Assessing selected cognitive impairments using a driving simulator: a focused review

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Abstract

Driving simulation has become popular in the context of assessment of driving ability, as it provides a safe and economical method of assessing driving behaviors in comparable, controlled and repeatable driving conditions. The objective of the present paper is to provide a critical examination of issues that should be considered in the design of simulator experiments investigating driving performance in drivers with cognitive impairments. These refer mainly to methodological issues with a potential impact on the generalizability of research findings. The paper offers a focused review of studies investigating driving performance as assessed on simulators, targeting cognitive impairments which are age-related or caused by neurodegenerative disorders, including mild cognitive impairment (MCI), Alzheimer's disease (AD), Parkinson's disease (PD) and stroke. This focused review presents summaries of selected studies reporting assessments of the special populations of drivers noted above, including information on the research questions, the characteristics of the subjects, the type of simulators used (level of fidelity), the driving scenarios and tasks used, simulator outcomes, dependent measures, and the main findings, as well as further research suggestions. The paper references selected findings highlighting what they reveal about several key methodological issues: gauging task demands in relation to actual driving; how differences in cognitive ability affect performance, and how this varies for different driving tasks; issues related to scenario design, such as simulator limitations, scenario authoring and simulated driving tasks; the need to develop operational definitions and comparability; limitations that affect the generalizability of simulator studies; the simulator adaptation syndrome; the bias in performance assessment that can result when drivers have not adequately adapted to the simulator; and driving simulator validation. The issues covered would help readers recognize the many confounding variables and sources of measurement error that can flaw research of this type, and their implications for future investigations.

Keywords – road safety, driving performance assessment, driving simulation, cognitive impairment, off-road assessment

1. Introduction

1.1. Background

The ability to drive can be affected by various motor, visual, cognitive and perceptual deficits either related to normal ageing or caused by neurological disorders such as stroke, Parkinson's disease, Alzheimer’s disease, multiple sclerosis and traumatic brain injury, which are more prevalent among older persons [1]. Age and medical diagnosis are insufficiently reliable predictors of driver safety and crash incidence, while effective rehabilitation does not exist for neurologically impaired drivers [48]. According to Ball and Ackerman [6], driving performance assessment is “an in-depth examination of driving-related functional impairment and can be used to determine the extent to which driving ability is impaired”. In a review of older driver assessment methods, Ball and Ackerman [6] noted that “assessment provides a basis for identifying options for licensing recommendations and determining the possibility of remediation”. The gold standard of driving assessment is considered to be on-road evaluation. However, its effectiveness and efficiency is under investigation [6, 29]. Driving simulators are considered a promising tool for reliable and safe evaluation of driving performance in America and Europe, especially in people with a loss of functional ability(ies) needed to drive safely due to physical or neurological conditions [20, 41]. The use of driving simulators in the context of driving performance assessment has certain advantages: they provide objective measurements of driving performance in a safe environment; driving performance is challenged in driving tasks (e.g. crash-likely situations) which would be impossible on an open road; many confounding variables that occur in on-road driving can be controlled; events and scenarios can be identically repeated for each participant; and even low-cost, low fidelity simulators have the potential to address interesting research questions [1, 6, 8, 48]. However, Caird and Horrey [8] have also noted that driving simulators “are good at assessing driving performance or what a driver can do but are not able to address driver behavior, which is what a driver does in their own vehicle”; and that they “may create artificial situations which are not reminiscent of real-world situations.”

Studies have demonstrated that the use of driving simulators as part of an assessment battery may be a promising method for assessment of older drivers and also that performance on the simulator is associated with performance in on-road testing [6]. Uc and Rizzo [48] have pointed out that driving simulators have the capacity to distinguish between controls and drivers with Alzheimer’s disease, Parkinson’s disease or stroke, and have enabled a better understanding of driving impairments and driver error. Their view is that driving simulators may be of assistance in driver assessment and rehabilitation but that further research is required to validate their predictive ability in real life driving and their rehabilitation potential. When criteria such as at-fault crashes and traffic citations are used for persons with visual or neuropsychological deficits, there is little or no correlation between drivers’ performance on the simulator and their history of driving citations and crashes; this is attributed to the limited sensitivity of these indicators, which are discrete rare events [1]. Akinwuntan et al. [1] have noted that there is no evidence that driving simulators provide test-retest reliability and stress the need for further research in this area.

1.2. Objectives

Our objective in this paper is to provide a critical examination of issues that should be considered in the design of simulator experiments investigating driving performance in drivers with cognitive impairments. These refer mainly to methodological issues with a potential impact on the generalizability of research findings. This paper offers a focused review of studies investigating driving performance as assessed on simulators, targeting cognitive impairments which are age-related or caused by neurodegenerative disorders, including mild cognitive impairment (MCI), Alzheimer’s disease (AD), Parkinson’s disease (PD) and stroke. The goal is to help readers recognize the many confounding variables and sources of measurement error that can flaw research of this type, and their implications for future investigations.

1.3. Approach

This focused review presents summaries of selected studies reporting assessments of the special populations of drivers noted above, including information on the research questions, the characteristics of the subjects, the types of simulators used (level of fidelity), the driving scenarios and tasks used, simulator outcomes, dependent measures (e.g. behavioral data, crashes), and the main findings, as well as further research suggestions. Primary emphasis is placed on the studies' limitations and the interpretation of the findings (as noted or discussed by the authors) in an effort to identify issues which may limit the validity and generalizability of research results and which should be considered in the design of simulator experiments. Aspects of the experimental design as well as inherent limitations of the simulators are discussed in this regard. The specific studies selected for inclusion in this review paper were those deemed most illustrative of the range of assessments that may feasibly be carried out with special populations of drivers – older drivers and those with neurodegenerative disorders – using a driving simulator, and the methodological challenges involved in obtaining valid and reliable measurements using such techniques. The studies were selected on the basis of expert opinion/judgment by the paper's authors. It was not the goal to provide an exhaustive review of studies that have applied simulator-based measures for these driver populations; but simply to include sufficient examples of such studies to describe to readers the associated methodological limitations and strategies researchers have used to address them. Sources consulted in selecting studies for the present review included major international medical and engineering bibliographical databases, relevant reviews and books, reference lists of relevant studies, and proceedings of conferences on driving simulation and assessment. The dates of candidate material for this discussion ranged from 2000 to 2013.

2. Research results

This section presents summaries of studies on MCI, AD, PD and stroke, as well as summaries of studies comparing performance in older and younger drivers. A brief description of the studies referenced here can be found in Table 1.

2.1. Driving performance of people with mild cognitive impairment (MCI) and Alzheimer's disease

Rizzo et al. [35] studied the response of 18 drivers with AD (with mild to moderate cognitive impairment) and 12 non-demented drivers of similar age to a vehicle incursion at an intersection in a high-fidelity simulator (Iowa Driving Simulator). The results showed increased crashes in the AD group, inappropriate or too slow control responses, and inattention 5 sec preceding a crash event. Measures of lateral control and longitudinal vehicle control on the uneventful segments before the intersection varied within restricted ranges and did not differ significantly between the AD group and control group. These findings were combined with those of another study examining rear-end collision avoidance in drivers with AD. The combined crashes were predicted by performance scores on cognitive tests indicating visuo-spatial impairments, disordered attention, reduced processing of visual motion cues, and overall cognitive decline. Interestingly, the authors suggest in their discussion that by manipulating task demands in a simulated environment, that is by increasing "exposure" of cognitively impaired drivers and posing sufficient challenge, it is possible to observe safety errors of different types and infer crash risk through these observations [35]. Devlin et al. [12] examined the performance of older drivers with and without mild cognitive impairment (MCI) when approaching intersections, testing fourteen male and female older drivers with MCI and fourteen age-matched healthy drivers using a portable driving simulator comprising a small cab with genuine vehicle parts with a field of view of 120° (Monash University Accident Research Center). Relative validity had been established for some operations such as lane position, speed, brake onset, and risky driving behaviors. Specific performance measures included were approach speed, number of brake applications on approach to the intersection, failure to comply with stop signs, and braking response times on approach to critical light change. The preliminary evidence suggested that drivers with MCI performed less well when approaching controlled intersections and critical light-change intersections. Healthy drivers demonstrated a greater number of foot hesitations on approach to stop-controlled and critical light change intersections compared to the MCI group; this behavior was probably adopted as a strategic mechanism. A large variation in cognitive ability amongst the drivers with MCI was found. Some limitations of the study, as reported by the authors, included the representativeness of the sample, volunteer bias, the strict inclusion criteria, the small sample and the use of the Mini Mental State Examination (MMSE) as a screening tool, which might not detect highly-educated participants with age-related cognitive impairment in the control group [12]. The possibility of drawing general conclusions from the results is therefore limited.

