Road safety behavior of drivers with neurological diseases affecting cognitive functions: an interdisciplinary Structural Equation Model analysis approach

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Abstract

Cognitive functions which decline over age are of critical importance regarding driving performance. Neurological diseases affecting a person's brain functioning, may significantly deteriorate the person's driving competence, especially when unexpected incidents occur. What appears to be missing from the previous research, is the evaluation of driving behavior by using multiple driving indexes in a combined integrated manner instead of using single measures that focus on a sub-area of driving performance. The objective of the present study is to fill in this gap, mathematically, by latent analysis techniques, analyzing the traffic and safety behavior of drivers with neurological diseases affecting cognitive functions. More specifically, the impact of brain pathologies on reaction time, accident probability, and driving performance is under investigation. The neurological diseases affecting cognitive functions concern Alzheimer's disease (AD), Parkinson's disease (PD), and Mild Cognitive Impairment (MCI). A large-scale driving simulator experiment was carried out, comprising a medical/neurological and neuropsychological assessment of 225 active drivers, and a set of driving tasks for different scenarios. The statistical analysis methodology developed and implemented was based on Principal Component Analysis and Structural Equation Models (SEMs). SEM results indicated that the impact of neurological diseases affecting cognitive functions is significantly detrimental on the latent variables "driving performance" and on the observed variables "reaction time" and "accident probability". The AD group had the worse driving behavior profile among the examined groups with neurological diseases affecting cognitive functions.

Keywords – neurological diseases, cognitive functions, SEM analysis, driving simulator, driving performance, driving behavior

1. Introduction

Road accidents constitute a major social problem in modern societies, accounting for more than one million road accidents per year in EU-28 which consequences 1,4 million injured and 26.000 fatalities (WHO, 2015 [1]). Despite the fact that road traffic casualties presented a constantly decreasing trend during the last years, the number of fatalities in road accidents in several countries and in Greece in particular is still unacceptable and illustrates the need for even greater efforts with respect to better driving performance and increased road safety (OECD, 2013 [2]).

Cognitive functions which decline over age are of critical importance regarding driving performance. Diseases affecting a person's brain functioning, may significantly impair the person's driving performance, especially when unexpected incidents occur. A number of prevalent neurological diseases may be involved, ranging from very mild to severe states that include Parkinson's or Alzheimer's disease, Cerebrovascular disease etc. (Wood et al., 2005 [3]; Cordell et al., 2008 [4]; Cubo et al., 2009 [5]; Frittelli et al., 2009 [6]).

Mild Cognitive Impairment (MCI), which is considered to be the predementia stage of various dementing diseases of the brain, is a common neurological disorder that may be observed in about

16% of individuals over 64 years old in the general population (Ravaglia et al., 2008 [7]), a percentage that increases further if individuals with mild dementia are also included. Recent studies suggest that MCI is associated with impaired driving performance to some extent (Frittelli et al., 2009 [6]), as it is characterized by attentional and functional deficits, which are expected to affect the driver's ability to handle unexpected incidents. Moreover, self-reported road accident involvement was correlated with future diagnosis of dementia (Lafont et al., 2008 [8]).

Alzheimer's dementia (AD) is increasingly being recognized as one of the most important medical and social problems in older people in industrialized and non-industrialized nations (Yiannopoulou & Papageorgiou, 2013 [9]) and accounts for 60% to 70% of cases of dementia (Burns, 2009; WHO, 2015). It is a chronic neurodegenerative disease that usually starts slowly and gets worse over time (Burns, 2009 [10]; WHO, 2015 [1]). The most common early symptom is difficulty in remembering recent events (episodic memory loss) (Burns, 2009 [10]). Regarding AD, although research findings suggest that individuals with this disease may still be fit to drive in the early stages (Ott et al., 2008 [11]), they may show visual inspection and target identification disorders during driving (Uc et al., 2005 [12]). Moreover, the associated impairment in executive functions appears to have a significant effect on driving performance (Tomioka et al., 2009 [13]), especially when unexpected incidents occur.

Parkinson's disease (PD) is a degenerative disease of central nervous system that have an impact mainly on motor function. Symptoms of PD may vary from person to person and include: tremor, slowness of movement (bradykinesia), rigidity, flexed posture, shuffling gait or postural instability, impaired posture and balance, loss of automatic movements. Later, thinking and behavioral problems may arise, with dementia commonly occurring in the advanced stages of the disease. Studies regarding PD are less conclusive in terms of the impact of its clinical parameters on driving abilities (Cordell et al. [4], 2008; Cubo et al., 2009 [5]). Although these conditions have obvious impacts on driving performance, in mild cases and importantly in the very early stages, they may be imperceptible in one's daily routine yet still impact one's driving ability.

In summary, various parameters may affect the driving performance of individuals with neurological diseases affecting cognitive functions, including demographic, medical, neurological and neuropsychological parameters. The aforementioned neurological diseases affecting cognitive functions and other related parameters are rather common in the general population, especially in older adults, and may have an important effect on driving performance, especially at unexpected incidents, which has not been investigated sufficiently. Overall, the driving behavior and safety characteristics of patients with neurological diseases affecting cognition, haven't been examined, in-depth, and thus there is a gap that this study is going to fill in, mathematically, by innovative statistical techniques.

2. Objectives

This study is an interdisciplinary effort entering the scientific fields of traffic and safety behavior of drivers on one hand and neurological diseases affecting cognitive functions on the other. An open research issue in patients with neurological diseases affecting cognitive functions is the detection of multimodal predictors that have the capacity to predict sufficiently their driving performance. Moreover, what appears to be missing from the previous research is the evaluation of driving behavior by using multiple driving indexes in a combined integrated manner instead of using single measures that focus on a sub-area of driving performance. The objective of this study is to explore the impact of AD, PD and MCI, on driving behavior, as reflected by the latent variable "driving performance", as well as by the measured variables "reaction time" and "accident probability". For this purpose, Structural Equation Models (SEMs) were employed in order to explore the unique contribution of the aforementioned clinical conditions after controlling for various subject-related variables (motor skills, cognitive fitness, age) and driving-related variables (area type, traffic volume, conversing with passenger while driving, use of hand-held mobile phone while driving), that may influence driving behavior.

