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A Review of Driving Performance Assessment in Simulators with focus to cognitive impairments related to age or caused by neurodegenerative disorders.

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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 present paper is a review of studies on driving performance assessment with the use of driving simulators, aiming at: (i) identifying and summarizing 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; (ii) identifying issues that should be considered in the design of simulator experiments. Summaries of the studies are presented, which include 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 (e.g. behavioral data, crashes), and the main findings, as well as further research suggestions. Moreover, consideration is given to 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 generalisability of research results and should be considered in the design of simulator experiments.

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

INTRODUCTION

Background

The ability to drive can be affected by various motor, visual, cognitive and perceptual deficits which are either age-related or caused by neurologic disorders such as stroke, Parkinson's disease, Alzheimer's disease, multiple sclerosis and traumatic brain injury (Akinwuntan, 2012). Neurodegenerative conditions such as Alzheimer's disease, Parkinson's disease and stroke impair perception cognition and motor function, leading to reduced driver fitness and increased crash risk. On their own, age and medical diagnosis are insufficiently reliable predictors of the safety of drivers and crash incidence, while effective rehabilitation does not exist for neurologically impaired drivers (Uc and Rizzo, 2011). Driving performance assessment (Ball and Ackerman, 2011) is defined as "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 (2011) note 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 driving evaluations. However, their effectiveness and efficiency is under investigation (Ball and Ackerman, 2011; Mullen et al., 2008). Driving simulators are considered a promising tool for reliable and safe evaluation of driving performance, especially in people with loss of driving skills due to physical or neurological conditions in America and Europe (Singh et al., 2011; Hakamies and Peters, 2000).

The use of driving simulators in the context of driving performance assessment is associated with 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; even low-cost, low fidelity simulators have the potential to address interesting research questions (Uc and Rizzo, 2011; Ball and Ackerman, 2011; Akinwuntan et al., 2012; Caird and Horrey, 2011). However, Caird and Horrey (2011) also note 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 "driving simulators may create artificial situations which are not reminiscent of real-world situations".

Studies have demonstrated that the use of driving simulators as a 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 (Ball and Ackerman, 2011). Uc and Rizzo (2011) points 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 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 (Akinwuntan et al., 2012). Akinwuntan et al. (2012) note that there is no evidence that driving simulators provide test-retest reliability and stress the need for further research in this area.

Driving simulators vary in their characteristics, that is, motion base vs. fixed base, interactivity, resolution and field of view, as well as in their validity against actual road driving (Uc and Rizzo 2008). Different simulators pose different limitations to researchers that should be considered when they design their experiments. For example, simulator limitations in presenting visual information can have serious effect on driving performance. 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 (Staplin, 2010). Researchers are advised that questions setting specific requirements regarding traffic environment, features and tasks may not be able to be addressed by a simulator with limited capabilities (Caird and Horrey 2011).

In order to make comparisons between research studies conducted on different simulators or explain conflicting findings, it is important that the scenarios are specified in sufficient detail (Rizzo 2011). Furthermore, comparability across simulation studies can be improved by assessing and reporting relevant individual characteristics that are associated with driving ability (Ball and Ackerman 2011). These are related to demographic and health factors which may impact driving ability, such as age, gender, race, education, abilities, general health, medical diagnoses, medication use and driving frequency (Ball and Ackerman, 2011; Rizzo, 2011).

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 (Rizzo, 2011; Trick and Caird, 2011). Allen

et al. (2007), Park et al. (2007) and Park et al. (2006) have developed scenarios which were designed to minimize simulator sickness and to be sensitive to 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 (Stoner et al. 2011). 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 (Trick and Caird 2011).

Objectives

The present paper is a review of studies on driving performance assessment with the use of driving simulators, aiming at: (i) identifying and summarizing 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; (ii) identifying issues that should be considered in the design of simulator experiments with potential impact on the generalizability of the research findings. To this end, emphasis is put on study findings, experiment design considerations and limitations of studies, as discussed by the authors when interpreting the findings of their studies.