A study by Frittelli et al. [17] examined the impact of Alzheimer's disease (AD) and mild cognitive impairment (MCI) on driving ability using a low-cost, personal-computer-based interactive driving simulator (STISIM Driving Simulator). The study included twenty patients with mild AD (CDR = 1), 20 individuals with MCI (CDR = 0.5) and 19 neurologically normal aged controls. The groups were matched in terms of age, level of education and years of driving experience. There was a slight imbalance between patients and controls in terms of numbers of men and women and results were not adjusted for gender. The study detected greater impairment of driving performance in AD patients than in healthy and MCI subjects. Drivers with AD were rated as significantly worse than MCI subjects and healthy elderly drivers on three driving behaviors: length of the run (sec), mean time to collision and number of off-road events (defined as occurring when the centre of the car's hood crossed the lateral border of the road). The only statistically significant difference between MCI patients and healthy control subjects was in the shorter mean time to collision of MCI subjects. Although driving performance was significantly related to cognitive decline, correlations with the MMSE score for overall cognitive function were not significant [17]. The authors concluded that driving simulator tests are a valid and reliable screening tool for discriminating performance decrements of drivers with early AD and they suggested further research on whether the observed impairment translates into increased accident risk.

Uc et al. [47] tested avoidance of rear-end collisions (REC) in 61 drivers with AD and 115 elderly controls, all holding valid driving licenses, using a high fidelity driving simulator (SIREN). Participants were matched for educational level. AD participants were older and in this group, male gender predominated. Indexes of driving performance used were the standard deviations of mean steering wheel position, mean speed change, and mean number of large steering adjustments (>6) per minute. The response of the AD subjects in collision avoidance situations was less effective than that of the controls. This was not a result of the older age or lower driving exposure of the AD participants. Although the likelihood of REC in AD drivers was not significantly higher, they were less quick to react and were more likely to respond in an unsafe manner, by suddenly slowing down or stopping before reaching the intersection.

According to this study, multiple factors are predictive of unsafe outcomes in the REC avoidance task, consistent with its multilevel cognitive, sensory, and motor demands. AD participants showed poorer vehicle control than neurologically normal older drivers, based on significantly increased steering variability and a tendency for increased speed variability in baseline driving circumstances under low traffic conditions on an uneventful segment of two-lane highway. Poorer vehicle control at baseline predicted unsafe outcomes in the complex driving condition at the intersection, suggesting that basic measures of driving in the simulator can predict outcomes in high risk situations. The specific simulator experiment revealed that unsafe – "hidden" – driving behaviors are theoretically related to crashes and occur more frequently. The safe response of participants with mild dementia in the REC avoidance task implies that some older drivers with neurological disorders may continue to drive safely. The authors' findings suggest that decisions regarding fitness to drive should take performance-based testing into consideration and should not be made on the basis of diagnosis alone.

2.2. Driving performance of people with Parkinson disease and stroke

The study of Stolwyck et al. [44] examined the impact of a concurrent task on driving performance among 18 current drivers with PD (mean age 67.62) and 18 matched controls (mean age 67.13) using a fixed base Systems Technology Incorporated (STI) model driving simulator with STISIM Drive Software. The drivers with PD were in the mild to moderate stages but no driver in either group had any history or current evidence of any other neurological impairment, psychiatric illness or drug/alcohol dependence. Any driver impairment (physical, visual, or hearing) was corrected by aids. The presence of a concurrent task was manipulated between conditions. After 8 to 10 practice simulations participants were required to complete 20 concurrent task simulations and 20 nonconcurrent task simulations. The concurrent task consisted of 19 different sounds; three of them were target sounds, which differed significantly from the sixteen non-target sounds. In concurrent task conditions, two target sounds occurred consecutively only three times per simulation. Participants were required to press the turning indicator as quickly as possible when this occurred. The dependent variables which were investigated included several driving behaviors in respect to traffic signals (approach speed, deceleration point, stopping point) and road curves (mean speed, speed variability, mean lateral lane position, lateral lane position variability) and the concurrent task (accuracy and response time). The independent variables were the presence of a concurrent task and participant status. The study findings indicated that drivers with PD in the mild to moderate stages and matched controls (in respect to age, years of education and years of driving) were similarly affected by the concurrent task on most driving measures, both groups applying tactical adaptations to their driving behavior that resulted in more conservative driving. The concurrent task had a disproportionate effect on performance at the operational level (PD drivers started deceleration later, closer to the traffic signal). Drivers with PD tended to trade concurrent task performance to maintain driving performance. In people with PD, measures of cognitive status were associated with tactical and operational levels of performance. On the basis of their findings, the authors concluded that cognitive difficulties associated with PD compromise driving performance even in the mild to moderate stages of the disease. Vaux et al [50] studied how the ability of participants with neurodegenerative disease (AD and PD) to detect impending collisions differed from that of neurologically normal participants of comparable age (mean age 69.67) in a low-fidelity simulator (desktop computer). The groups consisted of men and women (27% women in the neurodegenerative disease group and 38% in the neurologically normal group).

Performance on a battery of standardized neuropsychological tests suggested early cognitive decline in the AD/PD group. 3D roadway scenes were presented on a 39.8x32^{o} visual angle display. The scenes simulated a roadway with objects moving at a constant speed on linear trajectories towards the observer. The display simulated both driver vehicle motion and motion of the objects towards the driver; the speed of the driver's vehicle and the speed of the approaching objects were both 43.2km/h. Collision and non-collision objects were located along an arc of fixed radial distance from the observer, and the motion of the objects was on a linear path towards the viewpoint of the observer. All objects remained in the field of view. For collision trials, one of the objects approached on a linear path that would eventually collide with the observer. The displays differed on the number of objects (either a single object/sphere or six objects/spheres) in the scene and time to contact (TTC) (either 1s or 3s TTC). At the beginning of the trial, all objects were located at an initial distance such that the TTC was 9s. For 3s TTC, the display depicted 6s of motion whereas for 1s TTC, the display depicted 8s of motion. Participants were asked to indicate whether or not a collision would have occurred in each trial. After eight practice trials, observers completed two separate blocks of the task; they were presented with 20 replications (10 collision and 10 non-collision events) for each combination of number of objects and TTC for a total of 80 trials. The dependent variables were the collision detection sensitivity (indicating the ability to detect collision), while the independent variables were the number of obstacles and time to contact (TTC). Group membership was a between-subjects variable, while number of objects (two levels: one and six objects) and TTC (1 second and 3 seconds) were the repeated-measures variables. When a single object was present in the driving scene both groups performed with some degree of sensitivity for each of the TTC conditions. For the 3-second TTC/6 objects condition, the results indicated that the comparison group had some degree of sensitivity whereas the neurodegenerative group had no sensitivity to detect a collision. For the 1-second TTC/6 objects condition, both groups had high sensitivity to detect a collision. The results suggest that the drivers with AD and PD required additional time to detect impending collisions, probably impairing their ability to avoid the collision events measured by the simulation task. Impairments on the collision detection tasks in the neurodegenerative disease group reflected a variety of combined disturbances of visual-sensory processing, motion processing, attention, visuo-spatial skills and executive functions as implied by the association between poor collision sensitivity and poor performance on tests of cognition and visual attention. The authors suggested that more data are needed to disclose relationships between performance on the collision detection task and real-world evidence of driver behavior [50]. Lee et al. [23] explored the validity of using the interactive PC-based STISIM Driving Simulator (Systems Technology Incorporated) in assessing drivers with PD. Fifty PD patients and 150 healthy controls of comparable age participated in the study. All aged between 60 and 80, they were current drivers with no history of violations. Participants were assessed in specific tasks and driving behaviors on the open road using well-defined on-road assessment criteria. The driving assessment criteria were combined by principal component analysis to develop a composite score representing overall driving performance, namely the Road Assessment Index. Driving performance was also assessed in driving tasks in the simulator using simulated assessment criteria. Using the same method, the simulated performance criteria were combined by principal component analysis to develop a composite score representing an overall Simulated Driving Index. An overall Simulator Driving Index and a Road Assessment Index were developed for the PD group and the control group. The indices were significantly different in the PD and control groups. In the simulated driving test, the drivers with PD performed less safely than the controls.

The PD patients did not perform well at either the tactical or the operational level. Participants with PD tended to drive more slowly in response to road hazards, and to be unable to control speed and movement of the steering wheel, to apply the brakes smoothly, to address two tasks simultaneously and to make quick decisions and judgments. These problems are related to decrements in motor skills, visuo-spatial processing, working memory and executive function planning. Forty percent of the variability in the Road Assessment Index of drivers with PD in the Lee et al. study can be explained by the Simulator Driving Index, after adjusting for age, gender and average miles per year.

The corresponding percentage of the control group was sixty-eight percent. The authors concluded from the findings of the study that driving simulators can provide valuable information on PD drivers' ability. The study's limitations, as noted by the authors, were the relatively few women participants, the non-representativeness of the target population, the probable self-selection bias, the use of medication and the fear of information technology in the older adult population. The authors suggested further research into which level of behaviors contributes more to the poor performance of PD patients and validation of the simulator with a randomized control sample. They also suggested that driving simulators can be developed into a cost-effective screening tool.

