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A Roadmap for Interpreting the Literature on Vision and Driving

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Abstract

Over the past several decades there has been a sharp increase in the number of studies focused on the relationship between vision and driving. The intensified scientific attention to this topic has most likely been stimulated by the lack of an evidence-basis for determining vision standards for driving licensure and a poor understanding about how vision impairment impacts driver safety and performance. Clinicians depend on the scientific literature on vision and driving as a resource to appropriately advise visually impaired patients about driving fitness. Policy makers also depend on the scientific literature in order to develop guidelines that are evidence-based and are thus fair to persons who are visually impaired. Thus it is important for clinicians and policy makers alike to understand how various study designs and measurement methods should be appropriately interpreted so that the conclusions and recommendations they make based on this literature are not overly broad, too narrowly constrained, or even misguided. In this overview, based on our 25 years of experience in this field, we offer a methodological framework to guide interpretations of studies on vision and driving, which can also serve as a heuristic for researchers in the area. Here we discuss research designs and general measurement methods for the study of vision as they relate to driver safety, driver performance, and driver-centered (self-reported) outcomes.

Keywords

driving; vision; vision impairment; eye disease; research methods

I. Introduction

Just as in a literate society the ability to read is important for quality of life, the same can be said for driving in a society dependent on the personal vehicle for mobility and transportation. Visual acuity testing is the most common functional method for determining eligibility for licensure world wide, in addition to on-road and knowledge tests. Yet there is little to no evidence that a visual acuity screening test, no matter which pass-fail cut-point is selected, enhances driver safety and performance.[99] The absence of evidence-based vision

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standards for licensure together with the negative health consequences of not being a driver[25, 31, 37, 38, 42, 43, 55, 77, 94, 105] have prompted growing interest in the link between vision and driving by clinicians and researchers alike. For example, the number of literature citations on vision and driving indexed in Pubmed has approximately tripled since the 1980s. In spite of the growth in this literature, there are widespread misunderstandings about the inferences that can be properly made from various types of study designs. These misunderstandings impede construction of a convergent evidence base, have the potential for wasting precious research resources, lead to study conclusions that are erroneous and clinical recommendations that are potentially questionable, and have slowed our ability to provide coherent guidelines for clinicians and government policies. In an attempt to provide a clear conceptual framework for the research field and for clinicians who use this information to counsel patients about driving, this article is our perspective, formulated over our 25 years of experience in vision and driving research, on how different types of study designs and methodologies can be properly utilized to address specific research questions and hypotheses and properly inform conclusions.

“Driving” can be measured using several different methods that may not produce consistent findings due to the fact that each method is designed to measure a unique aspect of driving or its component skills. As a result, the types of inferences that can be made from each type of method are distinct, although theoretically related because they all address aspects of driving behavior, albeit from different perspectives. Below we discuss these various constructs, the approaches used to measure them, and inferences that can be made in studies that use them.

II. Safety

Safety in the context of driving is typically defined by motor vehicle collisions (MVCs). The US Department of Transportation’s National Highway Traffic Safety Administration (NHTSA) characterizes driver safety this way as do most countries throughout the world.[90] From the standpoint of understanding the impact of vision on driving, MVCs in which the driver is at-fault[13, 79, 96] are of greater interest than those where the driver played no role other than being on the road (e.g., hit from behind when stopped at a red-light). Associations between vision impairment in older drivers and MVCs tend to be stronger when at-fault MVCs are the outcome measure compared to when all MVCs are used.[26, 79] However, the vision and driving literature is replete with studies using all MVCs, regardless of fault, as the outcome measure.[13, 32, 51, 97, 98, 111] This is the preference of many investigators since MVCs are rare events and thus utilizing all MVCs instead of at-fault MVCs increases the number of outcome events. In our research the proportion of MVCs that are determined to be the fault of the older driver is between 35% and 50%. The increase in statistical power often associated with an increase in the number of outcomes is potentially offset in this context because the effect size is diminished. Objective information on the occurrence of MVCs, including attribution of fault, for an individual driver can be acquired from motor vehicle administrations in the form of “accident” reports (electronically or on paper), although the availability and reliability of these reports is subject to laws and regulations regarding public access to such information.