Approach

The review, although not exhaustive, includes studies investigating driving performance as assessed on simulators of drivers with cognitive impairments which are age related or caused by neurodegenerative disorders including mild cognitive impairment (MCI), Alzheimer's disease, Parkinson's disease and stroke. Summaries of the studies are presented, which include 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 (e.g. behavioral data, crashes), and the main findings, as well as further research suggestions. Moreover, consideration is given to 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 generalizability of research results and should be considered in the design of simulator experiments.

RESEARCH RESULTS

Driving performance of people with Parkinson disease and stroke

The study of Stolwyck et al. (2006) examined the impact of a concurrent task on driving performance among18 current drivers with PD in the mild to moderate stages (mean age 67.62) and 18 matched controls (mean age 67.13) using a fixed base simulator. They found that cognitive difficulties associated with PD compromise driving performance even in the mild to moderate stages of the disease. The presence of a concurrent task was manipulated between conditions. 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 indicate that both groups of 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 (auditory task requiring driver's response) on most driving measures: when the concurrent task was present both groups applied tactical adaptations to their driving behavior, resulting in a more conservative driving. The concurrent task had a disproportionate effect in performance at operational level (PD started deceleration later, closer to the traffic signal. People with PD tended to trade concurrent task performance to maintain driving performance. In people with PD measures of cognitive tests were associated with tactical and operational level of performance.

Vaux et al (2010) 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. The dependent variables were the collision detection sensitivity (indicating the ability to detect collision) and independent variables were the number of obstacles and time to contact (TTC). Group was a between subjects variable and number of objects (two levels: one and six objects) and TTC (1second and 3seconds) were the repeated measures variables. When a single object is present in the driving scene both groups performed with some degree of sensitivity at each of the TTC conditions. For the 3-second TTC/6 objects condition, the results indicate that the comparison group has some degree of sensitivity whereas the neurodegenerative group has 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 drivers with AD and PD required additional time to detect impending collisions which likely impairs their ability to avoid collision events measured by the current 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. Authors suggest that more data is needed to disclose relationships between performance on the collision detection task and real-world evidence of driver behavior.

Lee and al.,(2007) explored the validity of using driving simulator technology 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. The criteria for assessing the simulator and on-road tests were combined by principal component analysis, while an overall simulated driving index and a road assessment index were developed for the PD group and the control group. The indices were significantly different in the experimental 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 in both the tactical and the

operational level. Participants with PD tended to drive slower 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. These problems are related to decrements in motor skills, visuo-spatial processing, working memory and executive function planning. They also failed to perform well at either the tactical or the operational level. Forty percent of the variability in the Road assessment Index of drivers with PD 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. Authors conclude that according to the findings of the study driving simulators can provide valuable information on PD driver's 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 suggest 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 suggest that driving simulators can be developed into a cost-effective screening tool.
Patomella et al. (2006) conducted across-sectional observational study investigating aspects of validity and stability of Performance Analysis of Driving Ability (P-Drive) for people with stroke using a technically-advanced 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 according to Michon's levels. The findings indicate that P-Drive is an assessment tool with properties of internal scale validity and person response validity, which also contains aspects of reliability in relation to precision of the estimates and separation. Items requiring great attention and rapid information processing were the most challenging and those concerning maneuvering were the least challenging. In addition, items requiring tactical decisions were more challenging than those for which only operational decisions were required. The authors suggest that the over-representation of male participants is probably attributable to the male dominance of referrals.

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

Rizzo et al. (2001) 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 AD group and control groups. 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 sensitive to declines in aging and AD. 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 (Rizzo et al., 2001).

Devlin et al. (2012) examined how older drivers with and without Mild Cognitive Impairment (MCI) perform when approaching intersections, testing fourteen male and female older drivers with MCI and fourteen age-matched healthy drivers using a portable driving simulator with an established relative validity for some operations. Specific performance measures include 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 intersection 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, include the representativeness of the sample, volunteer bias, the strict inclusion criteria, the small sample and the use of the MMSE as a screening tool, which might not detect highly-educated participants with age-related cognitive impairment in the control group (Devlin et al., 2012). These limitations would affect the possibility of drawing general conclusions from the results.