Devos et al. [14] developed a short clinical battery to predict the fitness to drive of people with Parkinson's disease with a high degree of accuracy. The study included 40 patients with PD (33 men and 7 women) and 40 age- and sex-matched controls (31 men, 9 women). Twenty-nine patients with PD and 36 controls had no cognitive deterioration (CDR = 0); eleven patients with PD and three controls showed very mild cognitive decline (CDR = 0.5). The patients with PD underwent a clinical assessment and an official fitness to drive evaluation. The official evaluation included visual tests, neuropsychological tests and an on-road test to evaluate practical fitness to drive using the Test Ride for Investigating Practical Fitness to drive (TRIP) checklist. The TRIP check list contains 13 items of driving performance and is made up of 49 sub-items that are each scored using predefined criteria on a four point scale. All participants were also evaluated in a driving simulator: a stationary full-sized Ford Fiesta 1.8 car with automatic gear transmission powered by the STISIM Drive System, Model 300, Version 1.03.05, manufactured by Systems Technology Inc. Before driving simulator performance evaluation, the participants drove a 6 km road course to become familiarized with the simulator. The driving scenario for the evaluation involved a 15 km course including frequently occurring traffic situations. Driving performance was scored on a modified TRIP checklist. Disease duration, contrast sensitivity, Clinical Dementia Rating and the motor part of the Unified Parkinson's Disease Rating Scale (UPDRS III) together provided a logistic regression model to predict fitness to drive (pass-fail decisions) with the highest accuracy ($R^2 = 0.52$) and correctly classified 90% of the patients (sensitivity = 91%, specificity = 90%). When the TRIP driving simulator score was added to the clinical screening battery the total explained variance increased to 60% and 97% of the drivers were correctly classified (sensitivity = 91%, specificity = 100%).

The study results suggested that driving simulation is strongly associated with actual on-road performance in PD. The TRIP driving simulator score discriminated significantly between drivers with PD and their healthy peers. The results indicated that driving performance in people with mild to moderate PD is affected by visuo-integrative (contrast sensitivity), cognitive (Clinical Dementia Rating) and motor deficits (UPDRS III). In their discussion, the authors noted that their findings differed from the results of previous studies, which emphasized the inclusion of detailed neuropsychological measures to predict on-road performance.

They also pointed out that the driving safety decision was made by a team of experts in assessing fitness to drive after a full assessment of visual, cognitive and on-road tests, and was predicted by a series of general clinical tests. In their discussion, the authors noted the small group of patients with PD with minor cognitive deterioration. The screening battery was validated in a different sample of PD patients in a recent study [13], in which the sensitivity of the screening battery improved from 91% to 96% and the specificity fell from 90% to 64%. The changes were attributed to the differences between the cohorts: the clinical severity of PD and the failure in fitness to drive was higher in the cohort of the later study than in the first one. The inclusion of driving simulation increased the specificity of the model to 94%. Patomella et al. [33] conducted a cross-sectional observational study investigating aspects of validity and stability of Performance Analysis of Driving Ability (P-Drive) for people with stroke using an interactive, realistic and technically-advanced driving simulator (Argus driving simulator). One hundred and one participants with stroke (referrals) were included in the study, having met specific inclusion criteria. P-Drive was used to score driving performance on the basis of observations and specific scoring criteria per item defined in P-Drive. P-Drive items were classified into tactical and operational tasks according to Michon's levels [28]. The goodness-of-fit statistics for the items (95%) and the participants (97%) (Rasch analysis) indicated that P-Drive had acceptable internal validity (unidimensional scale) and person response validity. Moreover, the person separation index and person separation reliability implied that P-Drive could separate participants with different driving abilities. Investigation of the standard error in the estimates indicated that P-Drive also contained aspects of reliability in relation to precision of the estimates. Items requiring tactical decisions were more challenging than those for which only operational decisions were required. The authors suggested that the over-representation of male participants was probably attributable to the male dominance of referrals.

McKay et al. [25] compared the accuracy of stroke survivors' self-evaluation of driving with that of healthy controls. The study included thirty stroke survivors and thirty same-age controls. The study examined self-awareness of neuropsychological performance and driving performance using the Doron AMOS (Advanced Mobile Operation System)-2 interactive simulator. Driving evaluation lasted 45 minutes and included 4 sequences of simulated real-life traffic situations: (a) residential and light business traffic; (b) rural traffic and roadways including lane changes; (c) challenging situations requiring forethought and quick response time (e.g., near collisions, emergency vehicles); and (d) a skills track module that included assessment of brake reaction, front-end parking, and distance estimation. The driving scenarios yielded an overall total score reflecting performance across several domains including speed, stop distance, lane placement, traffic signal use, hazard avoidance and obeying traffic signs and signals. Stoke survivors and controls were asked to predict their performance (pretest predicted performance ratings) in novel (neuropsychological) and familiar (driving) tasks and, after the administration of the neuropsychological tests and the driving simulator task, to rate their performance (post-test predicted performance ratings). The results of the study showed that across all measures, stroke survivors overestimated their performance in comparison with the accuracy of the self-evaluations of the controls, implying impaired self-awareness in both neuropsychological and driving tasks. The overestimation was present both before and after completion of novel and familiar tasks. Notably, both stroke survivors and healthy adults over-predicted their performance on the driving evaluation; however, the degree of overestimation was substantially larger among the stroke survivors than among healthy adults. Although the stroke survivors continued to overrate themselves, experiential feedback on the familiar task of driving produced a substantial improvement in the accuracy of the self-estimated performance. The results of the analysis also showed that the self-ratings of both stroke survivors and healthy controls were more accurate following driving simulator performance than post self-ratings of neuropsychological test performance. Study limitations noted by the authors were the modest sample size, the cross-sectional character of the study and the fact that they did not examine how emotional and psychological sequelae play a role in ISA [25].

2.3. Comparing performance in older and younger drivers

Using a fixed-base simulator with a 40-degree horizontal field of view (STISIM Drive 2.0 by Systems Technology Incorporated), Cantin et al. [9] examined whether the mental workload of young and older active drivers varies with the difficulty of the driving context. Twenty male drivers participated in the study, ten aged between 20 and 31, with a mean age of 24, and ten aged between 65 and 75, with a mean age of 69. Workload was measured using the probe (stimulus) reaction time (RT) technique. Reaction time was defined as the temporal interval between the presentation of an auditory stimulus and the onset of the corresponding verbal response. During the experimental drive, participants were exposed to three auditory stimuli in three increasingly complex driving contexts: at constant speed on straight roads; approaching intersections; and overtaking a slower vehicle. For both groups, there was an increase in the mental workload at intersections, with a further increase at more complex intersections, disproportionately so in the case of the older drivers. Vehicle control did not decline in response to stimuli. In each group there were few omissions, although in driving contexts of greater complexity, the older drivers failed to respond more than twice as often as the younger drivers. Accidents or incidents did not become more frequent for elderly drivers, but there was one serious error at an intersection. The authors noted that it would be interesting to examine whether this performance failure was observable in drivers older than 85 years of age or those suffering from mild cognitive impairment. Older drivers were observed to use compensatory driving strategies; they drove more slowly and had an increased number of braking events exceeding 0.1g. In discussing the limitations of their study the authors noted the participation of volunteers who, in addition, were active and cognitively fit, while the driving conditions were nearly ideal. Moreover, the increased number of braking events among the older individuals may be attributed to either increased workload or visual deficits (due to decreased sensory detection capability) or to an increased motor output variability associated with aging; however the data did not allow for discrimination between these possibilities. The results indicated that driving scenarios for simulator studies can be manipulated in such a way as to mimic the mental workload imposed by similar on-road driving contexts. The authors suggested that a more systematic examination of the interactions between aging and driving complexity may provide insight into the events leading to driving errors made by older drivers.

The driving simulation performance of 51 younger drivers (22 male, 29 female) aged 21-50 was compared to the driving simulation performance of 67 older drivers (37 male, 30 female) aged 70-90, with a minimum of 5 years' driving experience [2, 32]. A desktop driving simulator with wide field of view (135 degrees) was used (STISIM Drive Desktop by Systems Technology Incorporated). Participants were subjected to a large number of physiological, sensory and neuropsychological tests and completed a simulator sickness questionnaire. There were five sessions in the simulated driving part of the test battery. Simulation measures included standard deviation of curvature error, time taken for completion of a construction zone obstacle course, standard deviation of time-to-collision in multiple lane-changing tasks, composite vehicle collision count, number of hard braking (>0.5g) instances, average time to collision, pedestrian collisions, number of cone collisions in construction zone scenario, average vehicle speed, standard deviation of vehicle speed, and composite number of excessive steering instances. The results of this study indicated that older drivers were 4 times more likely to hit pedestrians; they also had more instances of hard braking and their average speed was lower, so they took longer to complete the scenario. The two age groups differed markedly in terms of TTC. Based on the results of regression analysis, the authors noted that cognitive variables (measures) are related to no more than two simulation variables, while simulation variables are related to four or five cognitive variables. Park et al. [32] showed that simulator performance is age-sensitive but does not appear to be sensitive to measures of discomfort. The simulator measures showed significant correspondence with traditional cognitive test instruments, and provided more age discrimination relative to the variability of the measures. The authors suggested that it might be possible to condense these scenarios, which lasted about an hour over four sessions, into a single 30-minute long scenario; they also stressed that procedures need to be developed to improve screening so as to minimize Type I errors (rejection of an unimpaired subject) and Type II errors (acceptance of an impaired subject).