Information on the occurrence of MVCs can also be obtained by self-report (i.e., reported by the driver being studied).[60, 76, 128] This approach is easier and cheaper when compared to acquiring MVC data from a jurisdiction's motor vehicle administration. However, the convenience of self-report may be offset by a number of factors, including the inability to obtain an objective assessment of fault. Even when accident reports are available and are obtained, collecting self-reported information is valuable as several studies have shown that there is a poor association between self-reported collisions and accident reports.[8, 11, 76, 81, 116] There are many possible reasons for this lack of agreement including faulty memory, social desirability, and privacy concerns. Critics of the reliance on police-reported MVCs observe that accident reports do not exist for all MVCs (e.g., those on private property, when the driver and any other involved drivers do not choose to report to police, those in jurisdictions where police do not routinely submit reports).[6, 76] Thus, while neither source captures 100% of all collisions that a driver incurs, this is not necessarily the primary goal; rather, if the goal is to obtain an unbiased measure of MVC occurrence, police-reported MVCs are more desirable. Collecting information via both mechanisms is also valuable in that it aids in the conduct of sensitivity analyses, i.e., conducting two sets of analyses, one using self-reported, the other using state-recorded MVCs as the dependent variable. If both sets of analyses yield consistent results, the validity of the findings is enhanced. But, for a given risk factor (e.g., vision impairment), the association may be different when using self-report versus police-reported MVCs, as McGwin et al. have demonstrated.[81] This discrepancy is partly attributable to the fact that any lack of agreement between self- and police-reported MVCs is associated with the risk factor in question. An example would be if cognitive impairment is associated with MVC occurrence and drivers with cognitive impairment are more (or less) likely to report MVCs accurately. This issue not only has important implications for the internal validity of a single study, but also sheds light on why the results of independent studies on the same topic may yield differing results if the dependent variables are not identical. Thus, researchers and readers need to be aware of differences in MVC variables when designing, conducting and comparing studies.

In general, cohort-based studies have the ability to estimate a number of measures of disease occurrence, the most common being risks and rates, the latter most frequently expressed as MVCs per miles driven. Research suggests that drivers can validly estimate the miles they drive per year, which is perhaps the most common measure of driving exposure.[15, 56, 67, 89] It should be noted however that, unlike the ubiquitous epidemiologic metric of person-years used as a uniform measure of time at risk, person-miles of travel may not be constant. This is due to the fact that MVC risk varies geographically and chronologically; for example, MVC risk is higher at night compared to during the day. To date, there has been little work on methods to "discount" mileage for differences in the underlying MVC risk. Just as studies using police-recorded and self-reported MVCs can yield differing results, studies estimating risks and rates may reveal different associations, partly attributable to the failure to account for driving exposure. This can occur when one of the groups being compared, despite having a similar MVC risk, drives less and thus will have a higher MVC rate. This problem can be obviated with the use of a randomized (i.e., randomized controlled trials) rather than an observational cohort-based study design. The main difference between these designs is the use of randomization to assign study participants to two or more treatment (i.e., “exposure”) groups in randomized designs versus simply characterizing behaviors or characteristics in observational designs. Randomized studies focused on driving safety are rare, partly reflecting a lack of consensus regarding modifiable risk factors that are amenable to intervention development and evaluation. Randomized designs have a number of other advantages over observational designs including less concern regarding the role of confounding factors though concern regarding other issues is equivocal, e.g., loss to follow-up. For example, a recent observational cohort study compared MVC involvement among drivers with homonymous hemianopia and quadrantanopia with that of age-matched drivers with normal visual fields. The MVC risk and rate ratios were 1.19 and 2.45, respectively, reflecting the fact that drivers with homonymous hemianopia and quadrantanopia were, on a per person basis, 1.19-times more likely to be involved in an MVC but, on a per mile basis, 2.45-times more likely. This also reflects the fact that the homonymous hemianopia and quadrantanopia patients drove approximately half as much as the comparison group.[85] In comparison, Owsley et al. conducted a randomized, control, single masked study to determine whether an individualized educational program designed to promote strategies to enhance driver safety reduced MVC occurrence in high-risk, visually-impaired older drivers.[98] In this study the two comparison groups were equivalent in all measures of driving exposure (i.e., miles, days, trips and places driven) and as a consequence the MVC risk and rate ratios were also nearly equivalent. The comparison of these studies brings up two important points. First, risk and rate ratios may differ despite the groups being compared having equivalent measures of driving exposure. This is attributable to the fact that the risk factor or intervention may not have an impact on the risk or likelihood of an MVC but does have an impact on the timing at which such events occur. Second, any inconsistency in risk and rate ratios does not call into question the validity of a study’s results. Rather, it reflects the very important point that risks and rates are two related but distinct outcomes and properly interpreting the results of studies using one versus the other relies upon the reader, and often the investigator, understanding their differences. The benefit of being able to calculate both risks and rates is offset by the requirement in cohort studies for large numbers of drivers. These large numbers are needed to have adequate statistical power to detect differences, say, between a visually impaired group of drivers and normally sighted drivers. Adequately powered cohort-based studies can be very costly, since in addition to characterizing the visual or ocular characteristics of interest, it is also necessary to determine driving exposure levels for a large sample of drivers at baseline and pay for the police-reported crash data from the governmental jurisdiction. Additionally, follow-up visits or telephone contacts must take place over the prospective period during which accident report data are also collected (usually multiple years) in order to track driving exposure and other changes in health and functioning.[97, 111]