A study by Frittelli et al. (2009) 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. 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 bonnet 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 (Frittelli et al., 2009). The conclusion of the authors is that driving simulator tests are a valid and reliable screening tool for determining the competence of drivers with early AD and they suggest further research on whether the observed impairment translates into increased accident risk.

Uc et al. (2006) 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. 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, 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 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.

Age comparisons

Using a fixed-base simulator with a 40-degree horizontal field of view, Cantin et al. (2009) examined if the mental workload of young and older active drivers varies with the difficulty of the driving context. Workload was measured using the probe reaction time (RT) technique. 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. 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. At more complex intersections there was a further increase, 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. Older drivers were observed to use compensatory driving strategies. Accidents or incidents did not become more frequent for elderly drivers and there was one serious error at an intersection. The authors suggest examining whether this failure state is observable in the case of at-risk drivers, such as those who are older than 85 years of age or those suffering from mild cognitive impairment.

In discussing the limitations of their study the Authors note the participation of volunteers who, in addition, were active and cognitively fit and nearly ideal driving conditions. Moreover, the increased number of braking events among the older individuals compared to younger 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. The results suggest that driving scenario for simulator studies can be manipulated in such a way to mimic the mental workload imposed by similar on-road driving contexts. A more systematic examination of the interactions between aging and driving complexity may provide insight in to the events leading to driving errors made by older drivers.

The study of Park et al. (2007), Allen et al., (2007), compares the driving simulation performance of 51 younger drivers (22 male, 29 female) aged 21-50, with 67 older drivers (37 male, 30 female) aged 70-90, with a minimum of 5 years driving experience. A desktop driving simulator with wide field of view driving simulator was used. They 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 used 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 indicate that older drivers were 4 times more likely to hit pedestrians; they also had more instances of hard braking and their average was lower and 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 note 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. (2007) 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 that simulator measures provide more age discrimination relative to the variability of the measures. The authors suggest that it might be possible to condense these scenarios, which lasted about an hour over four sessions, into a single 30-minute long scenario. 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. (2012) examined compensatory processes for age-related declines in cognitive ability in 22 younger (26-40years, nine men) and 22 older drivers (60+, 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 (Hakamies et al. 2005). 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 TXL), while the second consisted of a driving experiment conducted on a low-fidelity simulator. Participants performed a car-following task in one version that required no braking by the lead car and in another that required 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 show that older drivers adopted a compensatory behavior in terms of longer headways (by means of altered speed/timing strategy) to off-set the effects of age-related cognitive slowing. The older group was relatively homogeneous in adopting this strategy which was not dependent with scores of crystallized abilities or cognitive reserve. In the older group a subgroup of cognitively more able participants show a compensatory process, i.e., in that they anticipated traffic events more frequently than cognitively less able older participants. Authors refer to selective compensatory process which is applied a older participants with higher cognitive ability including an index of crystallized ability. This age-related compensation however is correlated with increased workload experienced by older individuals. Prediction of age-related compensatory processes may require an index of pre-decline intelligence, i.e. crystallized ability. Authors suggest the use of cognitive ability tests as a part of screening process for older drivers. The authors note a sampling bias related to volunteers who may not be representative of the population of interest. Regarding representativeness of older populations, the sample consisted of individuals who were healthy, fit and active. They also recognize that when examining the effects of aging, cross-sectional studies make it difficult to distinguish age from cohort effects.