3. Methodological Approach

3.1. Driving simulator experiment

This study was carried out by an interdisciplinary research team of engineers, neurologists and psychologists. The experiment includes three types of assessment: a) Neurological assessment which concerns the administration of a full clinical medical, ophthalmological and neurological evaluation, in order to well document the characteristics of each of these cerebral diseases, b) Neuropsychological assessment which concerns the administration of a series of neuropsychological tests and psychological-behavioral questionnaires to the participants, covering a large spectrum of Cognitive Functions: visuospatial and verbal episodic and working memory, general selective and divided attention, reaction time, processing speed, psychomotor speed etc., and c) Driving at the simulator assessment which concerns the programming of a set of driving tasks into the driving simulator for different driving scenarios.

The NTUA driving simulator is a motion base quarter-cab manufactured by the FOERST Company. The simulator consists of 3 LCD wide screens 40’’ (full HD: 1920x1080pixels), driving position and support motion base. The dimensions at a full development are 230x180cm, while the base width is 78cm and the total field of view is 170 degrees.

The driving simulator experiment started with a practice drive on the basis of several quantitative and qualitative criteria, until the participant fully familiarized with the simulation environment (usually 10-15 minutes). Afterwards, all participants drove at two sessions (approximately 20 minutes each). Each session corresponded to a different road environment: a rural route that was 2.1 km long, single carriageway, lane width was 3m, with zero gradient and mild horizontal curves and an urban route that was 1.7km long, at its bigger part dual carriageway, separated by guardrails and the lane width was 3.5m. Within each area type, two traffic scenarios were examined: a) low traffic conditions: ambient vehicles’ arrivals were drawn from a Gamma distribution with mean m=12sec, and variance σ^2=6sec, corresponding to an average traffic volume Q=300 vehicles/hour, and b) high traffic conditions - ambient vehicles’ arrivals were drawn from a Gamma distribution with mean m=6sec, and variance σ^2=3sec, corresponding to an average traffic volume of Q=600 vehicles/hour. The three distraction conditions concerned: a) undistracted driving, b) driving while conversing with a passenger and c) driving while conversing through a hand-held mobile phone.

Finally, during each trial, two unexpected incidents were scheduled to occur: sudden appearance of an animal (deer or donkey) on the roadway in the rural session, and sudden appearance of an adult pedestrian, or of a child chasing a ball on the roadway, or of a car suddenly getting out of a parking position and getting in the road in the urban session.

3.2. Ethics

The study was approved by the Ethics Committee of the "Attikon" University General Hospital. Informed consent was obtained from all individuals studied; it was clearly explained to them that participation was voluntary and that they had the right to withdraw any time they wished to.

Participants were informed on the nature of the study, the duration of their engagement and the type of information that they would be asked to give during the data collection process. Also, participants were ensured of the anonymity and confidentiality of the procedure.

3.3. Sample characteristics

For the purpose of this study 274 participants started the driving simulator experiment. Nevertheless, 49 participants were eliminated from the study because they had simulator sickness issues from the very beginning of the driving simulator experiment. Thus, the sampling scheme included 225 participants (76% males - 24% females): 133 “patients” with a neurological disease affecting cognitive functions: (28 AD patients, 45 MCI patients, 25 PD patients, and 35 patients with other neurological disorders affecting cognition) and 92 “Controls” without any cognitive disorder. From the age perspective the sample could be formatted as follows: 153 older drivers (age>55 years old), 42 middle aged (35 years old<age<54 years old) and 30 young participants (age<34 years old). The clustering process regarding the neurological state of the participants is beyond the scope of this paper and was made after a large battery of neurological and neuropsychological tests. It is important to mention though, that together with the confirmation of cognitive impairments, all MCI patients had Clinical Dementia Rating (CDR) = 0.5 and all AD patients had CDR=1.0 (Morris, 1993 [14]) (all controls had no cognitive impairments and a CDR score equal to zero).

3.4 Analysis methodology

The size and interdisciplinary nature of the database lead to implementation of three Principal Component Analyses (PCA) regarding driving performance variables, neurological variables and neuropsychological variables, in order to investigate which observed variables are most highly correlated with the common factors and how many common factors are needed to give an adequate description of the data. Then, the most highly correlated observed variables of each principal component which describe adequately the data, will develop three non-observed, latent variables: “driving performance”, “neurological state”, and “neuropsychological state”, respectively. In statistics, an exploratory Principal Component Analysis (PCA) is used in the early investigation of a set of multivariate data to determine whether the factor analysis model is useful in providing a parsimonious way of describing and accounting for the relationships between the observed variables. Moving on, in order to explore the impact of AD, PD and MCI, on the latent variable “driving performance”, as well as on the measured variables “reaction time” and “accident probability”, three Structural Equation Models (SEMs) were employed in order to explore the unique contribution of the aforementioned clinical conditions, of the neurological state, the neuropsychological state and several risk factors. SEMs represent a natural extension of a measurement model, and a mature statistical modelling framework. The SEM is a tool developed largely by clinical sociologists and psychologists. It is designed to deal with several difficult modelling challenges, including cases in which some variables of interest to a researcher are unobservable or latent and are measured using one or more exogenous variables, endogeneity among variables, and complex underlying social phenomena (Washington et al., 2011 [15]).

4. Results

4.1 Principal Component Analysis

A distinct part of the analysis is devoted to the estimation of driving performance factors, using 21 variables that are recorded from the driving simulator experiments, and the neurological and the neuropsychological state using the variables derived from the neurological and neuropsychological databases (19 and 32 variables respectively). Tables 1, 2, and 3 present a matrix of loadings for each of the variables. The factors presented in the figures indicate how much the variable explains its corresponding factor. It should be noted that small loadings (<0.500) are conventionally not printed (replaced by spaces), to draw attention to the pattern of the larger loadings. Moreover, all variables have been sorted regarding the loadings.

4.1.1 Driving performance PCA

Table 1. Driving simulator variables PCA loadings

Driving Performance Variables (simulator)

Rotated Component Matrix[a]

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

	Factor 1	Factor 2	Factor 3
StdLateralPosition	**.923**		
TTLAverage	**.905**		
StdWheelAverage	**.900**		
WheelAverage	.845		
LateralPositionAverage	.835		
HWayAverage	-.738		
StdHWayAverage	-.708		
StdTTLAverage	.666		
StdTTCAverage	.631		
TTCAverage	.623		
BrakeAverage	.553		
StdBrakeAverage	.553		
AverageSpeed		**.776**	
TheadAverage		-.697	
RalphaAverage		.677	
StdRalphaAverage		.669	
StdevAverageSpeed		.637	
GearAverage			**.753**
StdGearAverage			.751
StdRpmAverage			.664
RpmAverage			.573

a. Rotation converged in 6 iterations.