Andrews et al. [4] examined compensatory processes for age-related declines in cognitive ability in 22 younger (26-40 years, nine men) and 22 older drivers (60+ years, nine men). All the participants were active drivers with at least six years of driving experience. The two groups were similar in terms of visual status and general health and although they had different levels of driving experience, their current driving activity was matched in terms of frequency, annual mileage and road use [21]. There was no difference in their history of adverse events. The participants were tested in two separate 75-minute sessions. The first consisted of cognitive tests and self-report subjective workload questionnaires (NASA TLX), while the second consisted of a driving experiment conducted on a low-fidelity simulator with a horizontal viewing angle of approximately 45 degrees) [4]. Participants performed a car-following task in one version that involved no braking by the lead car and in another that involved braking in each of four driving scenarios representing a variety of urban demands. The dependent measures were mean time headway, minimum time to collision (TTC), anticipation of lead vehicle braking events, number of anticipated events, standard deviation of speed, and standard deviation of lane position.

The results showed that older drivers adopted a compensatory behavior in terms of longer headways (by means of altered speed/timing strategy) to offset the effects of age-related cognitive slowing. The older group was relatively homogeneous in adopting this strategy, which was not dependent on crystallized ability or cognitive reserve scores. In the older group, a subgroup of cognitively more able participants showed a compensatory process, i.e., they anticipated traffic events more frequently than cognitively less able older participants. The authors [4] identified a selective compensatory process applied by older participants with higher cognitive ability including an index of crystallized ability. This age-related compensation, however, was correlated with increased workload experienced by older individuals. The authors noted that prediction of age-related compensatory processes may require an index of pre-decline intelligence, i.e., crystallized ability. They also suggested the use of cognitive ability tests as part of a screening process for older drivers. Limitations of the study were a sampling bias related to volunteers, who, also being healthy, fit and active, might not be representative of the population of interest. In addition, the authors recognized that when examining the effects of aging, cross-sectional studies make it difficult to distinguish age from cohort effects.

Mullen et al. [29] investigated whether driver performance on one task was predictive of performance on another and also investigated the relationship between cognition and driving. Twenty-six drivers aged 55 to 80 (5 male and 21 female, mean age 63, s.d. = 6.8 years), all holding valid licenses, volunteered to participate in the study. Cognitive tests were conducted prior to the experimental drive, and a 15-minute orientation drive was completed by subjects to acquire familiarity with the driving simulator and controls. A desktop simulator with a wide field of view (135 degrees) was used to present a 3.0 mile rural highway course, a 0.5 mile parking lot course and a 1 mile construction zone course (STISIM Drive Software). In the rural highway course scenario, speed maintenance ability was assessed. The dependent variables were the percentage of time the participants drove within +-5mph of 55 mph and the total number of driving errors recorded throughout the drive. In the parking lot scenario, the situational awareness of participants and their emergency braking ability were assessed, while number of collisions (with vehicles and pedestrians) and number of driving errors were the dependent variables.

The construction zone scenario assessed motor control ability with steering wheel and pedals, while number of collisions (with road cones and workers) and number of driving errors were the dependent variables. Drivers were asked to perform three driving tasks requiring different skill sets that were expected to involve different areas of cognition sensitive to age-related declines in performance. The lack of correlation in the performance of the three driving tasks and the correlations found between the cognitive tests and the driving tasks indicated that the driving tasks involved different driving abilities and cognitive constructs. Interestingly, the authors noted that for the scenarios in question, incidence of errors was not an effective measure of driving performance and proposed that further research is needed to determine which components more effectively measure driving performance. They concluded that it is vital that every component of safe driving should be assessed in a standardized fashion that is consistent across research and evaluation programs.

Using a driving simulator (STI), Benedetto [7] compared speeds and absolute differences between theoretical lateral acceleration (expected by the road designer(s)) and observed lateral acceleration (in the simulator) for two age groups (younger and older drivers) on two road stretches of different complexity. The cumulative absolute value of the difference between the absolute values of theoretical and real lateral accelerations was assumed as an indicator of the complexity of the road geometry. On the basis of the results of a previous study, the author noted that as the value of this indicator increases, the accident rate increases with a parabolic trend. Two hypotheses were tested regarding the cumulative absolute value of the difference between theoretical and real (observed in the simulator) lateral acceleration: (1) it had the same trend along the roadway for older and younger drivers; and (2) it was greater for older than for younger drivers. Two homogeneous age groups of drivers participated in the study: the members of the younger group were 21 to 27 years old with an average age of 24.4 (s.d. = 1.9) and the members of the older group were over 65 with an average age of 69 (s.d. = 4.2). The investigation was conducted for two stretches of a two-lane dual carriageway road of different accident rates and geometric complexity. The stretches were homogeneous in their operational and environmental characteristics. After a training session of 10-15 minutes in the simulator, drivers drove the first stretch of road; the next day, they drove the second (less safe) stretch. Simulator measures used in the analysis included speeds and transverse accelerations. Average speeds, standard deviations of speeds of younger and older groups in each stretch and in each geometric element of each of the two stretches were compared. In addition, the cumulative absolute value of the difference between theoretical and real (observed in the simulator) lateral accelerations at each kilometer of the two stretches were computed and compared for the two age groups. Results indicated that if the geometry of a roadway was more complex and tortuous, the speeds of older subjects were generally much lower than the speeds of younger subjects.

