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Vision and Driving

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Abstract

Driving is the primary means of personal travel in many countries and is relies heavily on vision for its successful execution. Research over the past few decades has addressed the role of vision in driver safety (motor vehicle collision involvement) and in driver performance (both on-road and using interactive simulators in the laboratory). Here we critically review what is currently known about the role of various aspects of visual function in driving. We also discuss translational research issues on vision screening for licensure and re-licensure and rehabilitation of visually impaired persons who want to drive.

Keywords

vision; driving; vision impairment

1. Introduction

Driving is inarguably a highly visual task. Even though visual acuity is the ubiquitous screening test during application for a driver's license, many other aspects of visual function and visual processing are undoubtedly involved in supporting the effective control of a vehicle. During the last two decades there has been a burst of research activity focused on the role of vision in driving, much of which has been centered on what types and degrees of vision impairment hamper driver safety and performance. This body of work is largely motivated by society's need to preserve public safety on the roadways. The larger question emerging from this research is, what should be the visual requirements for obtaining or maintaining a driver's license? There is widespread agreement that vision standards for driver licensure need to be evidence-based so as not to unfairly prohibit individuals from driving who have the visual skills necessary to do so, in spite of being visually impaired. Even though the field does not yet have the evidence accumulated to define those standards, the research over the past two decades has gone far in contributing to this evidence base. This article will critically summarize these findings.

Before doing so, however, it is important to acknowledge that driving is not simply just a way to "get around", but in fact is the primary and preferred mode of travel for adults in the

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U.S. and many other countries (Hu & Reuscher, 2004). Being a driver has a profound impact on health and well-being. Driving cessation, regardless of whether it is voluntary or involuntary (i.e., license revocation), can have a number of adverse consequences. Cessation of driving has been associated with decreased health-related quality of life (DeCarlo, Scilley, Wells & Owsley, 2003), increased likelihood of depression and social isolation (Fonda, Wallace & Herzog, 2001; Marottoli, de Leon, Glass, Williams, Cooney, Berkman & Tinetti, 1997; Ragland, Satariano & MacLeod, 2005), reduced access to healthcare services (Owsley, McGwin, Stalvey, Weston, Searcey & Girkin, 2008; Owsley, McGwin, Scilley, Girkin, Phillips & Searcey, 2006), and increased likelihood of placement in long-term-care (Freeman, Gange, Munoz & West, 2006a). It also creates a need for alternative transportation options at both the societal and individual level that are potentially expensive (e.g., public transportation and para-transit systems, taxi) (Rosenbloom, 1993; Transportation Research Board, 2003) and are unavailable in many geographic areas, especially rural areas. Just as reading in a literate society is important to quality of life, so is driving in a society that depends on the personal vehicle for transportation.

Because vision impairment is much more prevalent in later adulthood, many studies on vision and driver safety and performance focus on adults ≥ 50 years old. Because of this focus on the older adult population, other medical and functional co-morbidities common in late adulthood are potential confounders in understanding the relationship between vision and driving. In particular, cognitive impairment elevates crash risk and impairs driving performance (Ball, Roenker, Wadley, Edwards, Roth, McGwin, Raleigh, Joyce, Cissell & Dube, 2006; Wood, Anstey, Kerr, Lacherez & Lord, 2008). Thus, study designs that make use of older adult populations to study associations between vision and driving must consider cognitive co-morbidities whenever possible.

In research on driving, there are two major outcomes (dependent variables) -- driver safety and driver performance. They are not synonymous in that they assess different constructs and use different types of methodology in doing so. *Safety* is defined by adverse driving events, typically motor vehicle collision involvement (e.g., at-fault crashes, injurious crashes). Information on these adverse events is typically provided by a state’s motor vehicle administration in the form of accident reports. The U.S. Department of Transportation’s National Highway Traffic Safety Administration (NHTSA) characterizes driver safety this way (National Highway Traffic Safety Administration, 2009), as do countries throughout the world. Safety measures are often expressed as rates -- crashes per miles driven or per person years of driving. The numerator of these rates can vary with respect to severity (e.g., property damage vs. fatalities) and attribution (e.g., all collisions vs. at-fault). These distinctions are not inconsequential as certain risk factors may be more strongly associated with some types of collisions than others. From an etiologic perspective collisions in which the driver was at-fault are of greater interest to those wherein the driver played no role while from a public health perspective injury-producing collisions may be more relevant. When computing crashes per miles driven, the denominator (miles driven) is based on the driver’s estimate of how many miles per year they have driven in the past year. Drivers of all ages can validly estimate the miles they drive per year (Hu & Reuscher, 2004; Leaf, Simons-Morton, Hartos & Northrup, 2008; Murakami & Wagner, 1997). For crash rate computed as crashes per person-years of driving, the denominator is the number of years the person was a driver during the observation period. These denominators are referred to as “driving exposure”. For inferential purposes crash rates (or risks) in a subgroup of drivers of special interest is compared to a reference group (e.g., drivers with visual acuity worse than 20/40 compared to those with 20/40 or better) using risk, rate or odds ratios. It should be noted that these two safety measures may yield different results, particularly if one group tends to drive less than another yet accumulates a disproportionate number of collisions.

It is not advisable to use self-report of crash involvement in computing crash rate. This issue has been discussed at length elsewhere (Arthur, Bell, Edwards, Day, Tubre & Tubre, 2005; Ball & Owsley, 1991; McGwin, Owsley & Ball, 1998; Smith, 1976). Self-report measures of driver safety come from questionnaires that ask drivers about the number of crashes they have had for some previous period. However, there is a poor association between self-reported crashes and crashes where the police came to the scene and an accident report was filed. Drivers who have been crash free over the past 5 years are very likely to validly report that they have not had crashes; however, those who have crashed, especially those with >1 on record, are less likely to validly report their crash histories. Many reasons undoubtedly underlie this mismatch, including recall problems, social desirability, and unwillingness to share this type of potentially embarrassing information. Rather, the state accident report is typically viewed as the gold standard for measuring safety. It should be noted that police reported crashes may not capture a 100% of the crashes a driver incurs (e.g., minor collisions, those on private property). However, police reported crashes are highly likely to reflect more serious crashes involving property damage and/or personal injury on public roads. From public health and safety perspectives, these are the most relevant crashes.

Performance refers to driver behaviors when operating a motor vehicle. Performance can be measured in 2 general ways. One is by physical measures of driving behavior (e.g., speed, braking, latency, scanning behavior, position in the lane). These measures are accomplished through the use of an instrumented vehicle having sensors or measuring devices that record elements of vehicle movement or driver behaviors directly (Muno, Jefferys, Gower, Munoz, Lyketsos, Keay, Turano, Bandeen-Roche, & West, 2010; Neale, Lauer, Knipling, Dingus, Holbrook & Petersen, 2002; Uc, Rizzo, Anderson, Sparks, Rodnitzky & Dawson, 2006; West, Hahn, Baldwin, Duncan, Munoz, Turano, Hassan, Munro, & Bandeen-Roche, 2010; Wood, Elgin, McGwin, Vaphiades, Kline & Owsley, under review; Wood, McGwin, Elgin, Vaphiades, Braswell, DeCarlo, Kline, Meek, Searcey & Owsley, 2009). A second way of measuring performance is by ratings given by a trained evaluator who rides in the vehicle and uses a standard rating scale (Bowers, Peli, Elgin, McGwin & Owsley, 2005a; Haymes, LeBlanc, Nicolela, Chiasson & Chauhan, 2008; Wood et al., 2008; Wood et al., 2009). Ratings are given for quality and effectiveness of overall (“global”) driving behavior and for specific skills (e.g., lane control). The rater should also have good inter-rater reliability established with a second rater, with both raters masked to driver functional and health characteristics and history.

Although driving performance should be theoretically linked to driver safety, there is little empirical evidence for this link. More specifically, no on-road driving performance assessment has been designed whose results are associated with motor vehicle collision rates (Ratz, 1978a; Ratz, 1978b). Practically speaking what this means is that persons who demonstrate impaired driving performance according to some metric are not necessarily at high risk for future crash involvement, or vice versa. The difficulty in establishing a link between driver performance and safety is probably due to many factors, including the fact that performance is assessed during a brief snapshot of driving time whereas safety is estimated over many person-miles or person-years of driving.