There are other non-experimental, observational study designs used to study driver safety including case-control and cross-sectional designs. The distinct advantage of these designs over a cohort study is the fact that the investigator does not have to wait for the events to occur. To quantify the effect of risk factors on MVC occurrence, cases and controls are compared with respect to risk factors and other characteristics of interest.[47, 78] Because at the time the study is conducted both the MVC and risk factors have already occurred, there is opportunity for bias, although bias can be minimized using objective measurements and with proper case and control selection. Using pre-existing measurements of risk factors, e.g., from medical records, is particularly advantageous in that these measurements were taken prior to MVC occurrence and generally represent a bias-free source of information. For example, a case-control study was used to evaluate the association between visual field defects and the risk of MVC among patients with glaucoma.[83] In this study cases were patients who sustained a police-reported MVC between January 1994 and June 2000; controls were those patients who did not experience an MVC. Then, for each patient, a visual field loss score was calculated based on automated visual fields already collected and pre-existing in the medical records of enrollees. In a case-control study it is reasonable to identify and enroll drivers who have sustained MVCs and *then* measure or assess their visual function. This approach can produce valid results assuming that the visual function measurements were not affected by the MVC and were stable over time. The latter can be solved by selecting a short time period for MVC occurrence, i.e., in the prior year.

Briefly, cross-sectional study designs are those where the study population is not selected with regard to either the primary exposure or outcome of interest; rather, they are selected at random or by convenience from a larger population of individuals. Once the sample is selected, information on exposures and outcomes is assessed simultaneously. For example, a recently published study enrolled 2,000 adults aged 70 and older who were licensed drivers obtained from the state's licensing agency.[46] Among other things, the investigators measured visual function, asked participants about their driving habits and obtained information on MVCs in the prior five years via police accident reports, respectively. Cross-sectional studies are more efficient than most other designs in that they do not have the financial and logistical burdens of long periods of follow-up, however, they retain the need for large sample sizes and are subject to a number of significant methodological limitations. For example, one of the well-known limitations of cross-sectional studies is the difficulty establishing temporality; i.e., did the outcome occur before or after the exposure. In the aforementioned study, for the observed association between visual acuity impairment and reduced driving exposure (e.g., lower mileage), it is not possible to know whether those with reduced driving exposure changed their driving habits in response to changes in their visual function.

Finally, ecologic study designs which, rather than measuring risk factors and measures of safety in individuals, measure these characteristics in the aggregate, typically geographically or temporally. These designs have been used to compare the impact of licensure laws as they relate to older drivers and vision re-screening policies.[45, 84, 92, 115] For example, Grabowski et al. compared state driver's license renewal policies with respect to older driver fatality rates and observed that states requiring in-person renewal had lower rates compared to those states that did not have such policies.[45] In another study McGwin et al. also compared fatality rates in a single state, Florida, before and after the implementation of a new licensure renewal law targeting older drivers.[84] The results indicated that following the implementation of a law requiring that license applicants pass a visual acuity test, the MVC fatality rate decreased. In both of these studies, the unit of observation/analysis was not the individual; rather it was the state or chronological time. While the limitations of ecologic designs are extensive and well-known,[86] they are valuable for exploring novel hypotheses as well as the impact of policies.

The main limitation of safety studies is that they tell us little about the mechanisms by which vision impairment impacts driving performance, i.e. how vision affects driver behaviors behind the wheel and vehicle control kinematics. An accident report has a wealth of information such as demographic information about the drivers involved and many details about the circumstances of the collision. Yet also vital are mechanistic questions such as how the driver's visual capacities impact lane control, speed, gaze, recognition of roadway obstacles, obeying traffic control devices and signage, navigation of a route, as well as what behaviors ensued before and during a vehicle crash.

III. Performance

Performance refers to driver behaviors and vehicle kinematics when a person is operating a motor vehicle on a roadway. Driver behaviors include the driver's use of vehicle controls (e.g., steering, directional signal, shifting gears), visual behaviors (e.g., eye and head movements, gaze direction), and secondary task behaviors (e.g., eating, smoking, cell phone use, conversations with passengers). Vehicle kinematics refer to physical variables such as speed, changes in speed and the smoothness with which these changes are adopted (e.g., smooth or jerky deceleration, acceleration), cornering and lane keeping. While there has been an abundance of epidemiologic research on the relationship between specific driver behaviors (e.g., cell phone use, the presence of passengers) and MVC occurrence, the relationship between both behaviors and kinematics and MVC occurrence has not been explored outside of controlled settings. The vast majority of driving performance studies to date, as summarized in this section, have utilized cross-sectional designs where driving performance was measured on a given day, and performance variables were then analyzed in terms of their relationships to various aspects of drivers' vision as measured on or near the date that driving performance was measured. A limitation of the literature is that longitudinal designs addressing vision and driving, where change in driving performance variables are tracked over multiple assessments over a period of months or years as a function of any vision changes, have not yet been conducted. Intervention evaluations where driving performance is assessed before and after an intervention to improve vision or visual skills have appeared in the literature yet are uncommon.[66, 126, 139]

Performance studies take place in two types of roadway environments – either on the open-road or on a closed-road circuit. There are also several different types of measurement tools that have been developed to measure driving performance. These issues will be discussed in the following sections.