Total Variance Explained

Rotation Sums of Squared Loadings

Componen	**1**	**2**	**3**
Total	8.5	5.7	2.2
% of Variance	38.5	25.7	10.1
Cumulative %	38.5	64.2	74.3

Results from the first PCA analysis indicate that three factors are best fitted regarding this specific database extracted from the simulator experiment, representing 74.3% of the overall database. Regarding the first factor (representing the 38.5% of the overall database), lateral position variability, time to line crossing and steering angle variability have the three highest loadings amongst all variables. This reveals that the first factor represents lateral control measures which indicates how well drivers maintain their vehicle position. In the second factor (representing the 25.7% of the overall database), average speed has the highest loading indicating that the second factor represents the longitudinal measure of speed. In the third factor (representing the 10.1% of the overall database), average gear has the highest loading, and with the other three loadings of variability of gear use, rounds per minutes and variability of rounds per minute indicating that the third factor represents the use of the gearbox.

In the next step, in order to implement SEMs on the specific database only one latent variable will be developed to estimate the overall driving performance. The variables which are selected to be included in the latent analysis and underline the latent variable "driving performance" are the three variables with the highest loadings of the first factor (variability of the lateral position, time to line crossing and variability of the steering angle), and the variables with the highest loadings of the next two factors (average speed and average gear use). Thus, the variable "driving performance" could be adequately described by the aforementioned 5 variables covering the 74.3% of the driving simulator database.

4.1.2 Neurological assessment principal component analysis

Table 2. Neurological PCA loadings

Neurological Variables

Rotated Component Matrix[a]

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
EvalF_Tapping_Errors	**.838**					
Evalsc_FBItot	.698					
Evalsc_CDRtot	.672					
Evalsc_NPItot	.649					
IADLBothGenders	.647					
Evalsc_MMSEtot	-.443					
EvalPHQ_Nine		**.865**				
Evalsc_GerDeprScale		.849				
EvalAthens_In_Scale		.656				
EvalTandemWalking_Errors			**.882**			
EvalTandemWalking_RNC_Errors			.859			
EvalTandemWalking_RNC_Time			.530			
EvalTandemWalking_Time				**.874**		
EvalR_P_Walk				.693		
EvalF_Tapping_Time				.591		
Evalsc_Hachinski_score					.771	
EvalEpworth_S_Sc					-.535	
EvalH_T_Rotation_Right						.816
EvalH_T_Rotation_Left						.607

a. Rotation converged in 11 iterations.

Total Variance Explained

Rotation Sums of Squared Loadings

Component	**1**	**2**	**3**	**4**	**5**	**6**
Total	3.1	2.7	2.5	1.9	1.7	1.6
% of Variance	16.3	14.2	13.3	9.8	9.1	8.6
Cumulative %	16.3	30.5	43.8	53.6	62.7	71.4

Results from the second PCA analysis indicate that six factors are best fitted regarding this specific database representing 71.4% of the overall neurological database. Regarding the first factor (representing the 16.3% of the overall database), the variable "Foot Taping Errors"[1] has the highest loadings amongst all variables. In the second factor (representing the 14.2% of the overall database), "Patients Health Questionnaire 9"[2] has the highest loadings amongst all variables. In the third and fourth factors (representing the 13.3% and 9.8% respectively of the overall database) "Tandem Errors" and "Tandem Walking Time"[3] have the highest loadings amongst all variables.

In the next step, in order to implement SEMs on the overall database, only one latent variable will be developed to estimate the overall neurological status. The variables which are selected to be included in the latent analysis and underline the latent variable "neurological state" are the first variables with the highest loadings of the first four factors (Foot Tapping Errors, Patients Health Questionnaire 9, Tandem Walking Errors and Tandem Walking Time). Thus, the variable "neurological state" could be adequately described by the aforementioned 4 variables covering the

[1] A neurological test which evaluates the feet movement coordination by tapping on a A4 paper (Marottoli et.al, 1994 [16])
[2] A questionnaire which evaluates the emotional state of the participants (Cameron et al., 2008 [17])
[3] A neurological test in which the patient is invited to walk through a straight line 2m long in heel-toe mode, with simultaneous aloud number counting. Balance, movement coordination, mistakes and time of execution are to be evaluated.

fields of emotional state and motor abilities: balance, movement coordination, mistakes and time of execution.

4.1.3 Neuropsychological assessment principal component analysis

Table 3. Neuropsychological PCA loadings

Neuropsychological Variables

Rotated Component Matrix[a]

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
EvalCTMT_1	**-.805**				
EvalCTMT_3	-.794				
EvalCTMT_2	-.773				
EvalTMT_A	-.752				
EvalCTMT_4	-.743				
EvalVigilanceTest	-.717				
EvalUFV_2	-.651				
EvalCTMT_5	-.569				
EvalTMT_B	-.557				
Evalsc_Ver_Fluency_Letter	.542				
Evalsc_VER_FLUEN_ANIMA	.524				
EvalBVMTTotal		**.850**			
EvalBVMT2Trial		.841			
EvalBVMT3Trial		.812			
EvalBVMT1Trial		.792			
EvalBVMTDelayed		.784			
EvalBVMTRI		.596			
EvalHopkinsRI			**.827**		
EvalHopkinsTotal			.760		
EvalHopkins2Trial			.749		
EvalHopkinsRecognition			.747		
EvalHopkinsDelayed			.724		
EvalHopkins3Trial			.721		
EvalHopkins1Trial			.668		
EvalEmbeddedTest				**.794**	
EvalSpatialSpan_For				.683	
EvalSpatialSpan_Back				.617	
EvalSDMT_Written				.559	
EvalSDMT_Oral				.555	
EvalSpatialAddition				.551	
EvalBVMTRecognition					.843

a. Rotation converged in 7 iterations.