Tab. 1 - Simulator studies on MCI, AD, PD, stroke as well as on age comparisons

Reference	Participants	Driving tasks/context/scenario	Performance measures	Main results
Devlin et al. [12]	14 older drivers with MCI, 14 controls	Signal-controlled and stop sign-controlled intersections	Performance measures were approach speed, number of brake applications on approach to the intersection, failure to comply with stop signs and braking response times on approach to critical light change.	Drivers with MCI performed less well (than controls) when approaching controlled intersections and critical light-change intersections (preliminary evidence); large variation in cognitive ability among the MCI drivers was found. The only statistically significant difference between MCI patients and healthy control subjects was in the shorter mean time to collision of MCI subjects.
Vaux et al. [50]	6 AD, 8PD, 18 controls	Collision detection task: one and six obstacles and two conditions for time to contact (TTC): 1-second TTC and 3-second TTC.	The dependent variable was the collision detection sensitivity (whether the approaching objects would collide or pass by them)	Drivers with AD and PD required additional time to detect impending collisions, probably impairing their ability to avoid collision events. For the 3-second TTC/6 objects condition the comparison group had some degree of sensitivity whereas the neurodegenerative group had no sensitivity to detect a collision. For the 1-second TTC/6 objects condition, both groups had high sensitivity to detect a collision
Frittelli et al. [17]	20 mild AD , 20 with MCI, 19 aged controls	Driving on a two-lane urban and an extra-urban road, encountering events such as traffic lights, trucks and cars on the oncoming lane or preceding the test car, intersections, pedestrian crossings	Rated behaviors: length of the run (sec), mean time to collision and number of off-road events.	AD patients showed greater impairment of driving performance than healthy and MCI subjects. Drivers with AD were rated as significantly worse than MCI subjects and healthy elderly drivers, on the length of the run (sec), the mean time to collision, and the number of off-road events.
Uc et al. [47]	61 drivers with AD and 115 elderly controls	Rear-end collision avoidance	Crashes, measures of vehicle control; steering variability and speed variability indexes of driving performance used were the standard deviations of mean steering wheel position, mean speed change, mean number of large steering adjustments (> 6) per minute.	The response of the AD subjects in rear-end collision (REC) avoidance situations was less effective than that of the controls. The likelihood of REC in AD drivers was not significantly higher (similar crash rates), they were less quick to react and were more likely to respond in an unsafe manner (poorer vehicle control).
Rizzo et al. [35]	Older drivers (18 AD and 12 controls)	Illegal vehicle incursion at an intersection	Crashes and measures of lateral control and longitudinal vehicle control.	AD drivers had increased crashes, inappropriate or too slow control responses and inattention 5 sec preceding a crash event. Crashes (combined with those of a previous study) were predicted by performance scores on cognitive tests sensitive to declines in aging and AD.
Lee and al. [23]	50 PD, 150 controls	Simulated driving tasks including: Road use obligation Decision and judgment Multi-tasking tasks Attention tasks	Assessed driving behaviors using specific assessment criteria; Overall simulated driving index and a road assessment index.	PD drivers did not perform well in either operational or tactical tasks, with tactical tasks being more challenging than operational tasks. PD drivers tended to drive more slowly in response to road hazards, unable to control speed and movement of the steering wheel, to apply the brakes smoothly, to address two tasks simultaneously, and to make quick decisions and judgments
Devos et al. [14]	40 PD and 40 controls	A 15km course including frequently occurring traffic situations.	Performance scored on the modified Test Ride for Investigating Practical fitness to drive checklist: it contains 13 items of driving performance and is made up of 49 sub-items that are each scored using predefined criteria on a four point scale. Number of accidents/traffic offences.	The results suggested that driving simulation is strongly associated with actual on-road performance in PD. A short screening battery assessing four clinical variables provided the best model for predicting fitness to drive; when the TRIP driving simulator score was added the total explained variance increased to 60% and correctly classified 97% of the drivers with PD into the pass/fail category (sensitivity 91%, specificity 100%). The TRIP driving simulator score discriminated significantly between drivers with PD and their healthy peers.
Stolwyck et al. [44]	18 PD and 18 controls	Driving behaviors in respect to traffic signals and road curves and a concurrent task.	Driving behaviors in respect to traffic signals (approach speed, deceleration point, stopping point) and road curves (mean speed, speed variability, mean lateral lane position, lateral lane position variability) and a concurrent task (accuracy and response time).	The concurrent task had a disproportionate effect in performance at operational level in drivers with PD. Drivers with PD tended to trade concurrent task performance to maintain driving performance. In a concurrent task (auditory task) condition, drivers with PD and matched controls applied tactical adaptations to their driving behavior, resulting in more conservative driving. In people with PD, measures of cognitive tests were associated with tactical and operational level of performance.
Patomella et al. [33]	101 stroke survivors	70 frequently encountered traffic situations representing different challenges for people with stroke.	Driving performance was scored in 20 items observed in different situations and sorted into 4 subgroups: maneuvering, orienting, obeying and responding to traffic rules and paying attention.	The most challenging items were those requiring great attention and rapid information processing. Items requiring tactical decisions were more challenging than those for which only operational decisions were required.
McKay et al. [25]	30 stroke survivors and 30 controls	4 sequences of simulated real-life traffic situations: (a) residential and light business traffic; (b) rural traffic and roadways including lane changes; (c) challenging situations requiring forethought and quick response time (e.g., near collisions, emergency vehicles); and (d) a skills track module that includes assessment of brake reaction, front-end parking, and distance estimation	Overall total score reflecting performance across several domains: speed, stop distance, lane placement, traffic signal use, hazard avoidance and obeying traffic signs and signals. Self-evaluation of driving: pre-test predicted performance in novel (neuropsychological) and familiar (driving) tasks and post-test predicted performance ratings	Stroke survivors had impaired self-awareness in both neuropsychological and driving tasks. Both groups predicted their performance on the driving evaluation; the degree of overestimation was substantially larger among the stroke survivors than among healthy adults. The self-ratings of both stroke survivors and healthy controls were more accurate following driving simulator performance than post self-ratings of neuropsychological test performance. For stroke survivors, experiential feedback on the familiar task of driving produced substantial improvement in accuracy of self-estimated performance.
Andrews et al. [4]	22 younger (26-40 years), 22 older drivers (60+)	A car-following task in one version that required no braking by the lead car (no delay event) and in another that required braking (a delay event) in each of four driving scenarios representing a variety of urban demands.	Mean time headway, minimum time to collision, anticipation of lead vehicle braking events, number of anticipated events, standard deviation of speed, standard deviation of lane position, NASA TLX assessment.	Older drivers adopted a compensatory behavior in terms of longer headways (by means of altered speed/timing strategy) to offset the effects of age-related cognitive slowing. A subgroup of older drivers with higher cognitive ability showed a selective compensatory process, i.e., in that they anticipated traffic events more frequently than cognitively less able older participants.
Cantin et al. [9]	10 aged 20-31 (mean 24), 10 aged 65-75 (mean 69)	Three auditory stimuli in three increasingly complex driving contexts: at constant speed on straight roads; approaching intersections; and overtaking a slower vehicle.	Reaction Time (mental workload). Count of speed limit exceedances, Speed and lateral position, number of edge excursions, the overall time to complete the run, number of crashes, number of braking events > 0.1g	In each group there were few omissions. For both groups the mental workload increased at intersections. When compared to younger drivers, older drivers showed performance decrements in concurrent tasks for more complex driving contexts. Vehicle control did not decline in response to auditory stimuli. Accidents or incidents did not become more frequent for elderly drivers.Older drivers were observed to use compensatory driving strategies (they drove more slowly and increased their number of braking events > 0.1g).

Mullen et al. [29]	26 drivers aged 55 to 80 (mean age 63 years)	Three courses: 3.0 mile rural highway course; 0.5 mile parking lot course and 1 mile construction zone course.	In the rural highway course: speed maintenance ability (percentage of time within 55mph+/-5mph, and the total number of driving errors). In the parking lot scenario: situational awareness and emergency braking ability (number of collisions with vehicles and pedestrians and number of driving errors). The construction zone scenario: motor control ability (number of collisions with road cones and workers) and number of driving errors)	Lack of correlation in the performance of the three driving tasks and the correlations found between the cognitive tests and the driving tasks suggesting that the driving tasks involve different driving abilities and cognitive constructs.
Benedetto [7]	younger group 21-27 years old (average age 24.40); older group, over 65 (average age 69)	Two stretches of a two-lane dual carriageway road of different accident rates and geometric complexity	Speed (average speeds, standard deviations of speeds). Pathologic Discomfort (cumulated absolute value of the difference between the absolute values of theoretical and real lateral acceleration).	Older drivers used compensatory driving strategies: their speeds were generally much lower than the speeds of the younger drivers; when road complexity increased, older subjects drove at slower speeds and experienced more difficulties than younger drivers.
Park et al. [32]; Allen et al. [2]	51 younger drivers, aged 21-50; 67 older drivers aged 70-90	10 scenarios, each one designed to examine certain aspects of driving performance and behavior: rural drive, high speed medium/high traffic in complex environment, residential street (emergency braking), brake reaction, construction zone, parking lot, truck passing task, freeway merges	Standard deviation of curvature error; time taken for completion of a construction zone obstacle course; standard deviation of time-to-collision in multiple lane-changing tasks; composite vehicle collision count; number of hard braking (> 0.5g) instances; average time to collision; pedestrian collisions, number of cone collisions; average vehicle speed, standard deviation of vehicle speed; composite number of excessive steering instances.	Compared to younger drivers, older drivers were 4 times more likely to hit pedestrians; they had more instances of hard braking and their average speed was lower. The two age groups differed markedly in terms of TTC.

The dispersion of speeds is much greater for older than for younger drivers. The two hypotheses tested were verified: the cumulative absolute value of the difference between theoretical and real (observed in the simulator) lateral accelerations had the same trend along the roadway for older and younger people, and it was greater for older people. On the basis of these findings, the author concluded that the unsafe stretch of road is expected to be unsafe for both younger and older drivers, and that the unsafe stretch is expected to be more unsafe for older people than for younger people.

3. Methodological issues

This section of the paper references selected findings from the body of work cited above and other studies investigating driving performance as assessed on simulators in relation to cognitive impairments, highlighting what they reveal about several key methodological issues: gauging task demands in relation to actual driving; how differences in cognitive ability (and cognitive style) affect performance, and how this varies for different driving tasks; issues related to scenario design, such as simulator limitations (fidelity), scenario authoring and simulated driving tasks; the need to develop operational definitions and comparability; limitations that affect the generalizability of simulator studies; the simulator adaptation syndrome; the bias in performance assessment that can result when drivers have not adequately adapted to the simulator; and driving simulator validation.

3.1. Task demand in a simulated environment

When assessing cognitively impaired drivers in a simulator, the presentation of driving conditions that are of increasing complexity and pose sufficient challenge allows performance inadequacies related to impairments in different cognitive domains to be identified and their interactions to be examined [7, 9, 15, 34, 50]. Such experimental designs are related to within-subject design, which tends to be more powerful since each driver serves as their own control [10]. Stolwyck et al. [44] observed that people with PD tend to trade concurrent task performance to maintain driving performance. Cantin et al. [9] showed that when compared to younger drivers, older drivers present performance decrements in concurrent tasks for more complex driving contexts; they suggested that research should be undertaken to identify the mechanisms relating to the tasks under investigation and understand how they evolve with driving complexity. Moreover, it would be interesting to examine the ability of individuals (who have increased mental workload or are cognitively impaired) to properly allocate resources or prioritize particular aspects of performance [9]. When tested in collision avoidance situations, drivers with AD showed poorer vehicle control than neurologically normal older drivers. In addition, poorer vehicle control at baseline driving circumstances (under low traffic conditions on an uneventful segment of two-lane highway) predicted unsafe outcomes in the complex driving condition at the intersection, suggesting that basic measures of driving in the simulator can predict outcomes in high-risk situations [47]. Stolwyck et al. [44] found that the concurrent task had a disproportionate effect on performance at the operational level, and noted that such operational level behavior might, under pressure of time, compete with concurrent tasks for controlled processing resources. The study findings indicated that both the PD and the healthy control groups were similarly affected by the concurrent task on most driving measures, and when the concurrent task was present, both groups applied tactical adaptations to their driving behavior, resulting in a more conservative driving style. The occurrence and the safety potential of tactical adaptations have been observed in the reviewed studies [4, 7, 9, 44]. These compensatory strategies are highly relevant to older drivers [19, 20]. Older drivers largely have extensive driving experience and, consequently, possess cognitive driving skills (such as anticipation and hazard recognition) that allow them to compensate for the difficulties they have due to age-related declines. Compensation, however, is also subject to functional limitations [22] and available time. Compensation might occur automatically as a reaction to cognitive overload [11]. When task demand begins to exceed capability, compensation may be related to performance degradation; where the demand is too high and exceeds capability (overload conditions) this would result in inappropriate task prioritization or a severe decline in basic driving skills [18].