Mullen et al. (2008) 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, SD=6.8 years), all holding valid licenses, volunteered to participate in the study. Cognitive tests were conducted prior to the experimental drive, a 15-minute orientation drive was completed by subjects in order for them to acquire familiarity with the driving simulator and controls. A desktop simulator with a wide field of view was used. 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 and expected to involve different areas of cognition which had been shown to be sensitive to age-related declines in performance (3.0 mile rural highway course; 0.5 mile parking lot course and 1 mile construction zone course. The lack of correlation in the performance of the three driving tasks and the correlations found between the cognitive tests and the driving tasks suggest that the driving tasks involve different driving abilities and cognitive constructs. Interestingly, the authors note that for the scenarios in question, incidence of errors was not an effective measure of driving performance. This suggests that further research is required to determine which components more effectively measure driving performance. In addition, 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, Benedetto (2008) compared speeds and Pathologic Discomfort indicator for two age groups (younger and older drivers) in two road stretches of different complexity. Pathologic Discomfort indicator is the cumulated absolute value of the difference between the absolute values of theoretical and real lateral acceleration; when the value of Pathologic Discomfort increases the accident rate increases with a parabolic trend. The two hypotheses tested were (1) Pathologic Discomfort has the same trend along the roadway for older and younger people; and (2) Pathologic Discomfort for older people is greater 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 average age 24.4 (s.d. 1.9) and the members of the older group were over 65 with average age 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 and the day after 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, Pathologic Discomfort at each kilometer of the two stretches were computed and compared for the two age groups. Results indicate that if the geometry of a roadway is more complex and tortuous, the speeds of older subjects are generally much lower than the speeds of younger subjects. The dispersion of speeds is much greater for older than for younger drivers. The two hypotheses tested were verified. Specifically, Pathologic Discomfort has the same trend along the roadway for older and younger people and that Pathologic Discomfort for older people is greater. This means 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 rather than for younger people.

METHODOLOGICAL ISSUES

Task demand in a simulated environment

Manipulation of task demands in a simulated environment allows the identification of performance inadequacies. Cantin et al. (2009) suggest 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; when compared to younger drivers, older drivers show performance decrements in concurrent tasks for more complex driving contexts. When assessing cognitively impaired drivers, the presentation of driving conditions of increasing complexity posing them sufficient challenge in a simulator allows performance decrements to be studied in different cognitive domains (Rizzo et al., 2001; Vaux et al., 2009; Cantin et al., 2009; Dijksterhuis et al., 20011). Stolwyck et al. (2006) found that people with PD tended to trade concurrent task performance to maintain driving performance. Cantin et al. (2009) suggest that a challenge in research is to identify the mechanisms that relate to the tasks under investigation and understand how they evolve with driving complexity.

Moreover, it would be interesting to examine the ability of individuals (with increased mental workload or cognitively impaired) to properly allocate resources or prioritize particular aspects of performance (Cantin et al. 2009). When tested in collision avoidance situations, drivers with AD showed poorer vehicle control of the vehicle 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 (Uc et al. 2006). Stolwyck et al. (2006) found that the concurrent task had a disproportionate effect on performance at operational level and they note that such operational level behavior being time-pressured may compete with the concurrent task for controlled processing resources. The study findings indicate that both PD and 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.

According to the findings of a study on older drivers in relation to road geometry (Benedetto 2008), the speeds of older drivers are generally much lower than the speeds of the younger drivers and as the road complexity increases older subjects drive at slower speeds; in addition, older drivers experience more difficulties as road complexity increases. The occurrence of compensatory behavior was also identified in a study of Cantin et al. (2009), who note that although older drivers exhibited a higher mental workload than younger drivers, their driving performance was not significantly different from that of younger drivers. In a comparison of older and younger age groups of active drivers, Andrews et al. (2012) found that older drivers

relatively homogeneously adopted a compensatory behavior in terms of longer headways, applying speed/timing strategy to off-set the effects of age-related cognitive slowing, and that this strategy was not dependent with scores of crystallized abilities or cognitive reserve.
A subgroup of older drivers with higher cognitive ability – including an index of crystallized ability – showed a compensatory process, i.e., in that they anticipated traffic events more frequently than cognitively less able older participants. This age-related compensation requires investment of greater effort as implied by its correlation with increased workload experienced by older individuals (Andrews et al. 2009). 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 (Devlin et al. 2012).