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

Total Variance Explained
Rotation Sums of Squared Loadings

	1	2	3	4	5
Total	7.8	7.1	6.3	4.8	1.4
% of Variance	22.2	20.4	18.0	13.7	3.9
Cumulative %	22.2	42.6	60.5	74.3	78.2

Results from the third PCA analysis indicate that five factors are best fitted regarding this specific database. These five factors represent 78.2% of the overall neuropsychological database. Regarding the first factor (representing the 22.2% of the overall database), the variable "Comprehensive Trail Making Test 1"[4] has the highest loadings amongst all variables. In the second factor (representing the 20.4% of the overall database), "Brief Visuospatial Memory Test"[5] has the highest loadings amongst all variables. In the third and fourth factors (representing the 18% and 13.7% respectively of the overall database), "Hopkins Verbal Learning Test – RI"[6] and "Witkin's Embedded Figure Test"[7] have the highest loadings amongst all variables.

In the next step, in order to implement SEMs on the overall database, only one latent variable will be developed to estimate the overall neuropsychological status. The variables which are selected to be included in the latent analysis and underline the latent variable "neuropsychological

[4] CTMT (Reynolds, 2002 [18]) is a neuropsychological test which consists of five trails that assess psychomotor speed, visual scanning, sequencing, task switching/cognitive flexibility, attention, inhibition, and distractibility.

[5] BVMT-R is used as a measure of visuospatial memory (Benedict, 1997 [19]).

[6] HVLT-R (Benedict, Schretlen, Groninger, & Brandt, 1998 [20]) is a brief verbal learning and memory instrument.

[7] Witkin's Embedded Figure Test (Witkin et al., 1971 [21]) is a test measuring the ability to distinguish a target object from an organized visual field.

state" are the first variables with the highest loadings of the first four factors (Comprehensive Trails Making Test, Brief Visuospatial Memory Test, Hopkins Verbal Learning Test - RI, and Witkin's Embedded Figure Test). Thus, the variable "neuropsychological state" could be adequately described by the aforementioned 4 variables covering the fields of verbal memory learning, spatial memory learning, processing speed, visual scanning and attention.

4.2 Structural Equation Modeling

The objective of the three SEMs is the quantification of the impact of MCI, AD, PD, distraction, age and road and traffic environment (risk factors) on the observed variable "reaction time", on the observed variable "accident probability" and on the latent variable "driving performance". Additionally, the quantified impact of two latent variables regarding neurological state and neuropsychological state of the drivers on the three examined variables is analyzed and the estimation results and the path diagram of the model are presented.

4.2.1 SEM regarding reaction time

Reaction time is an increasingly popular variable primary because of its relationship with accident probability. A range of reaction time parameters can be examined including number of number of incorrect responses, missed events, reaction time and reaction distance. In the first SEM we explored the impact of various latent and observed variables on the reaction time of the participants at the unexpected incidents during their simulated driving (calculated as the time between the first appearance of the incident on the road and the moment the driver starts to brake). After the initial SEM analysis approaches, the traffic flow was not found to affect significantly the dependent variable and for that reason this variable was eliminated from the final SEM. The estimation results are presented in Table 4 and the path diagram is presented in Figure 1.

Table 4. Estimation results of the reaction time SEM

Latent variables	Est.	Std.err	Z-value	P(>|z|)
Neuropsychological State *(latent 1)*				
Witkin's Embedded Figure Test	1.000			
Brief Visuospatial Memory Test	1.962	0.048	40.927	<.001
Comprehensive Trail Making Test (1)	-6.752	0.405	-16.685	<.001
Hopkins Verbal Learning Test (RI)	0.415	0.020	20.818	<.001
Neurological State *(latent 2)*				
Tandem Walking: Errors	1.000			
Tandem Walking: Completion Time	5.557	0.873	6.364	<.001
Patient Health Questionnaire (PHQ-9)	9.956	2.416	4.120	<.001
Foot taping errors	0.829	0.170	4.885	<.001
Regressions	**Est.**	**Std.err**	**Z-value**	**P(>|z|)**
Reaction Time				
Disease - MCI	103.575	52.205	1.984	.047
Disease - AD	327.075	87.927	3.492	<.001
Disease - PD	381.056	88.544	4.304	<.001
Urban Area	-345.309	33.260	-10.382	<.001
Advanced Age	190.137	43.877	4.333	<.001
Distraction - Conversation	80.614	37.769	2.134	.033

Distraction - Mobile Phone	225.921	54.088	4.177	<.001
Neuropsychological State *(latent)*	-20.899	6.464	-3.233	<.001
Neurological State *(latent)*	-789.943	226.670	-3.485	<.001
Summary statistics	ML			
Minimum Function Test Statistic	1928.87			
Degrees of freedom	81			
Goodness of fit				
SRMR	0.138			
RMSEA	0.132			
CFI	0.722			
TLI	0.702			

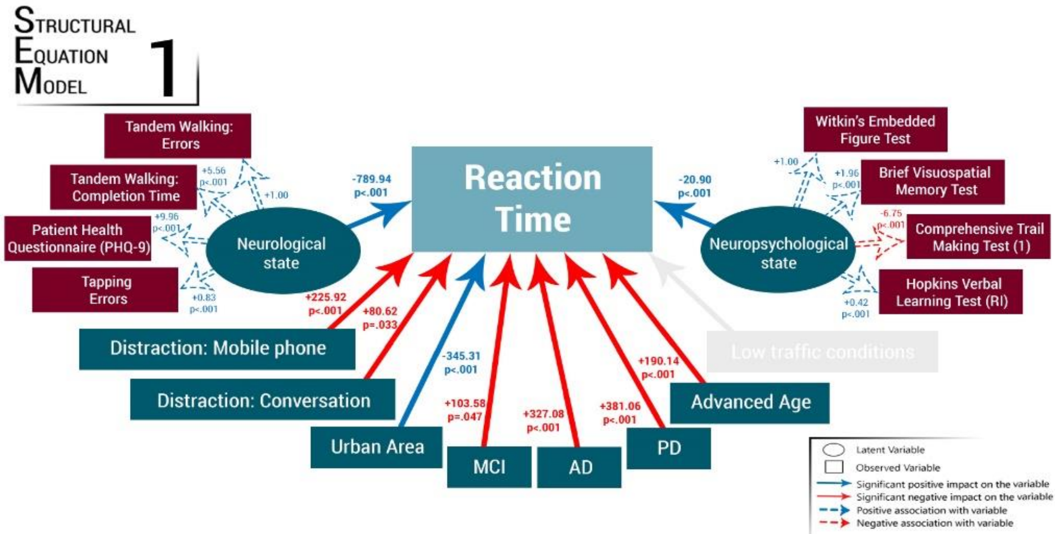

Figure 1. Path diagram of SEM1

It is important to mention that, in all three SEM path diagrams blue lines express a positive significant impact towards road safety, red lines express a negative significant impact against road safety and grey lines express the absence of a statistically significant association (grey lines correspond to variables that are not included in the model). Furthermore, dashed lines indicate which variables create the latent ones, while continuous lines indicate which variables exist in the regression part of the SEM. Finally, the label values represent the parameter estimates. Finally, model results are discussed and specific conclusions are extracted regarding each SEM.

