5):1128–1145.
- Atchison DA. Accommodation and presbyopia. *Ophthalmic Physiol Opt.* 1995;15:255–272.
- Aulhorn E, Harms H. The examination on fitness for driving at darkness with the mesoptometer [in German]. *Klin Monbl Augenheilkd.* 1970;157:843–873.
- Ball KK, Beard BL, Roenker DL, Miller RL, Griggs DS. Age and visual search: expanding the useful field of view. *J Opt Soc Am A.* 1988;5:2210–2219.
- Ball KK, Owsley C. The useful field of view test: a new technique for evaluating age-related declines in visual function. *J Am Optom Assoc.* 1993;64:71–79.
- Ball KK, Owsley C, Sloane ME, Roenker DL, Bruni JR. Visual attention problems as a predictor of vehicle crashes in older drivers. *Invest Ophthalmol Vis Sci.* 1993;34:3110–3123.
- Ball KK, Roenker DL, Bruni JR. Developmental changes in attention and visual search throughout adulthood. In: Enns JT, ed. *The Development of Attention: Research and Theory.* Amsterdam, The Netherlands: Elsevier Science Publishers BV; 1990, pp. 489–508.
- Bichao IC, Yager D, Meng J. Disability glare: effects of temporal characteristics of the glare source and of the visual-field location of the test stimulus. *J Opt Soc Am.* 1995;12:2252–2258.
- Boland MV, Ervin AM, Friedman D, et al. *Treatment for Glaucoma: Comparative Effectiveness.* Rockville, MD: Agency for Healthcare Research and Quality (US); 2012. Review No. 60.
- Bullough JD, Fu Z, Van Derlofske J. *Discomfort and Disability Glare From Halogen and HID Headlamp Systems.* Detroit, MI: Society of Automotive Engineers; 2002.
- Bundesamt für Statistik. [Federal Statistical Office]. [Mobility and Traffic 2010]. Neuchâtel, Switzerland: Bundesamt für Statistik; 2010 [in German].
- Charlton J, Koppel S, Odell M, et al. *Influence of Chronic Illness on Crash Involvement of Motor Vehicle Drivers.* 2nd ed. Clayton, VIC: Monash University Accident Research Center; 2010.
- Charlton J, Oxley J, Scully J, et al. *Self-Regulatory Driving Practices of Older Drivers in the Australian Capital Territory and New South Wales.* Clayton, VIC: Monash University Accident Research Centre; 2006.
- Chrysler ST, Danielson SM, Kirby VM. Age differences in visual abilities in nighttime driving field conditions. Paper presented at: Human Factors and Ergonomics Society—40th Annual Meeting, September 2–6, 1996; Philadelphia, PA.
- Classen S, McCarthy DP, Shechtman O, et al. Useful field of view as a reliable screening measure of driving performance in people with Parkinson's disease: results of a pilot study. *Traffic Inj Prev.* 2009;10:593–598.
- Clay OJ, Wadley VG, Edwards JD, Roth DL, Roenker DL, Ball KK. Cumulative meta-analysis of the relationship between useful field of view and driving performance in older adults: current and future implications. *Optom Vis Sci.* 2005;82:724–731.
- Collia DV, Sharp J, Giesbrecht L. The 2001 national household travel survey: a look into the travel patterns of older Americans. *J Safety Res.* 2003;34:461–470.
- Desapriya E, Wijeratne H, Subzwari S, et al. Vision screening of older drivers for preventing road traffic injuries and fatalities. *Cochrane Database Syst Rev.* 2011;(3):CD006252.
- Deutsche Ophthalmologische Gesellschaft. [German Ophthalmological Society]. [Driving Fitness Assessment for Road Traffic 2008]. München, Germany: Deutsche Ophthalmologische Gesellschaft; 2008 [in German].
- Deutsche Ophthalmologische Gesellschaft. [German Ophthalmological Society]. [DOG-Recommendations for Quality Assurance of Neurophysiological Assessments and Examination Devices]. München, Germany: Deutsche Ophthalmologische Gesellschaft; 2009 [in German].
- de Waard PW, Ijspeert JK, van den Berg TJ, de Jong PT. Intraocular light scattering in age-related cataracts. *Invest Ophthalmol Vis Sci.* 1992;33:618–625.
- Eberhard JW. Safe mobility for senior citizens. *IATSS Res.* 1996;20:29–37.
- Elliott DB, Patla A, Bullimore MA. Improvements in clinical and functional vision and perceived visual disability after first and second eye cataract surgery. *Br J Ophthalmol.* 1997;81:889–895.
- Elliott DB, Yang KC, Whitaker D. Visual acuity changes throughout adulthood in normal, healthy eyes: seeing beyond 6/6. *Optom Vis Sci.* 1995;72(3):186–191.