A. Open-Road and Closed-Road Designs

Open-road studies take place on actual public roadways (for example [16, 39, 50, 74]). Closed-road studies take place on a series of roads or circuits created especially for research investigations that are closed to public access; any obstacles or events along the closed route (e.g., vehicles, pedestrians, road signs) are "staged" by the investigator (for example [54, 143, 148, 150, 153]). The main advantage of an open-road design is that driving takes place amidst a natural traffic environment where vehicles, pedestrians, and other types of obstacles and events unfold during the course of everyday driving. The roadway and its environment are not created for the purpose of the study but rather are what the driver would normally encounter in daily driving along that roadway. Thus the open-road design has very high validity as a stimulus environment for assessing driving performance. The closed road does not have these naturally occurring events, but rather, the investigator creates test events (e.g., approaching vehicles, road signs, pedestrians) where the driver's behavior is assessed. The main advantage of the closed road design is that test "trials" can be standardized across research participants, where the same or very similar stimulus conditions can be presented to all drivers in the study and comparisons can be made, for example between drivers with vision impairment and those who are normally sighted.[146] Closed road courses can also be viewed as less risky from a collision perspective since the traffic environment and potential hazards are created by the researcher and thus predictable. The main limitation of closed road studies is that the roadway environment is much simpler than the open road; the lack of other naturally occurring vehicles and events along the roadway reduces the validity of testing and could potentially over-estimate driving skills. However, on balance, one of the main limitations of the open-road design is that tight stimulus control is impossible. However, investigators standardize the assessment as much as possible by selecting a route with, for example, a specified number of traffic control devices or curves in the road, although the number and pathways of other vehicles, pedestrians and other obstacles cannot be controlled.[149] In addition, the same route is typically used for all participants unless the study involves previously conducted on-road assessments for clinical purposes by a driving rehabilitation specialist where route standardization is not the norm.[104]

It is also possible to simulate the effects of various types and degrees of vision impairment in participant drivers, and then assess how impairment impacts closed-road driving performance using a repeated measures design.[53, 142] Simulating vision impairment in drivers (e.g., introducing blur through optical lenses, recreating the effects of cataracts through filters that reduce contrast and increase glare, restricting peripheral vision through occluders) and then introducing them to the open-road would not be legally possible in most jurisdictions. However, while simulated visual impairment in a repeated measures design provides the opportunity to partial out the effects of vision alone, the negative impact of simulated impairment on driving performance may be greater than for drivers with true vision impairment who have had the opportunity to adapt to their visual deficits and develop compensatory strategies.

Both open-road and closed-road designs have generated substantive advances in our understanding of how vision impacts driving. For example a series of studies on a closed-road circuit in Queensland, Australia in the 1990s were the first to document the association between vision impairment and road sign recognition and obstacle detection during driving.[141, 142, 144, 145] More recently, open-road designs have examined the relationship between vision impairment and driving performance. For example, studies have shown that in spite of having significant visual acuity loss (20/70 to 20/200) or field loss (homonymous hemianopia or quadrantanopia), some visually impaired drivers are capable of skilled driving performance that is indistinguishable from that of normally sighted drivers.[149, 155]

The kinds of conclusions that can be made from closed- versus open-road designs are somewhat different. Because closed road studies allow for the repetition of orchestrated stimulus events and trials, they provide good estimates about specific driver competences as a function of visual status; for example, they can establish the distance at which a pedestrian or cyclist can be detected or a road-sign can be read.[20, 127, 152, 153] Closed-road designs can be viewed as "proof-of-concept" studies in that they demonstrate under near-laboratory, highly controlled conditions, how vision impacts performance while the participant drives and controls a real vehicle. On the other hand, closed road studies do not allow for confident generalizations to the open road where the driving environment is highly complex and often chaotic. A reasonable research strategy is that the proof-of-concept closed road studies with interesting findings should stimulate open road studies as a next investigative step. Open-road studies can thus establish the relationship between vision and driving under an everyday roadway environment with all its complexity and spontaneity.[149]

B. Measuring Driving Performance

Thus far we have focused on driving performance study design in terms of the roadway. Also critically important to performance studies are the measurement tools used to assess driving performance, of which there are several.

A general point to make at the outset is that when studying vision and driving performance, participants should be currently active drivers; investigators typically define current driving as engaging in some minimum amount of "behind the wheel" exposure (miles or days per week). Just because someone has a driver's license does not mean that he/she is a current driver; some, particularly older adults, even though they no longer drive, choose to renew their license for identification purposes or because it potentially represents a "badge" of independence.[99] The reason that studies aiming to examine the relationship between visual abilities and driving should refrain from including non-drivers (or persons who have not been behind the wheel for an extended period of time, e.g., a year or more) is that such persons cannot be expected to be as skilled as normally sighted drivers who habitually drive, which is the primary comparison group with which the visually impaired drivers are compared. If one were to compare non-current drivers who are visually impaired to normally sighted drivers, one could erroneously attribute driving performance problems to vision impairment, when in fact driving problems may be more appropriately attributable to a lack of recent driving experience. It is well established that novice drivers display different on-road visual and vehicle control behaviors as compared to experienced drivers.[87, 114, 132] It is of course appropriate, however, to study non-current visually impaired drivers (e.g., those with learner's permits) if the aim of the study is to understand the process by which visually impaired persons learn to drive.[9, 134]