A critical finding that supports the validity of the overall SEM is that the contribution of the observed variables on the construction of the latent variables (neuropsychological state and neurological state) was in all cases statistically significant. Also, regarding the regression analysis, all predictors had a significant contribution on the prediction of the reaction time. Finally, the obtained goodness-of-fit measures are generally close to the respective limits[8], which is considered as very important when dealing with driving behavior variables.

In this SEM, reaction time is the dependent observed variable while the independent variables include a diagnosis of a cerebral disorder (AD, PD or MCI), neuropsychological state, neurological state, driver distraction, area type, and drivers' age. Regarding the effect of cerebral disorders on reaction time, it was found that the presence of MCI, AD or PD had a significant negative impact on reaction time. Concerning the effect of age, young and middle-aged drivers were found to outperformed older drivers in term of reaction time.

Moreover, neuropsychological state and neurological state that are commonly impaired in patients with cerebral disorders had a significant unique contribution on predicting better reaction times. Regarding the effect of in-vehicle distraction, both distractors were found to have a statistically significant negative effect on reaction time. Finally, regarding area and traffic characteristics, the results indicate that area type is a critical factor affecting drivers' reaction time as in urban areas reaction time was significantly affected in a positive way. On the other hand, traffic conditions didn't appear to influence reaction time significantly.

4.2.2. SEM regarding accident probability

In the second SEM we explored the impact of various latent and observed variables on the accident probability of the participants (calculated as the proportion of unexpected incidents resulting in accidents). After the initial SEM analysis approaches, the distractor "conversation with passenger", the traffic flow, the presence of MCI, the age and the latent variable "neurological state" were not found to affect significantly the dependent variable and for that reason they were eliminated from the final SEM. The estimation results are presented in Table 5 and the path diagram is presented in Figure 2.

Table 5. Estimation results of the accident probability SEM

Latent variables	Est.	Std.err	Z-value	P(>|z|)
Neuropsychological State *(latent 1)*				
Witkin's Embedded Figure Test	1.000			
Brief Visuospatial Memory Test	1.989	0.047	42.238	<.001
Comprehensive Trail Making Test (1)	-7.022	0.375	-18.740	<.001
Hopkins Verbal Learning Test (RI)	0.421	0.018	23.199	<.001

Regressions	Est.	Std.err	Z-value	P(>|z|)
Accident Probability				
Disease - AD	0.162	0.062	2.146	.032
Disease - PD	0.104	0.060	2.017	.041
Urban Area	-0.063	0.027	-2.306	.021
Distraction - Mobile Phone	0.054	0.036	1.909	.049
Neuropsychological State *(latent)*	-0.023	0.004	-5.612	<.001

[8] In order to evaluate the overall suitability of the whole SEM four summary goodness-of-fit measures are reported: Standardized Root Average Square Residual (SRMR), Root Average Square Error of Approximation (RMSEA), Comparative Fit Index (CFI), Tucker Lewis Index (TLI). It is noted that values of the SRMR range between zero and one, with well-fitting models having values less than 0.08. The appropriate acceptable cut-off point for the RMSEA has been a topic of debate, but in general it lies within 0.06 and 0.08, while 0.07 is often considered as having the general consensus. For the final two goodness of fit measures, the Comparative Fit Index (CFI) and the Tucker Lewis Index (TLI) values larger of 0.90 or even 0.95 are advised.

Summary statistics	ML
Minimum Function Test Statistic	711.78
Degrees of freedom	21

Goodness of fit	
SRMR	0.125
RMSEA	0.135
CFI	0.699
TLI	0.659

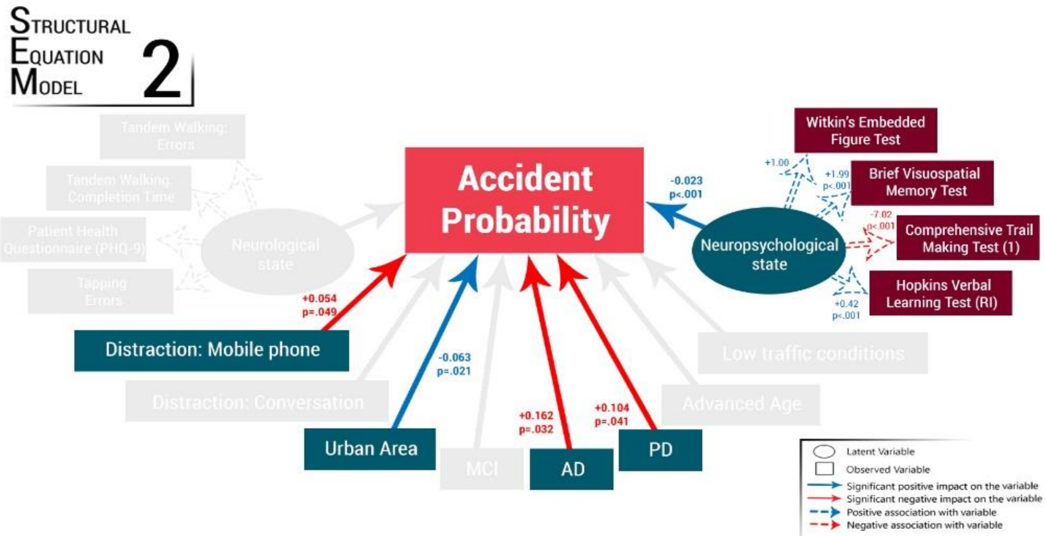

Figure 2. Path diagram of SEM2

A critical finding that supports the validity of the overall SEM is that the contribution of the observed variables on the construction of the neuropsychological state was statistically significant. Regarding the regression analysis, 5 predictors had a significant contribution on the prediction of the accident probability. The neurological state didn't have a critical contribution on the dependent variable of accident probability and for that reason it was eliminated from the model. Finally, the obtained goodness-of-fit measures are in general terms close to the respective limits, which is considered as very important when dealing with driving behavior variables.