- Eloholma M, Ketomaki J, Orrevetelainen P, Halonen L. Visual performance in night-time driving conditions. *Ophthalmic Physiol Opt.* 2006;26:254–263.



- Emsbach M, Friedel B. Traffic accidents of senior citizen car drivers. *Z Gerontol Geriatr*. 1999;32:318–325 [in German].
- Engeln A, Schlag B. [ANBINDUNG: Final Report of the Research Project: Requirements for Seniors for a User-Oriented Integration Individual and Collective Traffic]. Stuttgart, Germany: W. Kohlhammer GmbH; 2001 [in German].
- Ferree CE, Rand G. The effect of intensity of illumination on the acuity of the normal eye and eyes slightly defective as to refraction. *Am J Psychol*. 1923;34:244–249.
- Frisen L, Frisen M. How good is normal visual acuity? A study of letter acuity thresholds as a function of age. *Albrecht Von Graefes Arch Klin Exp Ophthalmol*. 1981;215(3):149–157.
- Haas A, Flammer J, Schneider U. Influence of age on the visual fields of normal subjects. *Am J Ophthalmol*. 1986;101:199–203.
- Haegerstrom-Portnoy G, Scheck ME, Brabyn JA. Seeing into old age: vision function beyond acuity. *Optom Vis Sci*. 1999;76(3):141–158.
- Hartmann E, Wehmeyer K. Investigation of mesopic vision and sensitivity to glare by means of the new “nyktometer.” *Klin Monbl Augenheilkd*. 1980;176:859–863 [in German].
- Hecht S. The relation between visual acuity and illumination. *J Gen Physiol*. 1928;11:255–281.
- Heijl A, Lindgren G, Olsson J. Normal variability of static perimetric threshold values across the central visual field. *Arch Ophthalmol*. 1987;105:1544–1549.
- Holland C. *Older Drivers: A Review*. London, England: Department for Transport; 2001. Road Safety Research Report No. 25.
- Holland CA, Rabbitt PMA. People’s awareness of their age-related sensory and cognitive deficits and the implications for road safety. *Appl Cogn Psychol*. 1992;6:217–231.
- Hu PS, Reuscher TR. *Summary of Travel Trends: 2001 National Household Travel Survey*. Washington, DC: US Department of Transportation; 2004.
- Jackson GR, Owsley C, McGwin G Jr. Aging and dark adaptation. *Vision Res*. 1999;39:3975–3982.
- Jaffe GJ, Alvarado JA, Juster RP. Age-related changes of the normal visual field. *Arch Ophthalmol*. 1986;104:1021–1025.
- Jefferis JM, Mosimann UP, Clarke MP. Cataract and cognitive impairment: a review of the literature. *Br J Ophthalmol*. 2011;95:17–23.
- Johnson CA, Adams AJ, Lewis RA. Evidence for a neural basis of age-related visual field loss in normal observers. *Invest Ophthalmol Vis Sci*. 1989;30:2056–2064.
- Johnson CA, Casson EJ. Effects of luminance, contrast, and blur on visual acuity. *Optom Vis Sci*. 1995;72:864–869.
- Johnson CA, Wilkinson ME. Vision and driving: the United States. *J Neuroophthalmol*. 2010;30:170–176.
- Johnson MA, Choy D. On the definition of age-related norms for visual function testing. *Appl Opt*. 1987;26:1449–1454.
- Katz J, Sommer A. Asymmetry and variation in the normal hill of vision. *Arch Ophthalmol*. 1986;104:65–68.
- Klein R. Age-related eye disease, visual impairment, and driving in the elderly. *Hum Factors*. 1991;33:521–525.
- Lachenmayr B. [Visual requirements for road traffic]. *Deutsches Ärzteblatt*. 2003;100:624–634 [in German].
- Lachenmayr B. Traffic ophthalmology. Assessment of ability to drive in road traffic. *Ophthalmologe*. 2006;103:425–443 [in German].
- Lachenmayr B, Berger J, Buser A, Keller O. Reduced visual capacity increases the risk of accidents in street traffic. *Ophthalmologe*. 1998;95:44–50. [in German]
- Langford J, Koppel S. Licence restrictions as an under-used strategy in managing older driver safety. *Accid Anal Prev*. 2011;43:487–493.
- Lim LS, Mitchell P, Seddon JM, Holz FG, Wong TY. Age-related macular degeneration. *Lancet*. 2012;379:1728–1738.
- López F, Rodríguez M, Marticorena J, Gómez-Ulla F. Diabetic retinopathy treatment. *Eur Ophthalmic Rev*. 2007;1:68–70.
- Mainster MA, Timberlake GT. Why HID headlights bother older drivers. *Br J Ophthalmol*. 2003;87:113–117.