Use of interactive driving simulators to provide information about the relationship between vision and driver performance is becoming more popular, spurred on by the increased design sophistication and commercial availability of off-the-shelf systems. Interactive driving simulators fill a research niche by providing a laboratory environment for the study of the complex behaviors that comprise driving. The primary advantage offered by simulators is stimulus control, that is various types of driving scenarios can be standardized for each participant and can be repeated in “trials” as many times as deemed useful for measuring a particular behavior. Also, it is sometimes impractical or impossible for a researcher to take research participants on the road for driving performance measurements because of limited technical or financial resources, legal reasons, and/or ethical concerns. Prior research has demonstrated that interactive driving simulators can be useful in studying visual capabilities and driving, including older drivers or drivers with vision impairment (Alexander, Barham & Balck, 2002; Bowers, Mandel, Goldstein & Peli, 2009; Donmez, Boyle & Lee, 2006; Gray & Regan, 2007; Lee, Lee, Cameron & LiTsang 2003; Rizzo, Reinach, McGehee & Dawson, 1997; Staplin, 1995). Yet it is also important to understand the noteworthy limitations of the simulator approach for understanding real-world driving performance. The visual displays of many simulators are relatively crude and have poor fidelity in terms of representing the visual complexity and different lighting conditions of common driving situations. Many simulator scenarios have not undergone the appropriate validation process necessary for generalizing the results of simulator performance measures to actual on-road driving, or if they have undergone validation, the validation study has been limited to certain driver populations. While it is tempting to conclude that impaired performance in the simulator means impaired performance on the road, this should be avoided unless a thorough validation of the simulator has been conducted, and much more convincing on-road studies have been done subsequent studies (e.g., with an instrumented vehicle). Nevertheless, interactive driving simulators are useful laboratory tools that can assist in generating hypotheses about vision-driving relationships that then can be tested on the open road or on closed-road courses in an actual vehicle. Another potential use of interactive simulators that could be more fully exploited in the future is their serving as a training intervention for drivers with visual impairments in order to improve skills critical to driving before the drivers are exposed to actual on-road traffic situations (Ivancic & Hesketh, 2000; Romoser, Fisher, Mourant, Wachtel & Sizov, 2005).

2. Visual Function and Driving

Below we review what is currently known about the role of different aspects of vision in driver safety and performance. For additional and historical perspectives the reader is referred to previous reviews of and commentaries on this topic (Brody, 1954; Charman, 1997; Committee on Medical Aspects of Automotive Safety, 1969; Owsley, 2004; Owsley & McGwin, 1999; Panek, Barrett, Sterns & Alexander, 1977; Subzwari, Desapriya, Babul-Wellar, Pike, Turcotte, Rajabali & Kinney, 2009).

2.1. Visual Acuity

The ability to resolve detail, or visual acuity, is the ubiquitous visual screening test used by licensing agencies for the determination of driving fitness. The use of visual acuity screening for initial and periodic re-licensure for driving has face validity. It is the choice of ophthalmologists and optometrists when assessing the integrity and health of the visual system and is the primary visual function evaluated during a comprehensive eye examination. In addition, road signs in the U.S. are designed based on sight-distances assuming that drivers have at least 20/30 binocular visual acuity (Federal Highway Administration, 2003). Drivers with acuity worse than that level are likely to have difficulty reading highway signage (e.g., speed limit signs, stop signs, exit signs on the interstate) at distances deemed safe for making vehicle control decisions (e.g. lane changes, turns, exiting) (summarized in Schieber, 2004). Thus, requiring that licensed drivers have visual acuity at the 20/30 level or better enhances the likelihood that drivers can read highway signs well in advance of the time they need to make decisions and execute motor responses.

However, in the United States, visual acuity requirements are highly variable from state to state (American Association of Motor Vehicle Administrators, 2006; American Medical Association, 2003; Peli & Peli, 2002). The following examples illustrate the diversity of visual acuity standards among the states. In Florida, drivers must have 20/70 in either eye with or without corrective lenses whereas drivers in Connecticut must have 20/40 in the better eye, with or without corrective lenses. In a proportion of states, drivers who do not meet the vision requirement may be eligible for a restricted driver license. For example, Iowa drivers with visual acuity of worse than 20/50 but not worse than 20/70, in addition to being restricted to daytime driving, must also drive no faster than 35 miles per hour. Some states (e.g., Maryland) allow for licensure even though the applicant does not meet the state's acuity requirement if, after reviewing the case, the Medical Advisory Board decides that there is potential for safe driving and a driving specialist determines the person is fit to drive based on a detailed on-road evaluation.

The earliest large-scale research examining the association between visual acuity and driver safety is that of Burg (1967; 1968) and subsequently Hills and Burg (1977) who demonstrated that for young and middle-aged California drivers, there was no relationship between poor visual acuity and motor vehicle collision involvement; however, significant, albeit weak, associations were observed among older drivers. This pattern of results (i.e., significant yet weak associations) has been observed in other studies (Davison, 1985; Hofstetter, 1976; Humphriss, 1987; Ivers, Mitchell & Cumming, 1999; Marottoli, Richardson, Stowe, Miller, Brass, Cooney & Tinetti, 1998); these findings are counterbalanced by other studies reporting no significant association (Decina & Staplin, 1993; Gresset & Meyer, 1994; Johansson, Bronge, Lundberg, Persson, Seideman & Viitanen, 1996; Marottoli, Cooney Jr., Wagner, Doucette & Tinetti, 1994; McCloskey, Koepsell, Wolf & Buchner, 1994; Owsley, Ball, McGwin, Sloane, Roenker, White & Overly, 1998a; Owsley, Stalvey, Wells, Sloane & McGwin, 2001). If there is a true yet small association between visual acuity and motor vehicle collisions, the lack of significant findings in some studies may be partly attributable to inadequate sample size (i.e., low statistical power) and/or failure to account for driving exposure. However, two recent well-designed cohort studies with 1,801 participants (Rubin, Ng, Bandeen-Roche, Keyl, Freeman & West, 2007) and 3,158 participants (Cross, McGwin, Rubin, Ball, West, Roenker & Owsley, 2009) did not find a significant relationship between visual acuity and motor vehicle collision involvement rates. It has been argued (and research supports) that visually impaired drivers tend to drive less and in more familiar surroundings (Ball, Owsley, Stalvey, Roenker, Sloane & Graves, 1998; Freeman, Munoz, Turano & West, 2005; Freeman, Munoz, Turano & West, 2006b; Lyman, McGwin & Sims, 2001); thus any excess risk they pose on a per capita basis is diminished once accounting for driving patterns.

Research regarding visual acuity and driver performance, actual or simulated, has been less extensive than that regarding driver safety. Higgins and colleagues (Higgins, Wood & Tait, 1998) used simulated acuity impairment (from induced optical blur) to evaluate its relationship with different components of the driving task on a closed-road course. Results suggested that road sign recognition and road hazard avoidance were impaired but the ability to navigate the vehicle through a road course was not. Further research confirmed these findings (Higgins & Wood, 2005). In addition to simulated visual acuity impairment, studies have also evaluated the driving performance of those with acuity-impairing conditions such as age-related macular degeneration (AMD). Szlyk and colleagues (Szlyk, Pizzimenti, Fishman, Kelsch, Wetzel, Kagan & Ho, 1995) compared the driving performance of older drivers with AMD to an age-matched group of drivers with normal vision and observed that the AMD drivers performed significantly worse on nearly all on-road and driving simulator measures. However, such performance decrements should not be wholly attributed to visual acuity impairment as a number of other factors (e.g., contrast sensitivity) may also play a role.