Compensatory behavior was identified in a study by Cantin et al. [9], who noted that although older drivers exhibited a higher mental workload than younger drivers, their driving performance was not significantly different. According to the findings of a study on older drivers in relation to road geometry [7], the speeds of older drivers are generally much lower than those of younger drivers, and as road complexity increases, older subjects adapt their speed, driving more slowly. In addition, older drivers experience more difficulties as road complexity increases. In a comparison of older and younger active drivers, Andrews et al. [4] found that older drivers relatively homogeneously adopted the compensatory behavior of longer headways, applying a speed/timing strategy to offset the effects of age-related cognitive slowing. This strategy was not dependent on crystallized ability or cognitive reserve scores. A subgroup of older drivers with higher cognitive ability – including an index of crystallized ability – showed a compensatory process, i.e., they anticipated traffic events more frequently than cognitively less able older participants. This age-related compensation requires greater effort, as implied by a correlation with the experience of increased workload on the part of older individuals [4]. A strategic mechanism was also observed in healthy older drivers who, in comparison with MCI age-matched drivers, demonstrated a greater number of foot hesitations on approach to stop-controlled and critical light change intersections [12].

3.2. Relationships between simulated tasks and cognitive domains

Mullen et al. [29] investigated whether performance on one driving task was predictive of performance on others. Their results showed a lack of correlation between performance in the three driving tasks, but correlations between the cognitive tests and the driving tasks. Accordingly, they suggested that driving tasks involve different driving abilities and cognitive constructs. They also stressed the importance of assessing seniors' performance on a range of driving tasks. Furthermore, Andrews et al. [4] noted that when considering associations between cognitive ability and driving performance, if younger and older drivers perform the driving task in different ways then we can predict that ability-performance associations will differ between groups. Cantin et al. [9] noted that a more systematic examination of the interactions between aging and driving complexity may provide insight into the events leading to driving errors made by older drivers.

Mullen et al. [29] stressed that every component of safe driving should be assessed in a standardized fashion that is consistent across research and evaluation programs; and that future research is needed regarding which components more effectively measure driving performance. In Rizzo et al. [35], the combined crashes were predicted by performance scores on cognitive tests sensitive to declines in aging and AD. In Vaux et al. [50], impairments on the detection collision tasks in the neurodegenerative disease group (AD and PD) appeared to reflect a combination of deficits in visual-sensory processing, motion processing, attention, visuo-spatial skills and executive functions, as implied by the association between poor collision sensitivity and poor performance on tests of cognition and visual attention. Lee et al. [23] observed that participants with PD tended to drive more slowly in response to road hazards and were unable to control speed and movement of the steering wheel, to apply the brakes smoothly, to address two tasks simultaneously, and to make quick decisions and judgments. These problems are related to decrements in motor skills, visuo-spatial processing, working memory and the executive function of planning. Uc et al. [47] found that multiple factors predict unsafe REC avoidance outcomes in drivers with mild AD, consistent with the multilevel cognitive, sensory, and motor demands of this task.

3.3. Design issues of simulation scenarios

Driving simulators vary in their characteristics, i.e. motion base vs. fixed base, interactivity, resolution and field of view, as well as in their validity against actual road driving [49]. Different simulators pose different technological limitations for researchers, making the replication of reality impossible. For example, poor quality of sensory information may result in fewer perceptual cues available to drivers, who rely on them to make tactical judgments. Drivers may have difficulty, e.g., in perceiving the speed of the oncoming vehicle or calibrating their speed. This is a serious limitation when the simulation scenarios are highly dependent on visual factors such as car-following, collision detection, speed regulation, braking or target identification [3, 43]. Staplin [43] showed how limitations in display resolution in low-cost simulators may affect the ability of drivers to discern momentary changes in distance-velocity of an oncoming vehicle during a passing maneuver on a two-lane highway. Researchers are advised that simulators with limited capabilities may not be able to address questions requiring a realistic presentation of the traffic environment, features and tasks [8]. In regard to driving assessment in subjects with medical disorders, Rizzo [34] noted that the particular choice of scenario depends on the specific clinical question being asked and suggested that “to develop appropriate simulator scenarios a hypothesis-based deductive approach to behavioral diagnoses (such as unsafe driving) is necessary”. Uc and Rizzo [48] pointed out that “scenario design should aim at discerning the effect of cognitive, visual and motor deficits on driving in AD, PD and stroke conditions and should take practical difficulties of implementation into consideration”. Furthermore, particularly when investigating the effects of age-related functional deficits, performance measures might be more efficient in revealing differences when the driving tasks challenge the capabilities in question and involve the individual factors that influence them. Issues to be considered in scenario design include driving context (driving goals), task complexity (situational factors) and the individual characteristics (e.g., knowledge, experience and expectations) of the population(s) under study [43]. When assessing measures of driving performance, scientists use the original research hypothesis to identify a broad class of events that provide sensitive measures, capable of validating the hypothesis. An overview of the issues involved in authoring scenarios for driving simulation applications is presented in Papelis et al. [30]. Important aspects of a scenario include specific attributes such as ambient traffic and simulation conditions, the starting position and route of the research participant, the way the participant is instructed to begin driving, and the series of events that will occur while the participant drives along the route. Scenario authoring involves coordination of the interactions among scripted objects, ambient traffic and the human driver. There are several challenges that are encountered during the development of scenarios. In Papelis et al. [30] and Manore et al. [24], relevant issues are discussed along with potential mitigating factors. For example, the development of the situational opportunity in order to reach a given outcome requires appropriate planning of scenarios, i.e. distribution of ambient traffic and careful placement of triggers to create the intended experience and estimation and correct prediction of (a range of) participant responses in a given situation. The authors suggested that pilot studies are necessary to assess the success of a given scenario and ensure that scenarios unfold as expected. The studies reviewed indicate that basic measures of driving in the simulator predict outcomes in high-risk situations in drivers with AD [47], and a disproportionate effect in performance at operational level when a concurrent task is present [44]. Operational and tactical levels are more relevant in simulator experimental settings. These levels influence each other with the operational level characterized by increased primacy when compared to tactical tasks [38].

For an experienced and familiar driver, under normal conditions, the control tasks are performed automatically and without cognitive control (skill-based task performance). Simulators allow (the limits of) performance to be measured in control (operational) tasks which involve time-pressured behaviors in a safe and controlled way (such as acceleration, lane position, braking and maneuvering to avoid crashes, and steering control) that may be challenged in emergency or unexpected situations. Tactical tasks take more time to complete and refer to more complex situations involving interactions with other road users, which relate to risk perception, risk taking, gap acceptance, choice of lane, choice of speed, space management, visual search behavior, visual attention and allocation [43]. Intersections, yielding right of way, driving with a secondary task, passing and overtaking, merging and lane changing are included in experiments designed to assess driving performance. The occurrence of safety errors in the execution of these tasks is more probable [43] and would allow the assessment of the specific mechanisms in question. Scenarios that have been used in persons with a variety of medical impairments include run-off-road on curves, car-following and rear-end collisions, intersection incursion avoidance, interaction with emergency vehicle/pedestrians, and merging with the potential for side impact collisions [34, 48].