- Mashige KP. Night vision and glare vision thresholds and recovery time in myopic and hyperopic eyes. *S Afr Optom*. 2010;69(3):132–139.
- Massie DL, Campbell KL, Williams AF. Traffic accident involvement rates by driver age and gender. *Accid Anal Prev*. 1995;27:73–87.
- McGwin G Jr, Chapman V, Owsley C. Visual risk factors for driving difficulty among older drivers. *Accid Anal Prev*. 2000;32:735–744.
- Michael R, Bron AJ. The ageing lens and cataract: a model of normal and pathological ageing. *Philos Trans R Soc Lond B Biol Sci*. 2011;366:1278–1292.
- Morgan R, King D. The older driver—a review. *Postgrad Med J*. 1995;71:525–528.
- Mortimer RG, Fell JC. Older drivers: their night fatal crash involvement and risk. *Accid Anal Prev*. 1989;21:273–282.
- Müri RM, Pflugshaupt T, Nyffeler T, von Wartburg R, Wurtz P. A new method of visual exploration analysis. *Rev Neurol (Paris)*. 2005;161:513–517 [in French].
- National Advisory Eye Council. *Vision Research—A National plan: 1999–2003*. Bethesda, MD: National Institutes of Health; 1999.
- Niemann S, Achermann Stürmer Y, Cavegn M. *SINUS-Report 2009: [Safety Level and Accident Occurrence in Road Traffic 2008]*. Bern, Switzerland: Swiss Council for Accident Prevention; 2009.
- Organisation for Economic Co-operation and Development. *Ageing and Transport. Mobility Needs and Safety Issues*. Paris, France: Organisation for Economic Co-operation and Development; 2001.
- Owens DA, Sivak M. Differentiation of visibility and alcohol as contributors to twilight road fatalities. *Hum Factors*. 1996;38:680–689.
- Owens DA, Tyrrell RA. Effects of luminance, blur, and age on nighttime visual guidance: a test of the selective degradation hypothesis. *J Exp Psychol Appl*. 1999;5:115–128.
- Owens DA, Wood JM, Owens JM. Effects of age and illumination on night driving: a road test. *Hum Factors*. 2007;49:1115–1131.
- Owsley C, McGwin G Jr. Vision impairment and driving. *Surv Ophthalmol*. 1999;43:535–550.
- Owsley C, McGwin G Jr. Vision and driving. *Vision Res*. 2010;50:2348–2361.
- Owsley C, McGwin G Jr, Sloane M, Wells J, Stalvey BT, Gauthreaux S. Impact of cataract surgery on motor vehicle crash involvement by older adults. *JAMA*. 2002;288:841–849.
- Owsley C, Stalvey BT, Phillips JM. The efficacy of an educational intervention in promoting self-regulation among high-risk older drivers. *Accid Anal Prev*. 2003;35:393–400.
- Owsley C, Stalvey B, Wells J, Sloane ME. Older drivers and cataract: driving habits and crash risk. *J Gerontol A Biol Sci Med Sci*. 1999;54:M203–M211.
- Pflugshaupt T, von Wartburg R, Wurtz P, et al. Linking physiology with behaviour: Functional specialisation of the visual field is reflected in gaze patterns during visual search. *Vision Res*. 2009;49:237–248.
- Pitts DG. Visual acuity as a function of age. *J Am Optom Assoc*. 1982;53:117–124.
- Plainis S, Murray IJ. Reaction times as an index of visual conspicuity when driving at night. *Ophthalmic Physiol Opt*. 2002;22:409–415.
- Puell MC, Palomo C, Sanchez-Ramos C, Villena C. Mesopic contrast sensitivity in the presence or absence of glare in a large driver population. *Graefes Arch Clin Exp Ophthalmol*. 2004;42:755–761.
- Ranney T, Masaloni A, Simmons L. Immediate and long-term effects of glare from following vehicles on target detection in driving simulator. *Transp Res Rec*. 1996;1550:16–22.
- Roge J, Pebayle T, Lambilliotte E, Spitzenstetter F, Giselsbrecht D, Muzet A. Influence of age, speed and duration of monotonous driving task in traffic on the driver’s useful visual field. *Vision Res*. 2004;44:2737–2744.
- Rosenfeld PJ, Brown DM, Heier JS, et al. Ranibizumab for neovascular age-related macular degeneration. *N Engl J Med*. 2006;355:1419–1431.
- Rubin GS, Adamsons IA, Stark WJ. Comparison of acuity, contrast sensitivity, and disability glare before and after cataract surgery. *Arch Ophthalmol*. 1993;111:56–61.