Based upon the research to date, it is clear that if there is an association between visual acuity and driver safety, it is at best weak, a conclusion expressed by others (Charman, 1997; Hu, Trumble & Lu, 1997). How does one rectify this conclusion in light of the significant findings from performance-based studies? One important consideration in this regard is that visual acuity-related performance decrements do not translate into reduced safety. That is, visual acuity-related driving skills (e.g., sign recognition) may not be crucial to the safe operation of a vehicle. Reading signage may be important for route planning or maintaining regulatory compliance with the "rules of the road", but it may not be critical for collision avoidance. Another consideration is that visual acuity testing does not measure the visual skills necessary for the safe operation of a motor vehicle. Visual acuity tests were originally designed for the clinical diagnosis and monitoring of eye disease, and do not by themselves reflect the visual complexity of the driving task. Guiding a vehicle along a roadway and through intersections involves the simultaneous use of central and peripheral vision and requires monitoring of primary and secondary tasks, all in the midst of a visually cluttered environment where critical events occur with little or no advance warning. Visual acuity tests do not generally include these stimulus features, and in fact seek to minimize distractions and secondary task demands. Acuity is typically evaluated under high contrast and luminance conditions, whereas driving encompasses wide ranging contrast and luminance levels. Another consideration is the fact that stationary visual acuity test targets do not represent the motion-based driving environment. Studies which have included both static and dynamic acuity measurements have generally found relatively stronger, yet still weak, associations for dynamic rather than for static acuity (Burg, 1966; Burg, 1967; Burg, 1968; Hu et al., 1997; Shinar, 1977).

There are other factors that must be considered when rectifying the seemingly illogical conclusion that visual acuity, the widespread measure for granting driving privileges, is not associated with driving safety. One such factor is directly related to state licensing restrictions. That is, it is possible that drivers with severe visual acuity impairment have simply been removed from the road; this would be particularly true in states that require vision re-screening at the time of license renewal. A related issue is the fact that drivers with vision impairment may voluntarily restrict or stop driving. A population-based cohort study in Maryland reported that reduced visual acuity was associated with reduced mileage and cessation of driving in unfamiliar places (Freeman et al., 2006b). Results from the same study failed to observe an association between visual acuity impairment and overall driving cessation after adjustment for contrast sensitivity and visual field impairment, both of which showed significant associations (Freeman et al., 2005). These seemingly contradictory results point to the fact that while visual acuity may be associated with modifications in driving habits, it may play less of a role when ultimately deciding to stop driving altogether. Though current research supports the relationship between driving cessation or restriction and vision impairment, particularly among older drivers (Ball et al., 1998; Campbell, Bush & Hale, 1993; Marottoli, Ostfeld, Merrill, Perlman, Foley & Cooney, 1993; Stutts, 1998), there is less consistency regarding specific changes in driving habits and specific visual impairments. And as a result, observational studies (as opposed to simulator or on-road studies) may fail to observe an association between visual acuity impairment and motor vehicle collision involvement.

Another consideration is that the relationship between visual acuity and driving safety and performance cannot be appropriately considered without taking into account other aspects of visual functioning. This has two important implications. First, vision screening protocols that address several domains of visual function may prove more useful in discriminating high and low risk drivers. For example, Decina and Staplin (1993) reported that Pennsylvania drivers who did not meet a combined vision screening criterion (including visual fields, acuity, and contrast sensitivity) had higher motor vehicle collision rates, whereas visual acuity by itself was not predictive. Another implication is that reported associations between visual acuity and motor vehicle collision involvement may truly reflect other, correlated, measures of visual function (e.g., contrast sensitivity). Freeman et al. (2005) observed that older drivers with visual acuity impairment had higher driving cessation rates, yet once the joint effect of contrast sensitivity was considered the relationship disappeared. The authors concluded that contrast sensitivity plays a more prominent role in driving cessation compared to visual acuity.

2.2. Visual Field

While not universal, visual field testing is used by many states for licensing purposes and like visual acuity, the specific visual field requirements are highly variable and the rationale for one requirement over another is often not clear. For example, in Arizona, the field of vision must be 60 degrees, plus 35 degrees on the opposite side of the nose in at least one eye. The field of vision for Connecticut drivers must be 140 degrees for a person with two eyes, and 100 degrees for a person with one eye.

The first large-scale population-based assessment of visual field impairment and driver safety was conducted by Johnson and Keltner (1983). They reported that drivers with severe binocular field loss had significantly higher motor vehicle collision and violation rates compared to those without any loss. This study is noteworthy for its large sample size (i.e., 10,000 drivers) and the use of mileage-based motor vehicle collision rates. However, several other studies (Burg, 1967; Burg, 1968; Decina & Staplin, 1993; Hu et al., 1997; Owsley et al., 1998a) have also accounted for driving exposure and have not reported elevated motor vehicle collision rates for those with visual field impairments. Moreover, studies that did not account for driving exposure have also failed to observe a significant association (Council & Allen, 1974; Danielson, 1957).

This is in contrast to other studies that have reported elevated rates for those with such impairments (Haymes, LeBlanc, Nicolela, Chiasson & Chauhan, 2007; McGwin, Xie, Mays, Joiner, DeCarlo, Hall & Owsley, 2005; Rubin et al., 2007). In the case of Rubin et al. (Rubin et al., 2007) as with Johnson and Keltner (1983), the association was specific to those with binocular field loss. McGwin et al. (2005) observed that the association was stronger when considering the extent of impairment in the worse eye. Haymes et al. (2007) observed that among glaucoma patients, those with visual field impairment in the worse eye had a nearly five-fold increase in motor vehicle collisions though this association was not statistically significant. This highlights an important consideration in comparing results across studies, perhaps more so than for visual acuity, namely that the definition of visual field impairment differs across the studies. Johnson and Keltner (1983) defined impairment as very significant binocular field loss (however it was not quantitatively defined), whereas most other studies have used less stringent definitions of impairment. And perhaps in the broadest sense, several studies have simply compared drivers with and without glaucoma, a disease whose hallmark is visual field impairment, and observed elevated motor vehicle collision risks (or rates) for drivers with glaucoma (Haymes et al., 2007; Hu, Trumble, Foley & al., 1998; Owsley, McGwin & Ball, 1998b) However, such findings have not been universal; in a study by McGwin and colleagues (McGwin, Mays, Joiner, DeCarlo, McNeal & Owsley, 2004), simply because persons were diagnosed with glaucoma did not transfer to an increase crash risk. Furthermore, in those studies where glaucoma was associated with an increased crash risk, it would be inappropriate to conclude that the elevated risk among glaucoma patients is solely attributed to their visual field impairment. In the study by Haymes et al. (2007) the glaucoma patients had higher motor vehicle collision rates compared to non-glaucoma patients after adjustment for visual field impairment suggesting that some other factor was responsible for the elevated rates. This underscores the problem with using an eye disease diagnosis as a surrogate for a visual functional loss in research on driving in that the disease can functionally manifest itself in very diverse ways, from very minor visual impairment to severe impairment.

The aforementioned studies have largely focused on driving safety as measured by real-world motor vehicle collisions. There have also been a number of studies evaluating the association between visual field impairment and on- and off-road driving performance. In a series of papers, Wood and colleagues (Wood, Dique & Troutbeck, 1993; Wood & Troutbeck, 1992; Wood & Troutbeck, 1995) used simulated visual field restriction to evaluate its impact on driving performance on a closed course. Collectively the results of this body of work suggest that simulated visual field impairment compromised some (e.g., identification of road signs, avoid obstacles, reaction time) but not all (e.g., speed estimation, stopping distance) aspects of driving performance. The relevance of the findings from these studies to real world driving is unclear. It is likely that the impact of sudden, simulated visual field restriction is different from that of naturally occurring restriction from eye disease, such that the persons with the latter may develop compensatory mechanisms over time. Despite the largely consistent observation that drivers with visual field defects have impaired driving performance, a number of authors have cautioned that large individual differences exist and that some drivers with such impairments may pose no more of a safety risk than normally sighted drivers (Elgin, McGwin, Wood, Vaphiades, Braswell, DeCarlo, Kline & Owsley, 2010; Racette & Casson, 2005; Wood et al., 2009). As a result, individualized assessments of driving skill rather than comprehensive prohibitions are recommended. However, closed course or simulator driving is less complex and less demanding than actual driving and may not allow for the identification of drivers that pose a true safety (i.e., collision) threat. Thus, whether closed course and simulator driving are valid and reliable measures of driving safety remains an important issue.