In this SEM, accident probability is the dependent observed variable while the independent variables include a diagnosis of a cerebral disorder (AD and PD), neuropsychological state, driver distraction through mobile phone, and area type. Regarding the effect of cerebral disorders on accident probability, it was found that the presence of AD or PD had a significant negative impact on accident probability (no significant effect was found for the group of MCI). Concerning the effect of age, young and middle-aged drivers were not found to have any significant difference with the older drivers concerning the accident probability.

Moreover, neuropsychological state (but not neurological state) that are commonly impaired in patients with cerebral disorders had a significant unique contribution on predicting lower accident probability. Regarding the effect of in-vehicle distraction, although conversation with passenger didn't have any significant influence on accident probability, the mobile phone use appeared to have a negative impact on having more accidents.

Finally, regarding traffic and area characteristics, the results indicate that traffic volume is not a critical factor affecting drivers' accident probability as in low traffic volumes the accident probability wasn't significantly affected. On the other hand, it seems that the rural area lead to more addidents than urban area.

4.2.4 SEM regarding driving performance

As presented in the methodological chapter, several driving performance measures exist for the evaluation of driving performance, the selection of which should be guided by a number of general rules related to the nature of the task examined as well as the specific research questions. In this section, driving performance is defined as a new, unobserved variable, within the framework of latent analysis. More specifically, in this SEM the latent variable reflects the underlying driving performance of the participants and is based on driving performance variables extracted from the PCA analysis of the previous section. In the second part of the SEM, driving performance is the dependent variable while the independent variables include a broad set of predictors. After the initial SEM analysis approaches, distractor "conversation with passenger", was not found to affect significantly the dependent variable and for that reason it was eliminated from the final SEM. The estimation results are presented in Table 6 and the path diagram is presented in Figure 3.

Table 6. Estimation results of the driving performance SEM

Latent variables	Est.	Std.err	Z-value	P(>|z|)
Driving Performance *(latent 1)*				
Average Speed	1.000			
Lateral Position Variability	-0.098	0.003	-29.483	<.001
Steering Angle Variability	-0.373	0.028	-13.303	<.001
Time to Line Crossing	-12.102	0.483	-25.039	<.001
Average Gear	0.049	0.002	29.762	<.001
Neuropsychological State *(latent 2)*				
Witkin's Embedded Figure Test	1.000			
Brief Visuospatial Memory Test	1.962	0.047	41.964	<.001
Comprehensive Trail Making Test (1)	-6.803	0.390	-17.430	<.001
Hopkins Verbal Learning Test (RI)	0.416	0.019	21.553	<.001
Neurological State *(latent 3)*				
Tandem Walking: Errors	1.000			
Tandem Walking: Completion Time	5.777	0.937	6.166	<.001
Patient Health Questionnaire (PHQ-9)	9.101	2.077	4.382	<.001
Foot taping errors	0.721	0.134	5.363	<.001

Regressions	Est.	Std.err	Z-value	P(>|z|)
Driving Performance				
Disease - MCI	-0.772	0.267	-2.889	.004
Disease - AD	-1.066	0.329	-3.237	<.001
Disease - PD	-0.705	0.336	-2.100	.036

Urban Area	-13.902	0.390	-35.638	<.001
Low Traffic Conditions	0.414	0.185	2.245	.025
Advanced Age	-1.296	0.235	-5.521	<.001
Distraction - Mobile Phone	-0.604	0.223	-2.701	.007
Neuropsychological State *(latent)*	0.082	0.026	3.174	.002
Neurological State *(latent)*	3.765	0.871	4.320	<.001

Summary statistics	ML
Minimum Function Test Statistic	3517.01
Degrees of freedom	146

Goodness of fit	
SRMR	0.122
RMSEA	0.124
CFI	0.755
TLI	0.700

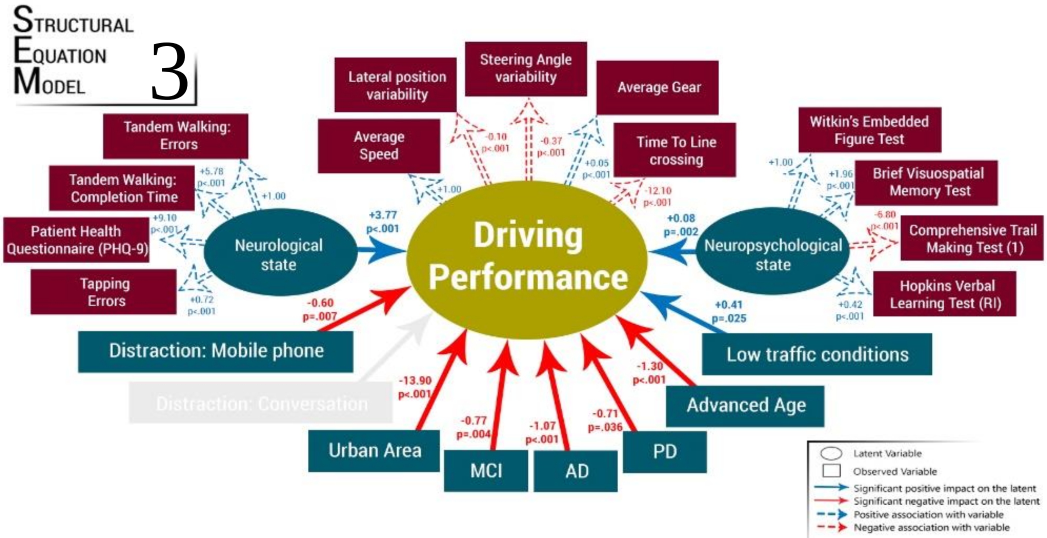

Figure 3. Path diagram of SEM3

A critical finding that supports the validity of the overall SEM is that the contribution of the observed variables on the construction of the latent variables (driving performance, neuropsychological state and neurological state) was in all cases statistically significant. Also, regarding the regression analysis, all predictors had a significant contribution on the prediction of the latent variable "driving performance". Finally, the obtained goodness-of-fit measures are generally close to the respective limits, which is considered as very important when dealing with driving behavior variables.