1. Clinical Gold Standard—The clinical gold standard for assessing on-road driving performance by persons who are functionally or medically compromised is an evaluation by a certified driving rehabilitation specialist (CDRS),[9] who is often also an occupational therapist. These clinical gold standard assessments typically occur on the open road, although some evaluations may begin in areas away from public roadways such as empty parking lots or private roads before the driver is asked to embark on the open road. Driving assessments usually take place in a specially equipped vehicle with a side front-passenger brake and, in some cases, an auxiliary gas pedal (positioned where the CDRS sits) and up-to-date safety equipment (e.g., air-bags and modern seat-belt designs). When the assessments are done for research purposes, they are typically conducted along the same route to ensure standardization across participants. The CDRS evaluates specific elements of the driver's performance as well as making an overall rating of driving fitness. While there are many rating scales in use by CDRSs,[39, 58, 61, 62, 74] most have common elements including assessing interaction-communication with other road users and pedestrians, driving style (margin of anticipation), vehicle control skills, adjustment to traffic speed conditions, responses to traffic control devices, reaction to unanticipated events, and unusually bad driving maneuvers (e.g., turning wrong way on one-way street). The CDRS makes ratings of driving quality typically using a 3 to 5 item Likert-type scoring system. Even though CDRS ratings are the gold standard for making judgments about driving fitness in a clinical care setting, they do have limitations as the sole measurement tool in research on the visual mechanisms underlying driving problems. The CDRS is generally familiar with the driver's medical and functional status and driving history and may also have predispositions toward certain driving fitness judgments based on prior clinical experience. This has strong potential for introducing bias into their ratings, which could be exacerbated in studies that include assessments performed by several different CDRS evaluators.[24, 104]

2. Backseat evaluators—Some researchers have used an alternative approach to generating ratings of driving performance by using "backseat" evaluators.[16, 57, 110, 147, 149, 155] These are generally research personnel, or in some cases occupational therapists, trained to use rating scales to make judgments about the quality of driving, who sit in the backseat while the driver and the CDRS or a driving instructor sit in the front seat. Since the backseat evaluators are not responsible for monitoring safety (unlike the CDRS), they can concentrate on making continuous judgments about driving throughout the route. Under ideal study conditions, the backseat evaluators are masked with respect to which drivers are visually impaired versus normally sighted, however, valid masking is easier for some visual disorders than others. For example, for drivers with hemianopic field loss back seat evaluators can be successfully masked,[149] whereas in studies on bioptic drivers it is obvious who is wearing a telescope and who is not.[155] In addition, high inter-rater agreement should be established with a second rater since judgments on rating scales are fundamentally subjective. The rating scales used by backseat evaluators are usually different from those used by the CDRS. While the CDRS rates general skill levels displayed during driving (as discussed previously), a backseat evaluator uses a rating scale that assesses the quality of specific elements of driving at a series of pre-determined places during the route.[16, 110, 147, 149, 155] For example, a location such as driving through a specific intersection is rated with respect to behaviors such as lane position, steering steadiness, gap judgment, braking, use of the directional signals, and obeying traffic control devices. The advantages of ratings provided by backseat evaluators, as compared to the CDRS, is that they can be relatively free of bias since they are masked to the clinical history of the driver. Yet, in the end, backseat evaluators make subjective judgments; the dependent measures they generate do not provide actual vehicle kinematics or objective records of driver performance. In addition, drivers are aware of their presence in the vehicle and may modify their driving behaviors as a result.

3. Instrumented Vehicles—Instrumented vehicles are a potentially major step forward in measurement techniques in vision and driving research. Multiple sensors and video cameras are placed in the vehicle and record vehicle kinematics, GPS location, nearby objects, driver behavior, and the roadway environment. The data streams from these recordings can then be analyzed to generate many types of objective measures such as speed, braking, rapid acceleration or stopping, steadiness, and cornering. Video cameras strategically positioned in the vehicle can capture videos of the driver's upper body including head, arms, as well as foot movement, which can later be analyzed for features of interest (e.g., gaze direction, using cell phone). Video recordings can also be made of the roadway environment around the vehicle in order to capture other events and objects in the roadway environment (e.g., vehicles, pedestrians, signs, traffic control devices). Currently the most common way that instrumented vehicles are implemented in vision and driving studies[3, 27, 30, 69, 108, 130, 131, 149, 151, 155] is to install instrumentation in the study's vehicle and then all study participants drive that vehicle, usually on a standardized route for about an hour. Study personnel are in the vehicle; for example, a CDRS often sits in the front passenger seat to monitor safety, and personnel are often in the backseat as raters and/or to monitor instrumentation installed in the vehicle via a laptop computer. Variables as mentioned above can be extracted from the data streams and analyzed in light of the drivers' visual or other functional characteristics.