When interpreting the literature on visual field impairment and driving safety and performance, there are several important issues to consider. The first relates to visual field measurement. For example, in some studies only the extreme limits of the visual field were determined. Such screening techniques provide little information about the type or severity of visual field impairment (e.g., scotomas, central field defects). Another important issue is adaptation and compensatory strategies. Drivers with visual field defects may partly overcome them by eye and head movement, restricted driving, or both. There is little research regarding eye and head movements but that which does exist suggests that drivers with field defects deemed to be safe drivers tended to engage in more scanning behavior compared to unsafe drivers having field defects (Coeckelbergh, Brouwer, Cornelissen, van Wolffelaar & Kooijman, 2002; Elgin et al., 2010; Wood et al., 2009). Additional research is needed to explore these findings. A related consideration is the extent to which drivers with visual field defects modify their driving behaviors in an attempt to moderate crash risks. It has been suggested that failure to account for such methodological issues may account for the lack of a relationship observed in some studies (North, 1985). However, research regarding this issue has produced mixed results. While some studies have reported that drivers with visual field impairment or related eye diseases (e.g., glaucoma) limit or cease their driving (Adler, Bauer, Rottunda & Kuskowski, 2005; Ramulu, West, Munoz, Jampel & Friedman, 2009), others have not (Keay, Munoz, Turano, Hassan, Munro, Duncan, Baldwin, Jasti, Gower & West, 2009). Given that some drivers self-regulate, it is interesting that most of the studies examining the relationship between visual field impairment or related diseases and motor vehicle collision involvement that have taken driving exposure into account have produced null results (Burg, 1967; Burg, 1968; Decina & Staplin, 1993; Hu et al., 1997; Owsley et al., 1998a).

2.3. Contrast Sensitivity

To our knowledge, contrast sensitivity is not currently used as a licensing requirement in any state in the U.S. While the literature regarding contrast sensitivity and driving safety and performance is less extensive than that for visual acuity, it is no less divergent. In population-based studies on older drivers, contrast sensitivity impairment was associated with a recent history of crash involvement (Ball, Owsley, Sloane, Roenker & Bruni, 1993), but was not associated with future crash involvement (Cross et al., 2009; Owsley et al., 1998a; Rubin et al., 2007). However, in an evaluation of contrast sensitivity as a screening test at licensure renewal in California, those who failed the screening test were more likely to incur future crashes as compared to those who passed (Hennessy, 1995; Hennessy & Janke, 2009). Contrast sensitivity deficits are common in older adults with cataract; Owsley et al. (2001) found that for older drivers with clinically significant cataract, contrast sensitivity impairment was strongly associated with a recent crash history. The association was twice as strong when both eyes were impaired compared to when only one eye was impaired. Furthermore, they found that cataract surgery and intraocular lens insertion in this same cohort (which improved their vision) reduced their risk of future crash involvement by 50%, as compared to those in the cohort who did not elect cataract surgery (Owsley, McGwin, Sloane, Wells, Stalvey & Gauthreaux, 2002).

The significant association between contrast sensitivity deficits and crash risk observed by Owsley et al. (Owsley et al., 2001) may reflect the increased representation of drivers with significant contrast sensitivity impairments (since the study focused on cataractous drivers) compared to the population-based samples used in other studies finding no association (Cross et al., 2009; Owsley et al., 1998a; Rubin et al., 2007). Rubin et al. (2007) suggest that the lack of an association in most prospective studies may reflect state licensing laws (where persons with vision impairment are less likely to get their licenses renewed) or self-regulation. Drivers with severely impaired contrast sensitivity (i.e., those with the highest risk) may reduce or eliminate their driving. Along these lines, numerous studies (Ball et al., 1998; Freeman et al., 2005; Freeman et al., 2006b; Keay et al., 2009; Lyman et al., 2001; McGwin, Chapman & Owsley, 2000; Rubin, Roche, Prasada-Rao & Fried, 1994) have reported significant associations between impaired contrast sensitivity and driving modification and difficulty.

As with visual acuity, the literature regarding contrast sensitivity and driving performance is more consistent than the driving safety literature. For example, Wood and colleagues (Wood et al., 1993; Wood & Troutbeck, 1995) used simulated contrast sensitivity impairment and assessed its relationship with driving performance on a closed road circuit. The results indicated that higher (i.e., better) overall driving scores were correlated with better contrast sensitivity. Contrast sensitivity measured under photopic conditions was a better predictor of the recognition of road signs, obstacles and pedestrians while driving at night than was photopic visual acuity (Anderson & Holliday, 1995; Wood & Owens, 2005). Wood and Carberry (2004; 2006) also demonstrated that for older drivers with cataract, cataract surgery improves driving performance, an effect that is mediated by improvement in contrast sensitivity following surgery. These driving performance results parallel the driver safety benefits of cataract surgery demonstrated by Owsley et al. (2002). Further evidence supporting the key role of contrast sensitivity in driving performance comes from both on-road and simulator studies on drivers with Parkinson disease (Amick, Grace & Ott, 2007; Uc, Rizzo, Anderson, Dastrup, Sparks & Dawson, 2009; Uc, Rizzo, Johnson, Dastrup, Anderson & Dawson, 2009; Worringham, Wood, Kerr & Silburn, 2006) and from on-road research on drivers with hemianopia and quadrantanopia (Elgin et al., 2010; Wood et al., 2009).

2.4. Visual Processing Speed and Divided Attention

Visual sensory abilities, such as measures of spatial resolution, contrast sensitivity, and light sensitivity throughout the visual field, are useful for understanding the visibility of objects and events during driving, yet by themselves they are insufficient for understanding the visual complexity of the driving task. The visual demands of driving are intricate.

Controlling a vehicle takes place in a visually cluttered environment and involves the simultaneous use of central and peripheral vision and the execution of primary and secondary tasks (both visual and non-visual). As the vehicle moves through the environment, the visual world is rapidly changing. The driver is often uncertain as to when and where a critical visual event will occur. These task demands have prompted researchers to examine relationships between driver safety and performance and attentional skills.

The earliest studies on attention and driving were from the 1970s and focused on commercial drivers. Kahneman and colleagues (Kahneman, Ben-Ishai & Lotan, 1973) reported that bus drivers in Israel with worse scores on an auditory selective attention task had a higher crash rate over the previous years. This finding was further confirmed for utility company drivers in the United States (Barrett, Mihal, Panek, Sterns & Alexander, 1977; Mihal & Barrett, 1976). Also around this time Shinar (1978) reported the results of a detailed analysis of accident report documents from a large sample of Indiana drivers, finding that “driver inattention” appeared to be the most common operator cause of motor vehicle collisions.

The role of visual attention in driver safety was largely ignored until the 1990s when there was increasing interest in the mechanisms underlying older drivers’ elevated rate of crash involvement; it is about double that of middle-aged drivers (National Highway Traffic Safety Administration, 1993). By this time there was considerable evidence that many older adults, even when free of dementia, had impairments in visual divided attention abilities under brief target durations, as compared to younger adults (Allen, Weber & Madden, 1994; Ball, Beard, Roenker, Miller & Griggs, 1988; Hoyer & Plude, 1982; Madden, 1990a; Madden, 1990b; Plude & Doussard-Roosevelt, 1989; Sekuler & Ball, 1986). The potential for these divided attention deficits to contribute to older adults driving problems was first suggested in a study by Ball, Owsley, and Beard (1990). Using a task called the useful field of view (UFOV) (Ball, Roenker & Bruni, 1990), they found that older adults with impaired divided attention abilities under brief target durations were more likely to report driving problems, as compared to those without this deficit. The UFOV estimates the minimum target duration needed by an observer to detect or discriminate targets presented in central vision, while localizing a simultaneously presented peripheral target. In some conditions the targets are embedded in distractors. This finding prompted Ball, Owsley and colleagues (Ball et al., 1993; Owsley, Ball, Sloane, Roenker & Bruni, 1991) to examine whether slowed visual processing speed under divided attention conditions as assessed by the UFOV task elevated crash risk in older drivers. They demonstrated that poor performance in the UFOV task by older drivers was associated with a history of an increased number of motor vehicle collision in recent years. Furthermore, a prospective study showed that older drivers with slowed visual processing speed, particularly under divided attention conditions, were 2.2 times more likely to incur a crash in the subsequent two years, as compared to those without this impairment (Owsley et al., 1998a). This association was independent of other factors that can impact crash involvement (e.g., visual sensory abilities, medical comorbidities, cognitive status); further, in this study no other visual functional test (e.g., acuity, contrast sensitivity, visual field sensitivity) was associated with increased crash involvement in future years.