In the first part of the model, driving performance (the latent variable) is positively associated with average speed and average gear and negatively associated with time to line crossing and lateral position variability. It should be kept in mind that the selected driving performance measures which create the latent variable have the highest loadings in the respective explanatory PCA analysis presented in the previous section.

In the second part of the SEM, driving performance is the dependent variable while the independent variables include a diagnosis of a cerebral disorder (AD, PD or MCI), neuropsychological state, neurological state, driver distraction, area type, traffic volume as well as drivers' age. Regarding the effect of cerebral disorders on driving performance, it was found that the presence of MCI, or AD, or PD has a significant negative impact on driving performance. Concerning the effect of age, young and middle-aged drivers were found to outperformed older drivers in term of driving performance.

Moreover, neuropsychological state and neurological state that are commonly impaired in patients with cerebral disorders had a significant unique positive contribution on predicting driving performance. Regarding the effect of in-vehicle distraction, conversation with the passenger was not found to have a statistically significant effect indicating that drivers do not change their driving behavior while conversing with a passenger compared to undistracted driving. On the other hand, the hand-held mobile phone use had a significant negative association with driving performance. Finally, regarding area and traffic characteristics, the results indicate that area type is a critical factor affecting drivers' performance as in urban areas driving performance was significantly affected in a negative way. Traffic conditions also influence driving performance since the presence of a low traffic volume had a significant positive association with driving performance.

5. Discussion and conclusions

The objective of this study was to quantify the impact of AD, PD and MCI and other critical risk factors, on driving behavior, as reflected by the latent variable "driving performance", as well as by the two most critical road safety measured variables "reaction time" and "accident probability". Several interesting results were extracted by the implementation of the 3 SEM analyses. Firstly, regarding neurological diseases affecting cognitive functions drivers with MCI, AD or PD (as compared with cognitively intact individuals of similar demographics) were associated with significantly lower levels of the latent variable "driving performance" that reflected a broad range of driving indexes and were associated with significantly worse "reaction time". Also, the clinical conditions of AD and PD were associated with a negative impact on accident probability. If we isolate the three examined groups of patients, the results indicated AD as the riskiest group of drivers (had the greatest impact on accident probability and driving performance and almost the greatest on reaction time), followed by PD, whereas the group of MCI is considered as safer compared to the other two examined brain pathologies.

The findings about the AD and the PD patients were in the expected direction and are in line with previous research that indicates impairments in driving performance of the two clinical groups both in the case of driving simulator experiments and on-road evaluations (Dubinsky et al., 1991 [22]; Man-Son-Hing et al., 2007 [23]; Uc & Rizzo, 2008 [24]; Uitti 2009 [25]). According to previous research, it seems that MCI patients have some driving difficulties, however their driving skills are not consistently worse than that of cognitively intact individuals of similar age and driving experience (Devlin et al., 2012 [26]; Frittelli et al., 2009 [6]; Kawano et al., 2012 [27]). The present analysis by utilizing latent variables that assess a broad range of driving indexes, indicates that patients with MCI had a significantly altered driving bahavior as compared to healthy controls.

Latent variable "neuropsychological state" had a significant positive effect on all outcome variables, namely, "driving performance", reaction time and accident probability. The current analysis by applying the SEM methodology indicates the importance of neuropsychological state as a predictor of driving competence that was assessed by the use of latent variables. Apart from the case of cerebral disorders, the role of neuropsychological state on driving behavior was also evident on the control group of our study, as indicated by the main effect that was observed in all SEM models.

Latent variable “neurological state” had a significant positive effect on “driving performance” and reaction time, whereas, its impact on accident probability was not statistically significant. Neurological and neuropsychological state appear to influence driving behavior as they reflect the level of motor coordination and behavioral stability on one hand and functioning on cognitive domains, such as working memory, information processing speed, and visual attention on the other.

Regarding driver distraction, conversation with the passenger was not found to have a critical impact on driving performance accident probability, indicating that drivers don’t alter their driving behavior in an important way under this type of distraction, but they have worse reaction time. On the other hand, mobile phone use had a significant negative effect on “driving performance”, “reaction time” and “accident probability”. The negative effect of mobile phone on driving behavior can be probably explained by the accumulating role of two synergistic mechanisms. Firstly, due to the amount of physical and cognitive resources that drivers allocate for performing the distraction task. Secondly, by adopting a compensatory behavior that however only partially counterbalances the impact of distraction on overall driving behavior.

Regarding age, it seems that advanced age had a significant negative impact on “driving performance” and reaction time, whereas, its impact on accident probability was not statistically significant. As indicated by the significant main effect that was observed in the three SEM models, the role of advanced age on driving behavior appears to generalize as well on the control group of our study that included cognitively intact individuals.

Regarding area and traffic characteristics, urban area had a significant negative impact on “driving performance”, whereas its impact on reaction time and accident probability was positive. Possibly, the more complex environment of the urban region increased the levels of awareness, thus leading to less driving errors, better reaction time and less accident probability. Low traffic conditions affected positively the “driving performance”, whereas it hadn’t any significant impact on reaction time and accident probability, which was an intuitive finding. In high traffic, the complicated road environment including a lot of interactions between vehicles has a totally negative effect on driving performance.

Road safety research often uses driving simulators, as they allow for the examination of a range of driving performance parameters in a controlled, relatively realistic and safe driving environment. However, there is a number of recurrent threats to validity when conducting driving simulator experiments, such as failure to adequately screen participants, generalization issues, learning effects and drop out due to simulator sickness (Caird & Horrey, 2011 [28]). Despite these limitations, driving simulators are an increasingly popular tool for measuring and analyzing driving behavior and performance, and numerous studies have been conducted, particularly in the last decade (Caird & Horrey, 2011 [28]; Papantoniou et al., 2015 [29]).

The application of this methodology revealed a number of open issues for further research in the inter-disciplinary field of driving behavior and brain pathologies. Firstly, in future research the experimental sample size could be strengthened in terms of size (more participants with MCI, AD and PD), in terms of the type of the neurological diseases affecting cognitive functions (participants with REM Behavior Disorder, Frontotemporal Dementia, Stroke, Multiple Sclerosis etc. are of great interest regarding their driving behavior and could be inserted in the research) and in terms of location and origin (MCI, AD and PD drivers in Greece may present differences in driving behavior with drivers of the same brain pathologies living in other countries).