The considerable advantage of installing instrumentation in the study vehicle is that, rather than subjective judgments from a rater, it provides objective data on vehicle kinematics and also video of driver behaviors and the roadway around the vehicle. The video can be later scored by a human observer who rates features such as vehicle excursions over the center-line or head turns to the left or right; this observer needs to establish good agreement with another rater, or be reviewed by a CDRS after the drive.[4, 5, 28, 151] An additional advantage of this approach is that the video of the driver's face can be occluded for judgments about vehicle kinematics (e.g., lane-keeping); thus if there is some physical feature of the driver (e.g., driver is wearing a bioptic telescope) that relays whether the person is visually impaired, the observer is masked to it. Image processing algorithms can be also used to discern behaviors from the vehicle kinematic variables and video, for example to assess lane-keeping and detect the driver's gaze direction,[29, 65] However, the development and widespread application of these algorithms is a relatively new field, yet a field that is rapidly growing. Initiatives are also underway to develop computer algorithms to automate the identification of safety critical events and near-crashes from vehicle kinematic variables.[10, 34, 65, 156] However, the data generated by the vehicle's instrumentation over many miles of driving will be of limited scientific value unless user-friendly automated analysis procedures can be implemented.

There are disadvantages to using an instrumented study vehicle in the manner described above. First, driving behaviors are likely influenced by the presence of study personnel in the vehicle. Second, the driver does not choose the route as one would do during the course of everyday driving, nor is the vehicle the driver's own vehicle. The latter is particularly relevant since previous research has shown that older drivers perform better in their own vehicle than in an unfamiliar research vehicle.[72] Third, the drive is relatively short, usually no more than one hour of driving time, which is a brief snapshot of driving when one considers the many miles most drivers cover over weeks and months. Thus, while the instrumentation adds a great deal of measurement power, the driving experience from the driver's perspective is unnatural and the epoch being studied is short.

4. Naturalistic Driving—The above-mentioned downsides have recently given rise to what is referred to as *naturalistic driving* methodology.[70, 133] Naturalistic driving techniques objectively measure driver performance over extended periods (weeks or months) in the driver's own vehicle, where the individual drives as they would normally during the course of everyday life. Study personnel are not in the vehicle. The vehicle is instrumented, similar to that described above, but in a more miniaturized and/or hidden way. The ability to practically place these measuring devices in a person's private vehicle unobtrusively has been facilitated by technological advances and miniaturization of computer, sensor, data storage, communications, and video technologies. Naturalistic driving techniques avoid the short snapshot of on-road driving evaluations, the staged analogues of the closed course, the standardized driving route, and the intrusiveness of study personnel riding in the vehicle. Naturalistic driving also allows for the study of driver behaviors and vehicle kinematics as related to vehicle crashes and near-crashes. Admittedly, crashes are rare events so a naturalistic driving study is likely to have very few of these events, if any. However, near-crashes occur at a rate 10 times higher than the rate of actual crashes yet are similar to crashes in terms of driver behavior and vehicle kinematics.[48] Thus they are a rich source of material for study. It is worth highlighting that a major advantage of these numerous video and vehicle kinematic data streams could also be viewed as a disadvantage, or at least a serious challenge. The data streams must be reduced into variables that can be used to test hypotheses about the relationship of vision and driving. As mentioned earlier, there is growing activity in developing computer algorithms to automate data reduction,[10, 29, 34, 65, 156] but the field has far to go in developing data reduction and analysis strategies for the data streams. Furthermore at present there is little, if anything, known about the relationship between variables collected through naturalistic driving by visually impaired drivers and assessments of their on-road driving by backseat evaluators or a CDRS, or the relationship between naturalistic driving variables relationship and the drivers' own impression of the quality of their driving. This is not surprising since, as mentioned, research using naturalistic driving techniques to study vision and driving is in its infancy.

There have been several large initiatives using naturalistic driving methods,[32, 52, 64, 91, 117, 129] most funded by the U.S. Department of Transportation, and also subsequent publications that make use of these databases. However there have only been a handful of publications to date using naturalistic driving data to focus on the relationship between vision, vision impairment, and driving.[7, 19, 64, 71, 73, 90, 135, 138] Yet with the continuing technological advances in the design and miniaturization of recording instruments and the advantages of naturalistic methods for understanding the visual mechanisms underlying driving, this field is expected to blossom over the next decade.