Since the initial reports, these findings have been replicated and extended (Ball et al., 2006; Clay, Wadley, Edwards, Roth, Roenker & Ball, 2005; Cross et al., 2009; Owsley et al., 1998b; Rubin et al., 2007; Sims, McGwin, Allman, Ball & Owsley, 2000; Sims, Owsley, Allman, Ball & Smoot, 1998). Collectively this literature has prompted several jurisdictions to examine the feasibility of using a speed of processing/divided attention task as a way to screen older drivers when applying for routine re-licensure (Ball et al., 2006; Hennessy & Janke, 2009). These studies imply that visual attention and visual processing speed are critical considerations in the evaluation of safe driving skills and may be better screening tests than visual sensory tests (e.g., visual acuity) for identifying crash-prone older drivers.

Visual processing speed and divided attention have also been associated with driving performance problems on the road. When evaluated on a closed-road course, those older drivers with divided attention deficits as assessed by a modified perimeter were less likely to detect and recognize signs and pedestrians and needed more time to complete the course (Wood et al., 1993). In a recent study on drivers with brain injuries causing hemianopia or quadrantanopia, those who exhibited slowed visual processing speed in a divided attention task (Trails B) (Retan, 1955) were rated as having vehicle control problems by trained backseat evaluators masked to driver health and functional characteristics (Wood et al., 2009). Several studies have shown that drivers seen at rehabilitation clinics because of dementia (e.g., Alzheimer's disease) or brain injury (stroke) were at higher risk of failing an on-road driving test administered by a driving rehabilitation specialist if they performed poorly on the UFOV test (Cushman, 1996; Duchek, Hunt, Ball, Buckles & Morris, 1998; Mazer, Korner-Bitensky & Sofer, 1998; Myers, Ball, Kalina, Roth & Goode, 2000).

With the widespread popularity of cell phones, there is concern about their impact on driver safety and performance since they are commonly used while people drive. Using a cell phone while driving is basically a dual-task situation, and thus raises questions about how the performance of the primary task (driving) is impacted by the secondary task (conversing on the phone). A 2004 study in the U.S. estimated that at any given time of day, 5% of drivers are using cell phones (Glassbrenner, 2005). Research has clearly demonstrated that cell phone use impairs both driver safety and performance (for recent overviews, see Caird, Willness, Steel & Scialfa, 2008; McCartt, Hellinga & Braitman, 2006). Drivers conversing on cell phones have about a fourfold increase in the risk of motor vehicle collision involvement, compared to those not using phones, and this increased risk applies to the use of hands-free devices as well (McEvoy, Stevenson, McCartt, Woodward, Haworth, Palamara & Cercarelli, 2005; Redelmeier & Tibschirani, 1997). Studies using interactive driving simulators indicate that drivers conversing on cell phones tend to take longer to react to relevant targets or events in the driving environment, take longer to recover their speed after braking, increase their following distance, reduce their overall speed, miss traffic signals and incur simulator crashes (Consiglio, Driscoll, Witte & Berg, 2003; Laberge, Scialfa, White & Caird, 2004; Strayer & Drews, 2004; Strayer & Johnston, 2001; Woo & Lin, 2001). On-road studies conducted with closed courses, tracks, and the open road reveal similar findings (summarized by McCartt et al., 2006). Many studies show that the negative impact of cell phone use is just as strong even when a hands-free device was used (Consiglio et al., 2003; Strayer & Drews, 2007; Strayer & Drews, 2004; Strayer & Johnston, 2001), but a few find problems worse for hand-held phones (Haigney & Westerman, 2001; Törnros & Bolling, 2005). Some studies suggest that younger and older drivers are equally vulnerable to the negative effects (Strayer & Drews, 2004), while others suggest older drivers are more vulnerable (Hancock, Lesch & Simmons, 2003; Shinar, Tractinsky & Compton, 2005). Furthermore, there is disagreement about whether practice driving while conversing on a cell phone mitigates the adverse effects of cell phone use (Cooper & Strayer, 2008; Shinar et al., 2005). Text messaging on cell phones is also very popular; recently Drews and colleagues (Drews, Yazdani, Godfrey, Cooper & Strayer, 2009) reported that the negative impact of text-messaging on a cell phone while driving exceeds that of conversing on a cell phone.

In attention blindness has been suggested as a mechanism underlying failure to detect relevant targets (e.g., traffic signals, pedestrians, other vehicles) during driving while using a cell phone (Strayer & Drews, 2007). In their studies Strayer & Drews (2007) showed that even though the driver's gaze was fixated on the target, the driver was less likely to remember the target when conversing on a cell phone compared to when not conversing. Rather than being a problem of retrieval, event-related potential (ERP) studies imply that the problem was a failure to adequately encode the target (Strayer & Drews, 2007; Strayer, Drews & Johnston, 2003). It is interesting that the driving performance decrements found with cell phones do not appear to extend to conversations with passengers (Charlton, 2009; Drews, Pasupathi & Strayer, 2008). These studies suggest that conversations with passengers differ from conversations on a cell phone in at least two ways. First, the surrounding traffic is sometimes a topic of conversation between driver and passenger that may help the driver's situational awareness of the roadway environment, and second, the language complexity and the speech production rate of both driver and passenger decreased as the surrounding traffic demands increase.

2.5. Eye Movements

Land (2006) has recently provided a comprehensive overview of research on eye movements and driving, and thus here we briefly summarize some of the main findings from this research area. Beginning in the 1970s with the development of eye movement recording systems that could be deployed in vehicles, there were a series of now seminal studies by Mourant and Rockwell (1970) addressing the impact of route familiarity on drivers' visual scanning behaviors (see also summary by Shinar, 2008). They found that when learning a new route, drivers' fixations are dispersed widely in the roadway environment, with the modal fixation above and to the right of the road (where there was signage). As drivers became more familiar with the route on repeated drives, fixations were confined to a smaller area with the modal point moving to the left, centering on the lane in front of them, far down the road. Lane markers (e.g., lines on the road) were rarely fixated implying that lane control is achieve largely through peripheral vision. Thus, practically speaking, it is critical that the angular subtense of lane markings, which fall on peripheral retina, be large enough to support this function.

Mourant and Rockwell (1972) also examined the visual processing mechanisms of novice drivers as compared to experienced drivers. In contrast to experienced drivers, novice drivers had eye fixation patterns distributed over a small area of the roadway environment, and fixations were mostly distributed on the road immediately in front of the vehicle, to the right of the road, and on lane markings. They infrequently used side- and rear-view mirrors. Novice drivers exhibited pursuit movements on expressways, whereas experienced drivers did not. More recent work has extended these findings to show that novice drivers have longer fixation durations in many situations, are relatively inflexible in search strategies in the face of varying roadway environments, have problems both engaging and disengaging attention to hazards, and often fail to scan elements of the roadway relevant to assessing potential risk (Chapman & Underwood, 1998; Crundall & Underwood, 1998; Crundall, Underwood & Chapman, 1999; Crundall, Underwood & Chapman, 2002; Pradhan, Hammel, DeRamus, Pollatsek, Noyce & Fisher, 2005; Underwood, Chapman, Bowden & Crundall, 2002).

The novice drivers in Mourant and Rockwell's study (1972) had completed a driver education course. However, research has shown that driver education courses do not enhance safety (i.e., reduce the rate of motor vehicle collisions) (Insurance Institute for Highway Safety, 2001). The visual skills needed for safe driving come with practice, prompting some to suggest that interactive driving simulators and/or PC-based training programs may be useful tools for novice drivers in learning scanning strategies and visual search skills without exposure to the open road (AAA Foundation for Traffic Safety; Chapman, Underwood & Roberts, 2002; Fisher, Narayanaan, Pollatsek & Pradhan, 2004; Pradhan et al., 2005).