Concerns of the studies

In the reviewed papers, the authors generally recognize limitations in their studies which potentially affect the generalizability of their findings. The over-representation of male participants, which is discussed by Patomella et al. (2006), is probably attributable to the male dominance of referrals. Andrews et al. (2012) note 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 recognize the difficulty in distinguishing age effects from cohort effects when examining the effects of aging in cross-sectional studies.
In their discussion on the limitations of their study, Devlin et al. (2012) mention 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 is also discussed in Frittelli et al. (2009), who compared the driving performance of drivers with MCI and AD patients with control subjects. They note 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. (2011), the occurrence of crashes is attributed to bad lateral control stemming from both driving simulator characteristics and the steering skills of crash-involved participants. Moreover, 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 e.g., in comparisons between different age-groups where conclusions should be drawn on whether any differences found are the result of age per se and not of variables confounded with age; and also when investigating the effects of age-related disorders. In respect of study design techniques, confounding can be treated by randomization as well as by matching experimental groups in terms of confounding variables or adequate screening (Trick and Caird, 2011). 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 probable. It is therefore advisable to measure confounding variables and their influences be accounted using analytical techniques (McGwin 2011).

Trick and Caird (2011) note that in research on older drivers, the increased variability among participants of the same age compared to younger drivers should be recognized. Furthermore, in studies of age-group comparisons, within-subject manipulations using complex designs with multi-session testing, the increased variability within the same individual over time is an issue of concern regarding the reliability of the measurements. In such designs, larger samples allow the effects of increased variability across time in the performance of older adults to be counteracted (Trick and Caird 2011). Common threats to internal and external validity when using driving simulation, together with advice on how to address relevant issues in the study design and implementation, can be found in Caird and Horrey (2011).

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. note that the trends found regarding the performance of older drivers (MCI and controls) when approaching intersections were not statistically significant and recognize limitations regarding the sample size and characteristics limiting the generalizability of the findings. Uc et al. (2006) note 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. Researchers suggested validation of the simulators with randomized samples (Lee et al. 2007) and larger samples (Shechtman et al. 2009).

Driving scenarios: relationships between tasks and cognitive domains

Mullen et al. (2008) investigated whether performance on one driving task was predictive of performance on other driving tasks. Based on the study results, which show a lack of correlation in performance between the three driving tasks and correlations between the cognitive tests and the driving tasks, they suggest that driving tasks involve different driving abilities and cognitive constructs. They also stress the importance of assessing performance by seniors on a range of driving tasks. Furthermore, Andrews et al. (2012) note 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. 2009 note 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. (2008) stress that in the driving assessment, each and 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 into which components more effectively measure driving performance. In Rizzo et al. (2001), the combined crashes were predicted by performance scores on cognitive tests sensitive to declines in aging and AD. In Vaux et al. (2010), impairments on the detection collision tasks in the neurodegenerative disease group (AD and PD) 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. Lee et al. (2007) 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 executive function planning. Uc et al. (2006) found that multiple factors predict unsafe outcomes in the REC avoidance task in drivers with mild AD, consistent with the multilevel cognitive sensory and motor demands of this task.

Adaptation syndrome and practice scenarios

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 (Sahami and Sayed 2013). Assessing 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. (2004) note that although drivers seem to adapt their steering control quite quickly, the adaptation period is likely to depend on a combination of simulator fidelity and the cognitive tasks involved. In their study, Ronen and Yair (2013) ascertained that roads of different complexity and demand (curved, urban and straight) require different adaptation times.