- Rubin GS, Bandeen-Roche K, Huang GH, et al., and Team SEEP. The association of multiple visual impairments with self-reported visual disability: SEE project. *Invest Ophthalmol Vis Sci*. 2001;42:64–72.
- Sanders AF. Some aspects of the selective process in the functional visual field. *Ergonomics*. 1970;13:101–117.
- Scharwey K, Krzizok T, Herfurth M. Night driving ability of persons with normal vision and variable age. *Ophthalmologe*. 1998;95:555–558 [in German].
- Schieber F. Vision and aging. In: Birren JE, Schaie KW, ed. *Handbook of the Psychology of Aging*. 6th ed. San Diego, CA: Elsevier; 2006.
- Schieber F, Kline DW. Age-differences in the legibility of symbol highway signs as a function of luminance and glare level: a preliminary report. *Proc Hum Fact Ergon Soc Annu Meet*. 1994;38:133–136.
- Schiefer U, Patzold J, Dannheim F. Conventional perimetry I: introduction—basics. *Ophthalmologe*. 2005;102:627–644 [in German].
- Scialfa CT, Thomas DM, Joffe KM. Age-differences in the useful field-of-view—an eye-movement analysis. *Optom Vis Sci*. 1994;71:736–742.
- Seiple W, Szlyk JP, Yang S, Holopigian K. Age-related functional field losses are not eccentricity dependent. *Vision Res*. 1996;36:1859–1866.
- Sekuler AB, Bennett PJ, Mamelak M. Effects of aging on the useful field of view. *Exp Aging Res*. 2000;26(2):103–120.
- Sekuler R, Ball K. Visual localization: age and practice. *J Opt Soc Am A*. 1986;3:864–867.
- Shlaer S. The relation between visual acuity and illumination. *J Gen Physiol*. 1937;21:165–188.
- Sivak M, Olson PL. Nighttime legibility of traffic signs—conditions eliminating the effects of driver age and disability glare. *Accid Anal Prev*. 1982;14(2):87–93.
- Sivak M, Olson PL, Pastalan LA. Effect of driver's age on nighttime legibility of highway signs. *Hum Factors*. 1981;23:59–64.
- Stringham JM, Hammond BR Jr. The glare hypothesis of macular pigment function. *Optom Vis Sci*. 2007;84:859–864.
- Sturgis SP, Osgood DJ. Effects of glare and background luminance on visual acuity and contrast sensitivity: implications for driver night vision testing. *Hum Factors*. 1982;24:347–360.
- Sturr JF, Kline GE, Taub HA. Performance of young and older drivers on a static acuity test under photopic and mesopic luminance conditions. *Hum Factors*. 1990;32:1–8.
- Theeuwes J, Alferdinck JWAM, Perel M. Relation between glare and driving performance. *Hum Factors*. 2002;44:95–107.
- Trauzettel-Klosinski S. Rehabilitation for visual disorders. *J Neuroophthalmol*. 2010;30:73–84.
- van Rijn LJ. *New Standards for the Visual Function of Drivers*. Brussels, Belgium: European Commission Eyesight Working Group; 2005.
- van Rijn LJ, Wilhelm H, Emez M, et al. Relation between perceived driving disability and scores of vision screening tests. *Br J Ophthalmol*. 2002;86:1262–1264.
- von Hebenstreit B. Visual acuity and traffic accidents. *Klin Monbl Augenheilkd*. 1984;185(2):86–90 [in German].
- Walsh JWT. *Photometry*. 3rd ed. New York, NY: Dover Publications; 1965.
- Weijland A, Fankhauser F, Bebie H, Flammer J. *Automated Perimetry—Visual Field Digest*. 5th ed. Haag-Streit AG; 2004.
- Werber S. [Accidents at Night]. Bonn, Germany: Deutscher Verkehrssicherheitsrat; 2003 [in German].
- Wilcox WW. The basis of the dependence of visual acuity on illumination. *Proc Natl Acad Sci U S A*. 1932;18:47–56.
- Williams AF. Teenage drivers: patterns of risk. *J Safety Res*. 2003;34:5–15.
- Williams TA, Blyth CP. Outcome of ranibizumab treatment in neovascular age related macula degeneration in eyes with baseline visual acuity better than 6/12. *Eye (Lond)*. 2011;25:1617–1621.
- Winn B, Whitaker D, Elliott DB, Phillips NJ. Factors affecting light-adapted pupil size in normal human subjects. *Invest Ophthalmol Vis Sci*. 1994;35:1132–1137.
- Wood JM, Owens DA. Standard measures of visual acuity do not predict drivers' recognition performance under day or night conditions. *Optom Vis Sci*. 2005;82:698–705.
- Wright RW, Brand RA, Dunn W, Spindler KP. How to write a systematic review. *Clin Orthop Relat Res*. 2007;455:23–29.