Effective steering requires that the arms and hands be guided by visual information so they can turn the wheel the appropriate direction and amount in order to stay in the vehicle’s lane. Land and Lee (1994) determined that when on a curvy road, drivers spent a lot of time looking at the “tangent point” on the upcoming bend, where the tangent point is defined as the moving point on the inside of each bend where the driver’s line of sight is tangential to the road edge. This point is conspicuous because it is the point that protrudes most into the road. Drivers search for this point 1 to 2 seconds before a bend, and then return fixation to it many times as they drive through the bend. Their data suggest that the visual information that drivers use as they steer through a curve is the direction of the tangent point relative to the car’s heading, which essentially predicts the curvature of the road (see also Underwood, Chapman, Crundall, Cooper & Wallén, 1999).

For drivers with extensive binocular visual field loss due to ocular or neurological conditions, research implies that eye movements can serve as a compensatory strategy so that more areas in the visual world can be seen. Drivers with hemianopia or quadrantanopia were videotaped as they drove in real-traffic situations (Wood et al., under review). Backseat evaluators, masked to drivers’ visual and other medical characteristics, rated the quality of their driving using a standard assessment tool. Those hemianopia and quadrantanopic drivers who received good driving performance ratings made more excursive eye movements as revealed in the videotapes, as compared to those who received poor driving ratings. Further research with quantitative eye movement recordings is needed to examine this issue in greater depth. Along similar lines, Coeckelbergh et al. (2002) using an interactive driving simulator observed that drivers with binocular visual field loss from retinal conditions who passed the on-road test displayed more scanning behavior as indicated by eye and head movements, as compared to those who failed the on-road test. These findings raise the possibility that scanning training could be used successfully in driver rehabilitation of at least some drivers with binocular field loss.

2.6. Monocularity

A question that arises is whether one needs two eyes to drive. Two eyes provide for a wider visual field than a single eye and also make possible binocular summation (and thus improved visibility by lowering the threshold) (Blake, Sloane & Fox, 1981). The operational definition of “monocularlity” varies widely in the literature, ranging from denoting a total absence of function in one eye to one eye having impaired vision below some cutpoint with respect to some aspect of visual function (usually visual acuity). The literature on the safety and performance of monocular drivers is largely devoted to studies on commercial drivers (e.g., truck, delivery vehicle, taxi, bus). With respect to drivers of personal vehicles, most jurisdictions visually screen drivers using both eyes, or only consider the better seeing eye when persons apply for licensure. Thus, the question of licensure of monocular drivers for personal drivers does not practically arise that often. However, in the U.S. interstate truck drivers must have visual acuity of 20/40 or better in each eye, which has stimulated research examining whether requiring good acuity in both eyes is really supported by data.

A study in California (Roger, Ratz & Janke, 1987) examined the 2-year crash and conviction rates of 16,465 heavy-vehicle operators, including a subgroup of 1,202 drivers who were visually impaired. Visually impaired drivers (those with 20/40 visual acuity or worse in the worse eye) had significantly more total crashes and convictions than did non-impaired drivers. Driving exposure did not differ in the two groups. On the other hand, another study examined the visual and driving performances of monocular and binocular commercial drivers and found no differences with respect to visual search, lane placement, clearance judgment, gap judgment, hazard detection, and information recognition (McKnight, Shinar & Hilburn, 1991). Monocular drivers were less adept than binocular drivers in sign-reading distance in both daytime and nighttime driving, which is consistent with what is known about binocular summation and binocular inhibition (Blake et al., 1981; Pardhan, Gilchrist & Douthwaite, 1989). The authors concluded that although monocular drivers have some reductions in certain driving functions compared with binocular drivers, differences in the performance of most day-to-day driving functions were not apparent. A limitation with this study is that the definitions of monocular versus binocular drivers were not clearly stated.

The importance of good vision in both eyes for commercial drivers of heavy trucks may also be called into question by a study of commercial vehicle drivers who received waivers of the federal vision requirements (Federal Highway Administration, 1996), i.e. the waiver allowed for drivers that had worse than 20/40 visual acuity in one or both eyes. The severity of the vision impairment and the extent to which it involved both eyes or a single eye was not described in the report. The crash rates of the 2,234 drivers in the waiver program as of 1995, adjusted for self-reported miles traveled, were compared to the crash rates of heavy trucks provided by the 1994 General Estimates System of the National Highway Traffic Safety Administration. The waiver group’s crash rate was not higher than the national reference group, nor were their crashes more severe.

Caution is needed in generalizing the results of studies on commercial drivers to drivers of personal vehicles. Commercial drivers have very high levels of driving exposure compared to non-commercial drivers of personal vehicles since they are on the road almost continuously during their workday, logging in more miles per day than many drivers of personal vehicles cover in a week. Routes routinely involve traffic congestion, multiple stops, parking, and back-up maneuvers. The visual challenges of commercial driving are arguably more intense than personal use driving, the point being that the visual requirements for commercial driving may not be wholly transferrable to personal driving.

2.7. Other Aspects of Vision

Here we consider several aspects of vision that play prominent roles in our theories and models of visual processing, which on face validity would appear to be important to the driving task. Yet the research to date has not strongly established their relevance to driving performance (vehicle control) or to driver safety (crash risk).

With respect to stereoacuity, several studies on commercial drivers have reported that commercial motor vehicle drivers with impaired stereoacuity were at elevated risk for motor vehicle collisions (Maag, Vanasse, Dionne & Laberge-Nadeua, 1997), or once in a crash, their crashes tended to be more severe (as measured by the total number of crash-related victims) as compared to drivers who had normal stereoacuity (Dionne, Desjardins, Laberge-Nadeau & Maag, 1995; Laberge-Nadeau, Dionne, Maag, Desjardins, Vanasse & Ekoe, 1996). As mentioned earlier, studies on commercial drivers may not be generalizable to drivers of personal vehicles since the former have very high driving exposure often under dense traffic conditions. Large sample studies on older drivers that have examined deficits in stereoacuity as a risk factor for future motor vehicle collision involvement have found no association (Owsley et al., 1998a; Rubin et al., 2007). Stereoacuity may be more relevant for the driver’s interactions with the dashboard (e.g., seeing controls or gauges), than for understanding crash risk. In general the impact of binocular vision disorders on driving has not been comprehensively addressed.

Color vision is tested at license application in over 40 states in the U.S., and the ability to respond properly to color traffic signals is a requirement for a commercial vehicle license in the U.S. (Decina, Breton & Staplin, 1991). The reason for testing color vision in both personal and commercial licensing is not because it is widely held that color vision deficiency is a major risk factor for crash involvement; rather, color vision screening is meant to ensure that drivers can obey color traffic control devices and other color signals on the road (e.g., tail-lights) (Heath & Schmmidt, 1959). Laboratory and field studies have confirmed that drivers with color deficiencies have longer reaction times to traffic control devices with color signals and are also likely to make more color confusions, than persons with normal color vision (Atchison, Pendersen, Dain & Wood, 2003; Vingrys & Cole, 1988). However, in naturalistic driving, the critical cues on the road can typically be obtained through multiple sources of information (e.g., luminance, position, pattern). Thus, it is not surprising that the literature largely supports no link between color deficiencies and vehicle crash involvement (Atchison et al., 2003; Vingrys & Cole, 1988). It is also important to emphasize that most drivers with color deficiency are not color blind, rather, they have a reduced ability to discriminate color. One study (Verriest, Naubauer, Marre & Uvijls, 1980) supporting an association reported that drivers with color vision defects were more likely to have rear-end collisions. However, because of the overwhelming wealth of evidence to the contrary, it is reasonable to conclude that color vision deficiency by itself does not increase crash risk in personal or commercial drivers, although in some circumstances it may impact performance of interpreting traffic control devices and other color coded signals if other cues (luminance, position, pattern) are not sufficiently informative.