Below are examples of various simulated traffic situations and driving tasks suggested by Arno et al. [5] for the evaluation of driving problems in cognitively impaired drivers. The associated problems that older or neurologically impaired drivers have when exposed to these situations are also summarized, along with the main cognitive skills underlying performance in these tasks. Visibility problems due to vision impairments and inadequate knowledge/understanding of traffic rules with implications on giving right of way can be assessed by exposure to various road signs. In the particular simulated situations, drivers can be assessed in interpretation of traffic signs, yielding right of way, situation awareness and inhibition of dominant responses. Way-finding tasks can be used to evaluate problems with way finding in unfamiliar areas. These problems are related to decreased abilities in planning and scheduling of subtasks, executive control and working memory. Drivers can also be assessed in interpretation of traffic signs, selective attention, visual scanning, situation awareness and interaction with other road users. Exposure to different types of intersections (signal-controlled, stop-controlled or uncontrolled) or complex driving environments – involving, in addition, interaction with vulnerable road users (e.g. pedestrians) – poses various demands on driving skills for older drivers or drivers with functional deficits due to medical conditions. When negotiating intersections, cognitively impaired drivers have problems in detecting other road users, in correctly estimating the actual speed/distance of other cars, and in quickly prioritizing and deciding on appropriate responses. The drivers are assessed in visual scanning, attention to and interaction with other road users, hazard recognition, estimating speed and judging movement of other drivers/users, situation awareness, mental flexibility, quick prioritization and inhibition of dominant responses. Simulated tasks involving merging with traffic (merging to highway and or starting up in traffic) are associated with problems in estimating the speeds and distance of other vehicles, making quick and appropriate decisions and merging with traffic travelling at a different speed. Drivers can be assessed in visual scanning, speed and distance judgments, interaction with other road users, and merging in and out of traffic flow [5].

3.4. Developing operational definitions and studies' comparison issues

In the reviewed studies, researchers have stressed the need to develop widely accepted (operational) definitions of safe and unsafe driving; to examine which components more effectively measure driving performance; to examine in a systematic way the interactions of driving complexity with age-related cognitive decline and the effects of brain injuries and neurological and neurodegenerative diseases on cognition (in order to get insight into the events leading to driving errors); to assess the components of safe driving in a standardized and consistent way; to develop and use standardized sets of scenarios and scenario components in performance assessment – including the assessment of individuals with specific impairments; and to determine sensitivity and specificity of simulation tests in impaired subjects (including specific neurologically impaired populations) [1, 6, 9, 15, 29, 32, 34]. Furthermore, comparability across simulation studies can be improved by assessing and reporting relevant individual characteristics that are associated with driving ability [6]. These are related to demographic and health factors which may impact driving ability, such as age, gender, race, education, functional status, general health, medical diagnoses, medication use and driving frequency [6, 34].

3.5. Limitations of the studies

In the reviewed papers, the authors generally recognize limitations in their studies that may affect the generalizability of their findings. The over-representation of male participants, discussed by Patomella et al. [33], is probably attributable to the male dominance of referrals. Andrews et al. [4] noted that their sample may not be representative of the population of interest since it consisted of volunteers (sampling bias) who were also healthy, fit and active individuals. They also recognized the difficulty in distinguishing age effects from cohort effects in cross-sectional studies. In their discussion on the limitations of their study, Devlin et al. [12] mentioned the small sample as well as the volunteer bias, the strict inclusion criteria and the use of the MMSE as a screening tool, which might not be adequate to screen out highly educated participants with age-related cognitive impairment in the control group. The use of MMSE was also discussed in Frittelli et al. [17], who compared the driving performance of drivers with MCI and AD patients with control subjects. They noted that although driving performance was significantly related to cognitive decline, the correlations with MMSE score of overall cognitive function were not significant. In Dijksterhuis et al. [15], the occurrence of crashes was attributed to bad lateral control stemming from both driving simulator characteristics and the steering skills of crash-involved participants. Moreover, what appeared to be dangerous driving over lane markings in a narrow lane on a two-lane roadway with oncoming traffic might be related to driving simulator characteristics. An issue of concern in studies on differences in driving performance is whether the differences in the dependent variables are a result of the independent variables under investigation, or other confounding variables. This is particularly relevant, for example, in comparisons between different age groups, where it must be determined whether any differences found are the result of age *per se* rather than variables confounded with age. Similarly, when investigating the effects of age-related disorders, an issue of concern is whether any differences found between groups are the result of the disorder *per se* rather than variables confounded with the disorder, that is, age or other individual age-related characteristics associated with driving competence such as differential driving experience (e.g., years since acquisition of driving license) and driving exposure (e.g., kilometers driven per week) that relate to acquired driving skills and their practice [46]. Difference in gender between groups of participants is also an issue of concern due to gender's relationship to driving habits and experience [19, 42].

Confounding can be treated in study design by randomization, by matching experimental groups in terms of confounding variables, or by appropriate screening [46]. Randomization allows equal distribution of all characteristics – both measured and unmeasured – between experimental groups, thereby diminishing the potential for confounding.

Yet the effectiveness of the technique is largely dependent on the sample size. Either because of small samples or by chance, imbalances are still possible. It is therefore advisable to measure confounding variables, and to account for their influences using analytical techniques [27]. Trick and Caird [46] noted that in research on older drivers, their increased within-group variability compared to younger drivers should be recognized. Furthermore, in studies with age-group comparisons, using within-subject designs with multi-session testing, the increased variability within the same individual over time can affect the reliability of the measurements. In such designs, larger samples can counteract the effects of increased variability across time in the performance of older adults [46]. Common threats to internal and external validity when using driving simulation, together with advice on how to address a range of issues in study design and implementation, can be found in Caird and Horrey [8].

The variation in cognitive abilities and in driving performance of drivers with impairments has been discussed in the reviewed studies. For example, Devlin et al. [12] noted that trends in the performance of older drivers (MCI versus controls) when approaching intersections were not statistically significant; they recognized limitations regarding the sample size, and that simulator characteristics limit the generalizability of the findings. Uc et al. [47] observed that drivers with mild dementia responded safely in the REC avoidance task, implying that some older drivers with neurological disorders (mild dementia) may continue to drive safely. Use of larger and randomized samples is also important for research aimed at validation of simulators [23, 40].

3.6. Simulator Adaptation Syndrome

A disadvantage of driving simulators, which has implications for simulator research, is simulator adaptation syndrome (SAS). SAS is characterized by autonomic symptoms including nausea and sweating. It is more common among older drivers and females and it can be reduced using appropriate techniques and through scenario design [34, 46]. Allen et al. [2], Park et al. [32] and Park et al. [31] have developed scenarios designed to minimize simulator sickness and to be sensitive to an aging driver; they observed that when the scenarios were presented in order of suspected symptom propensity, participants were more likely to drop out after completing or when attempting a scenario requiring a higher driving speed (45mph) within a visually complex background and intersection turning.

The issue of adaptation is a concern in relation to participant exposure and a threat to the validity of results. Drivers should be given the opportunity to practice and adapt prior to the experimental phase of the simulation application [45]. Screening is often used (simulator sickness questionnaire) to exclude participants who are susceptible to simulator sickness. However, it is still possible that people who pass the screening tests will develop SAS. It is therefore probable that the remaining sample will no longer be representative of the study population. Therefore, researchers are strongly advised to report the incidence of simulator adaptation syndrome and the characteristics of dropouts [46], as well as the characteristics of those who complete a simulator study.

3.7. Adaptation requirements for stable performance

An important precondition for validity of experiments carried out using a driving simulator is adaptation. Learning how to control a simulated vehicle imposes a mental workload on participants which can potentially distract them from performing the main task and bias the results of experiments.

Most researchers have a practice session before the main experiment to ensure participants have adapted [37]. Addressing the time required by older and younger experienced drivers to adapt to a fixed-base simulator and steer in a stable manner, McGehee et al. [26] noted that although drivers seem to adapt their steering control quite quickly, the adaptation period depends on a combination of simulator fidelity and the cognitive tasks involved. In their study, Ronen and Yair [36] ascertained that roads of different complexity and demand (curved, urban and straight) require different adaptation times. They used five driving performance measures: root mean square (RMS) of the lane position, RMS of the longitudinal speed, RMS of the steering wheel deviations, road excursions, and number of accidents. Participants needed more time to adapt to the relatively demanding curved road, where there was also a need for improvement in a greater number of performance measures than for urban and straight roads. Subjective assessment of adaptation (based on self-reports of participants in respect to when they felt fully adapted) correlated with the majority of the performance measures that had a relatively faster rate of improvement than other significant performance measures with a lower rate of improvement that showed the need for a longer period of time until total adaptation was achieved. Each road type had its distinctive performance measure according to its unique characteristics that showed the need for longer adaptation in comparison to other measures in the same road type: RMS of lane position on the curved road, RMS of longitudinal speed on the urban road and RMS of steering wheel on the straight road. The difference in demand and workload between road types was demonstrated by the physiological measures used in the study. The curved road showed some degree of improvement in all performance measures during the first part of the drive. Three out of five measures showed significant patterns of adaptation. For RMS of steering wheel deviations and number of deviations from the driving lane, significant patterns of adaptation were achieved after about 11.1 minutes (corresponding to the subjective assessment of adaptation after 11.3min).

According to the RMS of lane position, adaptation was achieved after 15.4 minutes. The relatively lower rate of improvement of this measure compared to the other two significant measures, was probably due to the need for fine adjustments to remain in lane while driving on a winding road. In most of the performance measures, deterioration was observed towards the end of the drive, implying a build-up of fatigue after a certain period, as was observed in changes in total heart rate variability.