IV. DRIVER-REPORTED OUTCOMES

In addition to driver safety and performance research methods, a third method for measuring driving is a driver's self-report on his/her own perspectives about driving experiences. In the medical literature, these measures based on patient reports are referred to as patient-reported outcomes (PRO), so it is fitting in our context to call them driver-reported outcomes (DRO). DROs play an important role in understanding the relationship between vision and driving since they provide insights into drivers' attitudes and beliefs about their own skill-sets and driving behaviors, including how their vision and other medical/functional issues impact their driving and what compensatory strategies they implement when driving (if any). DROs are typically elicited through questionnaires that are specially designed for this purpose.[2, 23, 95] However, a limitation of many DRO instruments is that they have not been developed using item-response theory. Common domains that are addressed by these questionnaires are driving difficulties in or avoidance of general or specific situations, driving habits (e.g., where, when, how much one drives), driving errors (e.g., "close-calls" or near-crashes), and adverse events (e.g., moving violations, collisions). DRO questionnaires also have addressed drivers' attitudes and beliefs about changes in vision re-screening policies[80] and have been developed as "self-assessment" tools designed to stimulate self-awareness by the driver regarding how visual and other functional limitations could impact their driving.[35]

The published literature on vision and driving using self-report measures is extensive, as summarized recently.[99] The vast majority of studies examine the cross-sectional relationships between DROs and the visual function or eye disease status of drivers. There is widespread evidence that compared to drivers who are normally sighted, drivers with vision impairment and eye conditions are more likely to report driving difficulty (particularly under reduced visibility conditions or unfamiliar areas), avoidance of challenging driving situations, and driving cessation.[1, 12, 43, 63, 82, 100, 103, 106, 113, 121] DRO research has the advantage of being less costly to conduct as compared to driver performance and safety studies, and it is also relatively straightforward since there is great flexibility in how DRO data is collected (e.g., in person, by phone, mail-out, web-based). When DROs are used appropriately in research to understand the driver's perspective, they can add a great deal to our understanding of vision and driving. For example, DRO data strongly suggest that many visually impaired drivers and drivers with eye conditions are aware of driving challenges and self-regulate their driving by limiting their driving exposure (e.g., limiting or stopping night driving).[1, 12, 43, 63, 82, 103, 106, 113, 121] However, it is highly problematic when DRO measures are used as surrogates for driver safety and performance measures. Some drivers with reduced contrast sensitivity secondary to cataract may report driving difficulties, which is verifiable by closed-road driving performance measures such as reduced hazard detection.[139] However, some drivers with reduced contrast sensitivity report no driving difficulties, when in fact they do have elevated MVC rates.[97] The capacity of some drivers to validly self-rate their own driving is limited; those with the greatest mismatch between actual and self-reported driving abilities tend to be those most at risk.[154] It is therefore important that investigators and readers are aware that DROs are the driver's opinion, by definition; and, they cannot be used to make conclusions about performance or safety. A similar case can be made for self-reported collisions, as discussed earlier with reference to safety measures.

Proxy reports from family members or other caregivers about a patient's driving performance have also been used in research,[22, 93, 136] although studies have mostly focused on cognitively impaired drivers. Agreement among the patient's assessment of his/her driving, a caregiver's assessment, and a professional driving evaluator's assessment has been evaluated; there may be moderate agreement between proxy reports and driving evaluators, however their agreement with the patient's report is not typically good. In addition, these relationships may be different for drivers who are cognitively impaired, versus those drivers from the general driving population including visually impaired drivers.

V. DRIVING SIMULATORS

Interactive driving simulators are becoming more commonly used to measure the relationship between vision and performance in driving tasks given the increased availability of off-the-shelf, commercial systems.[41] For example, simulator studies have examined the impact of vision impairment on vehicle control such as lane-keeping in drivers with retinal degenerations,[123, 124] near-crashes in drivers with slow visual processing speed,[110] and pedestrian or vehicle detection in drivers with homonymous hemianopia.[17, 101, 102] Simulator studies typically adopt a cross-sectional design. There are wide differences in the sophistication of various simulators, ranging from desktop PC-controlled displays with steering wheel controls and gas/brake pedals to those using the cab of a real vehicle situated on a moving base, to virtual reality systems.[17, 101, 107, 120, 122, 137] Driving simulators offer the advantages of standardizing testing conditions and driving scenarios for all participants and allow the safe assessment of task performance in potentially dangerous roadway scenarios since the environment is pretend, not real. Simulators are also useful in studying persons whose functional impairments are so severe that taking them on the road would be too dangerous and/or illegal. Compared to on-road studies, simulator studies may be more practically convenient for the investigator since they are based in the laboratory rather than out amidst the complexity and challenges of the real-world driving situation. Simulators are also particularly well-suited for eye movement studies using currently available systems since the physical environment (e.g., lighting) can be controlled and the vehicle is not actually moving, which facilitates valid and reliable eye movement recording.