Motion perception has a great deal of face validity to the driving task since the vehicle and thus the driver is moving through the roadway environment, but only a few studies have addressed how impairments in motion processing may affect driving performance and safety. When driving on a closed-road course, older drivers with an elevated minimum displacement threshold in a coherent motion task had difficulties in detecting signs and hazards and took longer to complete the course (Wood, 2002). In addition, when evaluated on the open road in natural in-traffic conditions, older drivers with elevated thresholds in a coherent motion task had worse performance evaluations as assessed by raters specialized in on-road evaluation (Wood et al., 2008). Older adults with Alzheimer disease were evaluated in a driving simulator, and reduction in performance in a structure-from-motion task was a strong predictor of collisions in the simulator (Rizzo et al., 1997). Research has not linked motion perception to increased crash risk on the road, except for a study that collected self-reported collision data, not state-recorded collisions (Shinar, 1977).

Disability glare (increased glare sensitivity), particularly among older adults, is discussed as a serious threat to the safety of older drivers (e.g., (Wolbarsht, 1977)) but studies have not scientifically supported this notion (Ball et al., 1993; Owsley et al., 1998a; Owsley et al., 2001). This failure to find an association between glare and road safety may be attributed to methodological difficulties in defining “glare” and in measuring a multifaceted phenomenon (e.g., discomfort glare, disability glare), as well as to a poor understanding of what people mean when they say they have “glare” problems. Rubin et al. (2007) reported a seemingly paradoxical relationship between disability glare and motor vehicle collisions. They found that disability glare reduced crash risk in older drivers with good vision, which could not be attributed to changes in driving habits (e.g., reduced exposure).

3.0. Translational Research Issues

Because driving is a task integral to daily life for many people around the world, research on the role of vision in driving has implications beyond basic research. For example, research on vision and driving can serve as a basis for policies that set rules for determining who can be licensed to drive and for developing rehabilitation strategies that help visually impaired persons acquire skills so that they can drive as long as it safely possible for them to do so. These translational research issues are discussed below.

3.1. Policies for Vision Screening for Licensure and Renewal of Licensure

As mentioned previously, visual acuity testing, under high contrast and luminance conditions, is the ubiquitous screening test for driver licensure. This is true not only in all 50 U.S. states and the District of Columbia but in Canada, Australia, and the countries of the European Economic Community (American Medical Association, 2003; Transportation Research Board, 1988; Peli & Peli, 2002). Of all the various visual, cognitive, and physical abilities that are relevant for driving a vehicle, visual acuity testing stands out as the one aspect of function that is consistently viewed by policy makers and the public as important for licensure. Besides the knowledge test about the “rules of the road” and a brief on-road driving performance evaluation, visual acuity is often times the only ability evaluated when one applies for a driver’s license or for license renewal. Some jurisdictions do have visual field and color discrimination screening tests as mentioned above, but these are less common as compared to the universal use of visual acuity screening (American Association of Motor Vehicle Administrators, 2006; Peli & Peli, 2002).

Most states in the U.S. require visual acuity screening when applying for renewal of a license, although the interval and age group these policies apply to varies by state (American Association of Motor Vehicle Administrators, 2006; American Medical Association, 2003). Ten states do not require visual acuity re-screening after initial licensure. In these states, the visual acuity screening test is administered only when applying for the driver’s license for the first time, for most people typically when one is a teenager or young adult. When the license comes up for renewal, even in the later decades of life where functional problems like visual impairment are relatively prevalent, the visual acuity screening test is not re-administered. License renewal is accomplished by mail or by visiting the licensing office and paying a renewal fee without any functional evaluation. Therefore, in these states, drivers with visual acuity impairment could maintain a license and continue driving. While prevailing views among the public may lead one to question the appropriateness of not having a visual acuity re-screening policy, it is important to point out that there is no clear evidence supporting the benefits of visual acuity re-screening laws. Epidemiological studies using ecologic designs compared states with re-screening laws to states without these laws, reporting that the fatality rate for older drivers was lower in states that have re-screening laws (McGwin, Sarrels, Griffin, Owsley & Rue, 2008; Nelson, Sacks & Chorba, 1992; Shipp, 1998). However, because ecologic studies are based upon population-level rather than individual-level data, the results from such studies must be interpreted with caution and cannot be considered definitive. In addition, these studies did not separate out the effect of visual acuity re-screening from in-person renewal, and thus it is unknown to what extent the lower fatality rate was due to visual acuity testing itself. Another ecologic study (Grabowski, Campbell & Morrisey, 2004) found that when vision re-screening was evaluated as an independent contribution, it had no impact on fatality rates in adults age ≥ 65 years. Thus, owing to the methodological shortcomings of the literature, the question remains unanswered as to whether visual acuity screening at re-licensure for older drivers is a policy that has a safety benefit. Furthermore, a recent cost-benefit analysis of current vision screening approaches at driver licensing offices suggested that they have no economic benefit to society (Viamonte, Ball & Kilgore, 2006). At present, government motor vehicle departments and legislative bodies essentially have a poor evidence basis upon which to formulate their re-licensure screening policies, even though these very agencies are asking for guidance from the research community about how to modify existing laws. Yet without a sound evidence-basis, there is little to offer except personal perspective.

3.2. Rehabilitation of Drivers with Vision Impairment

Since driving is so critical for maintaining a high quality of life in many societies, persons with irreversible vision impairment, most often those with moderate as opposed to severe deficits, sometimes want to be drivers even though they do not meet their jurisdictions' visual acuity or visual field standards for licensure. Many view this desire as reasonable given the lack of evidence that establishes a visual acuity or visual field cutpoint beyond which driving is unsafe.

Driving assessment and rehabilitation clinics, usually based in rehabilitation services at medical centers, provide rehabilitation interventions designed to assist functionally impaired drivers to remain behind the wheel, if it is safely possible for them to do so. Bioptic telescopic spectacles (BTS) are an option for persons with visual acuity impairment who want to drive in 35 states in the U.S, although individual states differ widely in the specific requirements and provisions in the law. BTS consist of telescopes mounted in the superior portion of a regular lens (referred to as a “carrier lens”), which incorporates the refractive correction as does the telescope. In most cases they are prescribed for one eye, although some drivers may prefer a binocular BTS depending on individual characteristics and preferences. The most common telescope magnifications are between 2X and 4X and provide a field of view between 6° and 16°. While driving the BTS user views the world through the carrier lens and then dips the head down to use the BTS to view signs, traffic control devices, and potential obstacles. A number of authors have discussed the use of BTS and training programs for drivers who wish to use such devices (Barron, 1991; Feinbloom, 1977; Jose, Carter & Carter, 1983).

Although most would agree that severely visually impaired individuals (e.g., those having visual acuity worse than 20/200, or less than a 20 degree visual field in the better eye) should not drive, controversy remains regarding drivers with visual acuity between 20/60 and 20/200. It has been recommended that the use of BTS for drivers with visual acuity impairment should be considered on an individual basis and the BTS should not be mandatory for persons with moderate visual acuity impairment in order to obtain a driver's license if they can demonstrate driving fitness with a BTS (Barron, 1991). In fact some jurisdictions are now licensing persons with visual acuity as low as 20/200 if they can demonstrate safe driving skills in a detailed on-road evaluation even if they do not use a BTS. Other recommendations include drivers using BTS must complete a mandatory training program plus annual vision examinations by an ophthalmologist or optometrist to ensure their visual acuity impairment is not progressive. Fonda (1983; 1988) has opined that the use of a BTS while driving by persons with visual acuity impairment may, in fact, increase rather than reduce crash risk, and that they may be safer drivers without BTS. However, quantitative evidence to support such an opinion is lacking. A BTS occludes part of the visual field, an under-appreciated deleterious aspect of BTS.

As we have commented elsewhere (Owsley & McGwin, 1999), previous research on crash risk among drivers who use BTS has methodological problems, thus making it difficult to make firm conclusions. Studies have generated a wide array of findings. Four studies from California (Janke, 1983), New York (Vehicles, 1989), Maine (Department of State, 1983), and Texas (Lippman, 1979; Lippman, Corn & Lewis, 1988) have reported that users of BTS have higher crash rates than control groups. An additional study from Texas found crash rates of visually impaired drivers to be similar to those of drivers with cardiovascular and neurologic impairments (Lippman, 1979). A study of drivers using BTS in Massachusetts reported crash rates lower than those of the general population (Korb, 1970). Methodological problems with the prior work include the following. Several of the studies used the general population of drivers as the control group. It is not clear whether the BTS itself and its “side effects” (e.g., reduced field of view) or visual acuity impairment or both are responsible for the elevated crash rates. Furthermore, it is likely that drivers using BTS restrict their driving (e.g., avoid night driving), and failure to account for such self-regulation in etiologic studies may lead to invalid results.