Results from the urban road, which was less demanding than the curved road, according to the physiological reactions measured, showed improvement in four performance measures during the first part of the drive. There were significant patterns of adaptation in two of these measures, i.e., RMS of steering wheel deviations and RMS of longitudinal speed. The RMS of steering wheel deviations showed adaptation being achieved after 9.2 minutes (sensation of adaptation time was 9.1 min). The RMS of longitudinal speed showed adaptation after 14.8 minutes, probably due to maneuvering on narrow and busy roads. The least demanding scenario was the straight road, with two performance measures showing improvement during the drive. The statistically significant road edge excursions measure showed adaptation established after about 6.3 minutes of driving. Similarly, in McGehee et al. [26], adaptation to a two-way roadway was achieved after 6 min, while

Sahami and Sayed [37] found the mean adaptation time to be more than 7 min. In their study, Sahami and Sayed [37] made recommendations to improve the quality of design of practice scenarios and to minimize their impact on experimental scenarios. They asserted that participant adaptation to a driving simulator is task independent as long as the practice scenario provides the chance to repeatedly practice a scenario using pedals and steering.

In their recommendations, they suggested that a practice scenario should provide opportunities for participants to modify all their driving skills (distance judgment, pedal and steering control). A repetitive scenario will help the researcher track the learning under identical conditions and determine whether adaptation has occurred. However, the scenario should not cause drivers to focus on one specific aspect of driving. Improper practice design can introduce unwanted bias as drivers tend to focus on specific sub-skills that they have practiced more.

In a study of steering adaptation, McGehee et al. [26] assessed the time taken by older and younger experienced drivers to adapt to a fixed base simulator and to steer in a stable manner. The measures of steering adaptation were steering wheel reversals using a 6-degree steering reversal criterion, magnitude of steering inputs, lane position deviation and frequency components of the lane position and steering inputs. They also applied Fourier analysis to assess driver steering performance. The theoretical basis of the Fourier analysis is that any time-varying signal can be represented as the sum of an infinite series of sine waves, where each sine wave is defined by its frequency and amplitude. A signal that changes slowly over time will be composed of low-frequency sine waves with relatively large amplitudes and high-frequency sine waves with relatively low amplitudes. Fourier analysis identifies the relative contributions of the high- and low-frequency components of a signal, and allows the rapid oscillations that might occur when someone is weaving erratically to be distinguished from a slow gradual drift from side to side, and thus the differentiation between these types of variability. The study found that younger drivers had lower steering variability than older drivers and that both adapt at similar rates. The results showed that drivers adapted and steering variability decreased (steering was stabilized) for both age groups within 5min. Fourier analysis results of steering and lane position paralleled those of the more conventional measures. Fourier analysis also identified that different types of variability are differentially sensitive to adaptation and age. Although adaptation of steering control appears to take place relatively quickly, the actual length of time that is required for drivers to adapt will hinge on the fidelity of the simulator in combination with the cognitive tasks being tested. Therefore, because pre-adaptation steering behavior is unstable and does not reflect real-world behavior, adaptation must be assessed and collection of data should not begin until adaptation has taken place [26]. The authors noted that Fourier analysis may help identify more subtle differences within the driving population, such as those who are afflicted with Alzheimer's disease or have suffered a stroke.

3.8. Driving Simulator Validation

Research has shown that it is possible to use driving simulators to assess the abilities of drivers who are at increased risk due to a variety of medical conditions. Yet crash risk and safety under actual driving conditions depend upon factors (e.g., situational complexity) that cannot be recreated in a simulator, as well as on drivers' personal tendencies, awareness of risks, risk acceptance and self-assessment of (diminished) driving skills [8, 34]. Dijksterhuis et al. [15] recognized the usefulness of the simulator as a research tool when investigating the effects of independent measures in a relative sense. However, a challenge for driving simulator research is to determine whether driving performance as measured in the simulator is predictive of driving performance on the road, with the goal of predicting the magnitude (not just the direction) of changes in behind-the-wheel behavior, based on changes in behavior in the simulator. Simulator validation studies focus either on how closely the simulator dynamics and visuals replicate the vehicle that is being simulated, or on external validity, which is tested by simulator users [16, 39].

The latter refers to the generalizability or predictability of results, which is dependent on a specific simulator, a specific driving task and/or a specific population [39]. Simulator validation studies compare specific driving tasks between the simulator and an instrumented car on-the-road. In her review of driving simulator validation studies, the reasons presented by Shechtman [39] for the controversy in the literature regarding driving simulator validity (i.e., whether or not driving simulators are valid and reliable predictors of on road driving performance) included the differences between studies in types and brands of driving simulators, driving tasks, subject population, research design and/or terminology. The author suggested ways to relate existing simulator validation terminology from the engineering literature to measurement validity vocabulary from health sciences. In addition, types of measurement validity were matched to examples of existing simulator validation studies. The study provided a list of validation studies which were summarized on the basis of the (operational or tactical) tasks involved, the approach followed for validation, the population and the main conclusions [39]. The most commonly studied driving tasks in validation studies include lateral control, speed regulation, braking, driving through a tunnel, response to road markings such as rumple strips and distraction or crash avoidance scenarios. Subject populations that have been studied in driving simulators include older drivers, and people with conditions such as attention deficit hyperactivity disorder, dementia, stroke, traumatic brain injury, multiple sclerosis, spinal cord injury, and Parkinson's disease [39]. Shechtman et al. [39] tested the driver response validity of a high fidelity simulator (STISM simulator) by comparing the number and type of driving errors committed by drivers performing a left and a right turn during a driving assessment both in the simulator and on the road. There were 20 younger (25-45) and 19 older (65-85) participants. The errors identified comprised speed, lane maintenance, signaling, visual scanning, adjustment to stimuli and vehicle positioning. According to the results, relative validity was obtained for all driving errors, implying that the same trend of an effect exists between the simulator and real life, whereas absolute validity was obtained for lane maintenance and adjustment to stimuli errors, implying that the same scale of effect exists between real life and the simulator. The authors discussed the limitations of their study (e.g., the small size of the sample) but they noted that they examined a wider concept of driver response validity by studying a complex driving maneuver with the use of a multidimensional task (i.e., assessing errors when negotiating turns at intersections) and incorporating the gold standard method for evaluating driving performance into the simulator validation study [39].

4. Discussion and conclusions

The present paper offers a focused review of studies investigating driving performance as assessed on simulators in relation to cognitive impairments, particularly those which are age-related or caused by neurodegenerative disorders, including mild cognitive impairment (MCI), Alzheimer's disease, Parkinson's disease and stroke. This focused review provides a critical examination of issues that may limit the generalizability of research results and which should be considered in the design of simulator experiments. Several studies have recognized the potential usefulness of simulators in the identification of different types of safety errors and how they are associated with impairments in certain cognitive domains. This applies, in particular, when driving performance assessment in a simulator is combined with neuropsychological testing. Driving simulators allow performance to be assessed and driver errors of different risk severity to be observed in a range of operational and tactical tasks in populations of various demographic characteristics and driving impairments due to various diseases or conditions.

A major challenge to researchers when designing an experiment is to choose effective and well defined measures of performance as well as scenarios that would allow the manifestation of driving behavior problems and the identification of the specific mechanisms of impairment that underlie them. Scenario design and related driving tasks along with dependent and independent measures of driving performance are based on specific research question(s), which in turn should be transformed into explicit test hypotheses; however the limitations of driving simulators should be taken into consideration. Manipulation of driving task complexity and use of concurrent tasks allow the investigation of the abilities of individuals (including cognitively impaired individuals) to appropriately prioritize particular aspects of performance and especially to examine whether basic driving abilities are challenged in complex tasks or in concurrent task conditions. By increasing task complexity, it might be possible to assess the effectiveness of the compensatory potential still available to drivers. Appropriate experiment design (research question, dependent and independent variables, scenarios) combined with cognitive tests involving relevant cognitive constructs might allow researchers to identify the occurrence and the effectiveness of compensatory behavior. It should be stressed that demographic and health factors having an impact on driving ability as well as confounding variables that occur in driving should be measured and accounted for in comparisons between different age-groups and in investigations of the effects of age-related disorders. Various techniques can be used to treat confounding variables; however, their effectiveness largely depends on the sample size.

Challenges that researchers commonly face in assessing performance with the use of driving simulators relate to participant adaptation and scenario validation. When conducting driving simulation experiments, it is essential that simulator adaptation syndrome is taken into account if they are to be valid. The studies reviewed suggest that the adaptation period required for stable performance by participants is likely to depend on the combination of simulator fidelity and the cognitive tasks involved; roads with different characteristics (complexity/demand) require different adaptation time. The issue of driver response validity of simulators, particularly in assessing individuals with cognitive impairments which are either age-related or related to neurodegenerative and other medical impairments, is significant. When they are used in populations with medical disorders, either as a complement to road testing (for fitness to drive decisions) or as a tool to understand mechanisms of driving impairment – in both cases accompanied by tests evaluating functional abilities important to safe driving – it is imperative to validate the results before generalizing beyond the laboratory or clinic.

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