The relatively demanding curved road required longer adaptation times and there was a need for improvement in more performance measures than for urban and straight roads. Subjective estimations corresponded very closely with most performance measures in all road types, although underestimation was found for the more sensitive measures that required longer time for adaptation in each road type. In particular, for the least demanding the straight-road scenario adaptation (according to the statistically significant road edge excursions measure) was established after driving about 6.3 min. Similarly, in McGehee et al. (2004) adaptation to a two-way road way was achieved after 6 min, while Sahami and Sayed (2010) found the mean adaptation time to be more than 7min. According to the results from the urban road (Ronen and Yair 2013), the RMS of steering wheel deviations showed adaptation after 9.2 min., whereas the RMS of longitudinal speed showed adaption after 14.8 min, probably due to maneuvering on narrow and busy roads. The curved road was the most demanding road, requiring more negotiation of the wheel and pedals, since it is a control task.

RMS of steering wheel deviations and the number of deviations from the driving lane showed significant patterns of adaptation, which was achieved after about 11.1 min., corresponding to the subjective assessment of adaptation. RMS of lane position was the other significant performance measure for the curved road type, adaptation being achieved after 14.4 min. In their study, Sahami and Sayed (2013) provide recommendations to improve the quality of design for the practice scenario and to minimize its impact on the experiment scenario, suggesting that participant adaptation to a driving simulator is task independent as long as the practice scenario provides them with the chance to repeatedly practice a scenario using pedals and steering. In their recommendations, they suggest that a practice scenario should provide chances for them 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 make sure whether adaptation has occurred. Furthermore, the scenario should not be defined for 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. Fourier analysis (McGehee et al. 2004) showed that different types of variability are differentially sensitive to adaptation and age, with the higher frequency components discriminating between older and younger drivers relative to the low frequency components. The authors note that Fourier analysis may help identify more subtle differences in driving populations, such as those who are afflicted with Alzheimer's disease or have suffered stroke.

CONCLUSIONS

The present paper is a 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. The review aims at summarizing research findings and identifying issues that are considered to be important as probably affecting the generalizability of the results.

In the studies reviewed, emphasis was put on simulator test design considerations, which are outlined herein. Driving simulators are used to identify relationships between driving impairments and performance in cognitive tests. They also provide the possibility of safe and controlled observation of driver errors of different risk severity in a range of operational and tactical driving tasks in populations of various demographic characteristics and driving impairments due to various diseases or conditions. 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.

Scenario design and related driving tasks along with dependent and independent measures are based on the specific research question(s) which in turn should be transformed into explicit test hypotheses. Manipulation of driving task complexity and use of concurrent tasks allow the identification of different types of safety errors and how they relate with impairments in certain cognitive domains. Challenges that researchers commonly have in performance assessment with the use of driving simulators relate to limitations of the simulators, scenario validation as well as participant adaptation. A discussion on these issues follows.

The potential usefulness of the simulator in providing valuable information on driving performance has been shown in several studies. This is evident particularly when driving performance assessment on simulators are combined with neuro-psychologic testing. The reviewed studies provide evidence that driving performance impairments measured in the simulators relate to decrements in cognitive tests (Rizzo et al., 2001; Uc et al., 2006; Stolwyck et al., 2006; Mullen et al., 2008; Park et al., 2007; Frittelli et al. 2009; Devlin et al., 2012; Patomella et al., 2006; Vaux et al. 2010). The studies reviewed 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; and to determine sensitivity and specificity of simulation tests in impaired subjects (including specific neurologically impaired populations) (Akinwatan et al., 2012; Dijksterhuis et al., 2011; Ball and Ackerman, 2011; Rizzo, 2011; Cantin et al., 2009; Mullen et al., 2008; Park et al., 2007).

The need to develop and use standardized sets of scenarios and scenario components in performance assessment – including the assessment of individuals with specific impairments – is stressed among researchers. In regard to driving assessment in subjects with medical disorders, Rizzo (2011) notes that the particular scenario to use depends on the specific clinical question being asked and suggests that "to develop appropriate simulator scenarios a hypothesis-based deductive approach to behavioral diagnoses (such as unsafe driving) is necessary". Uc and Rizzo (2011) point out that "scenario design should aim at discerning the effect of cognitive, visual and motor deficits on driving in these conditions and should take practical difficulties of implementation into consideration". In age-group comparisons, in order to reveal age differences, it is important that researchers investigate performance in tasks which are neither too easy nor too difficult (Trick and Caird 2011).