Most BTS drivers are young and middle-aged adults (Bowers, Apfelbaum & Peli, 2005b; Park, Unatin & Park, 1995). Even though central vision impairment due to age-related macular degeneration (AMD) is a relatively common cause of vision impairment in the U.S., drivers who use BTS are infrequently elderly. It remains to be determined why this is the case. Possible reasons are that clinicians may not be presenting BTS as an option for older drivers with AMD, older drivers are not interested in using BTS to drive and/or they in fact try BTS, but do not feel that it helps. Many older adults have medical comorbidities (e.g., cognitive impairment) that may make the training programs more challenging.

Some have argued that BTS are not primarily used by visually impaired persons for on-road driving but are principally used to pass visual acuity screening when applying for licensure, and then not used once the driver is licensed and on the road (Fonda, 1983; Keeney, 1974). There is no definitive evidence that can refute this claim. Essentially we do not know to what extent and under what conditions drivers with BTS actually use BTS when driving. Survey research has suggested that many bioptic drivers report that BTS is helpful (Bowers et al., 2005b; Park et al., 1995; Taylor, 1990); however there is no objective verification of these self-reports. Users may be particularly motivated to state how useful they are given that their licensure depends on their use of BTS when driving. Slightly over half report they wear BTS when driving (Bowers et al., 2005b), but once again there are no objective data to confirm self-reports. It remains to be determined to what extent BTS drivers actually wear and use BTS when driving and in what driving scenarios BTS are helpful from driver performance and safety perspectives.

Persons with hemianopia are sometimes prescribed spectacles that provide a prismatic correction to re-locate or expand the field (Bowers, Keeney & Peli, 2008; Perez & Jose, 2003; Smith, Weiner & Lucero, 1982). At present there is no evidence that such optical devices improve on-road driving performance or driver safety in persons with homonymous hemianopia (Szlyk, Seiple, Stelmack & McMahon, 2005). One study observed that 2/3 of hemianopic drivers evaluated on the road drove flawlessly or had only minor errors, yet none of these drivers wore prismatic devices while driving (Elgin et al., 2010). This suggests that hemianopic drivers have strategies that they use to compensate for their field loss during driving, and that a prismatic correction is not a necessary condition for safe driving for all individuals in this population.

It has been estimated that on a population-basis that up to one-third of older drivers have slowed visual processing speed under divided attention conditions (Rubin, et al., 2007). A training intervention has been developed that increases visual processing speed in older adults (Ball et al, 2002; Ball, Edwards, & Ross, 2007). This training involves trainer-guided practice of computer-based nonverbal exercises that are presented briefly and involve visual target detection, identification, discrimination, and localization. Recent findings from the ACTIVE clinical trial (Jobe, Smith, Ball, Tennstedt, Marsiske, Willis, Rebok, Morris, Helmers, Leveck, & Kleinman, 2001) indicate that this speed of processing training program reduces the risk of future motor vehicle collision involvement among older drivers (Ball, Edwards, Ross, McGwin, in press).

4.0. Conclusions

Many studies have converged in indicating that visual acuity is, at best, very weakly linked to driver safety (i.e., collision involvement) and thus is a poor screening test for identifying drivers who are at-risk for future crash involvement. In contrast, it is clear that visual acuity is related to certain aspects of driving performance (e.g., road sign recognition). As summarized above, there are undoubtedly many reasons for the lack of relationship between acuity and safety. Licensing authorities and policy makers are unlikely to give up visual acuity screening tests for driver applicants because of their high face validity, public acceptance, and association with highway sign legibility. A more practical approach to improving the efficacy of vision screening at licensure is to examine how visual acuity screening tests could be supplemented by other types of screening approaches, like contrast sensitivity, visual field, processing speed, and divided attention tests, some of which have a large evidence-basis for their relevance to driver safety. Well-designed population-based prospective studies on drivers are needed to identify the effectiveness of these vision screening tests both singly and in combination, in terms of their ability to identify the drivers who experience at-fault crashes in the future. This research could also inform the best pass-fail cutpoints for these tests.

Basic research on eye and head movements, scanning, visual search and attention during the driving task has high relevance to the rehabilitation of drivers with vision impairments. This research can contribute to developing interventions and training strategies for drivers with visual impairments in the range of 20/40 to 20/200 so that they can remain behind the wheel as long as it is safely possible for them to do so. The effectiveness of these interventions will need to be rigorously evaluated with respect to both driving performance and safety outcomes. This also applies to BTS devices and training programs, especially since BTS studies to date have been inconclusive with respect to both safety and performance, and many of these studies have methodological problems, as described above. Basic research on vision and driving, especially scanning and visual search, can also inform the design of training interventions for novice drivers (usually teenagers and young adults) who have the highest rate of collision involvement of all age groups.

Automotive manufacturers are interested in meeting the needs of older drivers since older adults are the fastest growing group of drivers in the U.S. both in terms of annual mileage and the number of current drivers (National Highway Traffic Safety Administration, 1989). By 2010 there will be 40 million adults ≥ 65 years in the U.S. (U.S. Census Bureau, 2004); 4 out of 5 will be drivers (32 million) (U.S. Department of Transportation, 2003). Vehicle manufacturers recognize that visual sensory impairments and deficits in the processing of visual information are common among older adults (Rubin, West, Munoz, Bandeen-Roche, Zeger, Schein, Fried & Team, 1997; Vitale, Cotch & Sperduto, 2006). These aging-related visual impairments could impact older adults’ ability to control the vehicle, detect relevant events and objects in the roadway environment, and to interact with the dashboard. It is conceivable that certain vehicle technologies could theoretically compensate, at least in part, for vision impairments typical of advanced age, and conversely other designs could exacerbate the negative effects of these visual deficits (Charness, 2008; Lee, 2008). However, little is known about what design options are more likely to facilitate older adults’ processing of visual information while driving. Studies are beginning to address these human factors issues for older drivers (Rokotoniraainy & Steinhardt, 2009; Owsley, McGwin & Seder, under review), although this research area is still in its infancy.

Research methodology for studying vision and driving also needs to move to the next level. As discussed throughout this paper, most studies examining the link between vision and driving rely on either of three outcomes (dependent variables) - motor vehicle collision involvement, performance on-road, and performance in an interactive simulator. However we know little about how measures of performance and safety relate to each other, or how simulated performance from the laboratory relates to on-road driving. There is a tendency to treat all three types of outcomes as equivalent when interpreting the literature even though the nature of their interrelationships is unknown. Furthermore, not until very recently research has examined the role of vision in naturalistic driving where driving performance measurements of drivers are made in a largely unobtrusive yet objective fashion over a period of days. Such research is attractive in that it avoids the artificial analogues of the laboratory, the simulator scenarios that are over-simplifications of the roadway environment, and the relatively short snapshot (e.g., one hour), onetime sampling of on-road driving evaluations. Naturalistic driving captures actual driving behaviors that may shed light on the visual and cognitive mechanisms underlying performance and safety decrements. For example, recent work (Munro, et al., 2010; West, et al., 2010) has used an in-vehicle monitoring system with older drivers whereby driver behaviors were recorded over a period of several days. The visual and cognitive abilities of these drivers were also characterized. Results suggest that visual-motor construction and attentional abilities are associated with lane-changing errors in older drivers (Munro, et al., 2010) and that a narrowing of the visual attentional field increases their risk for failure to stop at red lights (West, et al., 2010).

With respect to research focused on safety (i.e. crash involvement), there is a need to adopt study designs and to develop screening tests that can be more readily translated into licensing policies. However, this research cannot proceed without well-designed etiologic studies that shed light on those characteristics that both place drivers at risk for collision involvement but are also amenable to interventions to reduce those risks that have potential for widespread implementation.

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