A major disadvantage of simulators in the context of vision and driving studies is that the visual displays are obvious visual oversimplifications of the roadway, often looking cartoon-like; no matter how sophisticated they are, they can have questionable fidelity in terms of representing the visual complexity and variable lighting conditions of the actual road, including glare and variations in ambient lighting (e.g., sunny versus shaded, night, dusk, precipitation).[40, 112, 140] In addition, the participant is well aware that he/she is not having a real driving experience with all its associated risks, and thus there is an obvious recognition on the part of the participant that questionable driving behaviors have no adverse, real-world consequences. A collision in a simulator has no personal safety, vehicle, or environmental consequences. These factors can influence response contingencies in how one behaves in the simulator. For example, studies have demonstrated that drivers tend to adopt higher speeds in a simulator compared to the real road for some driving scenarios, implying that these differences could stem from differential risk perception on the simulated road as opposed to that on the real road.[14] Similar differences have been found for lane deviations.[128]

Another disadvantage is that “poor” or “unsafe” simulator performance (however that might be defined) does not automatically signify a driver would have impaired performance on the road or has an increased crash risk. Some investigators take their simulator studies to the next step by enhancing their results through companion on-road driving studies,[109] which is important when investigators seek to use their simulator results to make generalizations about actual driving ability. Although some researchers have reported a positive correlation between components of an on-road assessment and driving simulator performance measures,[49, 68] the best validity occurs when studying drivers who have no difficulties on the actual road; the validity is reduced when persons who have driving problems are studied. Thus, while there is evidence that drivers perform well in a simulator if they are good drivers, there is some question as to whether simulator performance corresponds to on-road driving performance when drivers have functional impairments (e.g., vision loss) that engender driving difficulties.

Simulator sickness is a further challenge that investigators routinely deal with when they use driving simulators to study driving in the laboratory. Simulator sickness is a syndrome with a range of possible symptoms, some more severe than others, such as sweating, dizziness, head ache, eye strain, nausea, vomiting, among others.[18, 21] The literature is clear that older adults and women are more prone to simulator sickness than other demographic groups.[18, 21, 36, 118] The stimulus characteristics of scenarios and the environment where testing takes place can influence the likelihood of symptoms so investigators need to be keenly aware of this literature in order to reduce these adverse complications in their simulator scenarios and study protocols.[119] Since vision impairment is more prevalent among older adults, the fact that advanced age increases risk for sickness is practically concerning since it suggests that some older enrollees will be unable to complete the protocol. This also potentially strikes at the generalizability of findings if a substantial segment of the population cannot provide usable data. Reports of simulator studies on vision and driving should always report the number of subjects who could not complete testing due to simulator sickness.

As for closed road driving studies, interactive driving simulators are useful for generating hypotheses regarding the role of vision and visual impairment in driving. The ultimate goal should be to subsequently test these hypotheses on the road whenever possible. Importantly, driving simulator results, by themselves, must not be the sole basis of driver safety and licensing policies without on-road confirmation of the findings and the consideration of safety data.

VI. CONCLUSION

Although the clinical gold standard for assessing driving performance is an evaluation by a CDRS, in research there is no one type of study design, study setting, or measurement tool that is patently superior to others for the study of vision and driving. All the methodologies discussed in this overview have scientific relevance in studying the relationship between vision and driving, and how impaired vision impacts driving. As ophthalmologists, optometrists and other health care providers read this literature in order to provide guidance about driving fitness to their visually impaired patients, it is important for them to recognize that study design, settings, and measurement tools will impact how studies can be properly interpreted. Similarly, policy makers depend on this literature in developing guidelines that are evidence-based and fair to drivers who are visually impaired. All methods have strengths and limitations, and some are more costly to implement than others. Some measurement methods are objective; some are derived from trained observers; and some are patient-centered. The challenge for the clinician, researcher, or policy maker is to understand whether the selected methodology is most appropriate for examining the question being asked and then to make conclusions that are consistent with the constructs that the methodology is designed to measure. Observational studies based on police-reported MVCs are the optimal approach for generating evidence to inform vision-related driver safety policies; different types of study designs, as discussed above, provide different levels of evidence. Closed-road, simulator and on-road studies are optimal for understanding the visual mechanisms underlying driver behaviors and vehicle kinematics, though closed-road and simulator studies are contrived environments; on-road studies are not contrived, but research personnel are in the vehicle. Naturalistic studies provide an opportunity to inform visual mechanisms in real-world settings, and if their samples are sufficiently large, naturalistic studies can also inform policy. Driver-reported measures can be implemented in all study designs. With the methodological framework presented in this article as a guide, it is our hope that we have offered a useful framework for researchers in this field, facilitated ophthalmologists and optometrists in evidenced-based clinical interpretations, and enhanced the appropriate use of vision and driving research for policy making. The ultimate public health aim is an improved understanding of vision and driving that best serves patients with visual impairment and other road users.

VII. METHODS OF LITERATURE SEARCH

In preparing this article we used the following methods for identifying relevant articles. We searched PubMed using the key words “driving”, “vision”, “vision impairment”, and “eye disease”. There was no constraint placed on publication date. Based on the reference sections of the articles that were generated in this PubMed search, we identified additional articles that addressed vision and driving, which did not arise in the original search. Many of these latter articles were government publications or conference proceedings that are not indexed in PubMed. Only full-length articles in English are cited. It was not our goal to review and cite all articles on vision and driving in this article; rather our focus was on those articles that shed light on the research designs and measurement tools used in the study of vision.

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