The studies reviewed indicate that basic measures of driving in the simulator predict outcomes in high-risk situations in drivers with AD (Uc et al., 2000), and disproportionate effect in performance at operational level when a concurrent task was present (Stolwyck et al 2006). 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 (Schaap et al. 2008). For an experienced and familiar driver, under normal conditions, the control tasks are performed automatically and without cognitive control (skill-based task performance). The simulators provide the possibility to measure (the limits of) performance 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, ad steering control) that may be challenged in emergency or unexpected situations.

The studies reviewed have shown the need to investigate the abilities of individuals (including cognitively impaired individuals) to appropriately prioritize particular aspects of performance and especially whether basic driving abilities are challenged in complex tasks or in concurrent tasks conditions. Tactical tasks take more time to complete and refer to more complex situations involving interactions with other road users and relate to risk perception, risk taking, gap acceptance, choice of lane, choice of speed, space management, visual search behavior, visual attention and allocation (Staplin et al. 2010). 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. In tactical tasks, the occurrence of safety errors in the execution of these tasks are more probable (Staplin 2010) 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 (Uc and Rizzo, 2011; Rizzo, 2011).

Compensation is highly relevant to older drivers (Hakamies, 2004; Hakamies and Peters, 2000). Older drivers largely have extensive driving experience. As experienced drivers they 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 (Knoblaugh et al. 1997) and available time. Compensation might occur automatically as a reaction to cognitive overload (De Raedt et al. 2000). When task demand begins to exceed capability, compensation may be related to performance degradation or 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 (Fuller 2005).

The occurrence and the safety potential of tactical adaptations have been observed in reviewed studies (Andrews et al., 2012; Cantin et al. 2009; Benedetto, 2008; Stolwyck et al., 2006). By increasing task complexity, the effectiveness of the compensatory potential still available to the drivers might be possible to be assessed. It seems that 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.

When assessing cognitively impaired drivers, presentation of driving conditions of increasing complexity posing them sufficient challenge in a simulator allows the identification of performance inadequacies related to impairments in different cognitive domains and the examination of their interactions (Rizzo et al., 2001; Benedetto, 2008; Vaux et al., 2009; Cantin et al., 2009; Dijksterhuis et al., 2011). Such experimental designs are related to within-subject design which tends to be more powerful since each driver serves as their own control (Dawson et al., 2011).

Dijksterhuis et al. (2011) recognize the usefulness of the simulator as a research tool when investigating the effects of independent measures in a relative sense. However, it needs to be determined whether driving performance as measured in the simulator is predictive of driving performance on the road. Simulator validity is dependent on the particular simulator and the specific driving task (Shechtman et al., 2009). 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 (Shechtman et al., 2009; Espie et al., 2005). 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 (Shechtman et al., 2009).

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 considered of significant importance. Shechtman et al. (2009) provided preliminary evidence regarding the generalizability of the results of assessing driving errors when negotiating turns at intersections in their simulator to the road under the same testing conditions.

When conducting driving simulation experiments it is essential that adaptation syndrome is taken into account if they are to be valid. Studies reviewed suggest that the adaptation period is likely to depend on the combination of simulator fidelity and the cognitive tasks involved; roads with different characteristics (complexity/demand) require different adaption time; participant’s adaptation to a driving simulator is task independent as long as the practice scenario provides them with the chance to repeatedly practice a scenario using pedals and steering.

When driving simulators are used in driving performance assessment their limitations should be taken into consideration. Moreover, 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. When they are used either as a complement to road testing (enabling assessment in emergency situations), or as a tool to understand mechanisms of driving impairment (in combination with tests evaluating abilities important to safe driving) in populations with medical disorders, it is imperative to validate the results before conclusions regarding their generalizability are made.

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