Moreover, it would be an interesting future research challenge to periodically assess the driving behavior of patients with cerebral diseases over time (i.e. driving simulator experiment combined to neurological and neuropsychological assessments, every year), in order to identify to which extent, the progression of the disease deteriorates several driving performance measures. Finally, this innovative methodology should be developed on different types of assessing driver behavior of drivers with neurological diseases affecting cognitive functions. More specifically, as the application of SEMs needs a large dataset with several parameters, they can be developed on on-road and naturalistic experiments or field survey studies in order to estimate the effect of the risk factors investigated directly on the overall driving performance and safety behavior of patients with MCI, AD or PD.

The results of this study can be exploited in the development of recommendations and measures for addressing all aspects of impaired driving due to neurological diseases affecting cognitive functions. It is important to mention that every driver with a neurological disease affecting cognitive functions should be treated individually, through a modern interdisciplinary driving evaluation including medical, neurological and neuropsychological criteria for safe driving and of course assessment of driving performance through simulator tasks or on-road trials. Additionally, it should be in positive direction an effective monitoring of drivers that are at-risk for developing an underlying neurological condition that is associated with unsafe driving and the development of interventions that have the capacity to improve or preserve the driving fitness of older individuals and of drivers with cerebral diseases. Enhanced understanding of the medical, behavioral and social issues related to impaired driving due to neurological diseases affecting cognitive functions will lead to more appropriate driver training and licensing, criteria for driver license renewal for persons belonging to vulnerable groups, more appropriate legislation and awareness campaigns.

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References

1. WHO, 2015. Global status report on Road Safety 2014, supporting a decade of action, World Health Organisation.
2. Organisation for Economic Co-operation and Development, European Conference of Ministers of Transport. Paris, OECD, 2013.
3. Wood, J. M., C. Worringham, et al. Quantitative assessment of driving performance in Parkinson's disease. J Neurol Neurosurg Psychiatry 76(2), 2005, pp.176-80.
4. Cordell, R., H. C. Lee, et al. Driving assessment in Parkinson's disease - a novel predictor of performance?. Mov Disord 23(9), 2008, pp 1217-1222.
5. Cubo, E., P. Martinez Martin, et al. What contributes to driving ability in Parkinson's Disease. Disabil Rehabil, 2009.
6. Frittelli C, Borghetti D, Iudice G, Bonanni E, Maestri M, Tognoni G, Pasquali L, Iudice A (2009) Effects of Alzheimer's disease and mild cognitive impairment on driving ability: a controlled clinical study by simulated driving test. Int J Geriatr Psychiatry 24, 232-238. DTFH-61-97-C-00051. Center for Transportation Research, Blacksburg, VA, Virginia Tech.

7. Ravaglia, G., Forti, P., Montesi, F., Lucicesare, A., Pisacane, N. Rietti, E. et al. 2008. Mild Cognitive Impairment: Epidemiological and dementia risk in an elderly Italian population. Journal of the American Geriatrics Society, 56, 51-58.
8. Lafont, S., Laumon, B., Helmer, C., Dartigues, J. F., & Fabrigoule, C. (2008). Driving cessation and self-reported car crashes in older drivers: the impact of cognitive impairment and dementia in a population-based study. J Geriatr Psychiatry Neurol, 21(3), 171-182. doi: 10.1177/0891988708316861.
9. Yiannopoulou K.G., Papageorgiou S.G., (2013), "Current and future treatments for Alzheimer's disease", Therapeutic advances in neurological disorders, Volume 6, Issue 1, pg. 19-33
10. Burns A, Iliffe S (5 February 2009). "Alzheimer's disease". BMJ 338: b158. doi:10.1136/bmj.b158. PMID 19196745.
11. Ott BR, Heindel W.C., Papandonatos G.D., Festa, E.K., Davis J.D., Daiello L.A., Morris J.C. (2008). A longitudinal study of drivers with Alzheimer disease. Neurology, 70, 1171–1178.
12. Uc E. Y., Rizzo M., Anderson S. W. et al. (2005). Driver landmark and traffic sign identification in early Alzheimer's disease. Journal of Neurology, Neurosurgery and Psychiatry, 76, 764–768.
13. Tomioka, H., B. Yamagata, et al. 2009. Detection of hypofrontality in drivers with Alzheimer's disease by near-infrared spectroscopy. Neurosci Lett 451(3): 252-6.
14. Morris JC (1993) The Clinical Dementia Rating (CDR): current version and scoring rules. Neurology 43, 2412-2414.
15. Washington S.P., Karlaftis M.G., Mannering F., 2011, Statistical and Econometric Methods for Transportation Data Analysis, Second Edition, Chapman & Hall/CRC, ISBN-13: 978-1420082852
16. Marottoli, R.A., Richardson, E.D., Stowe, M.H., Miller, E.G., Brass, L.M. & Cooney Jr., L.W. (1998). Development of a test battery to identify older drivers at risk for self-reported adverse driving events. The Journal of the American Geriatrics Society.46, 562-568.
17. Cameron I.M., Crawford J.R., Lawton K., et al; Psychometric comparison of PHQ-9 and HADS for measuring depression severity in primary care. Br J Gen Pract. 2008 Jan;58(546):32-6. doi: 10.3399/bjgp08X263794.
18. Reynolds, C. R. (2002). Comprehensive Trail Making Test: Examiner's manual. Austin, TX: Pro-Ed.
19. Benedict. R. H. B. (1997). Brief Visuospatial Memory Test—Revised. Psychological Assessment Resources, Inc, Odessa, FL.
20. Benedict, R. H. B., Schretlen, D., Groninger, L., & Brandt, J. (1998). Hopkins Verbal Leaning Test-Revised: Normative data and analysis of inter-form and test-retest reliability. The Clinical Neuropsychologist, 12, 43–55. doi: 10.1076/clin.12.1.43.1726.
21. Witkin, H. A., Oltman, P. K., Raskin, E., & Karp, S. A. (1971). A manual for the Embedded Figures Test. Palo Alto, CA: Consulting Psychologists Press.
22. Dubinsky, R. M., Gray, C., Husted, D., Busenbark, K., Vetere-Overfield, B., Wiltfong, D., . . . Koller, W. C. (1991). Driving in Parkinson's disease. Neurology, 41(4), 517-520.
23. Man-Son-Hing, M., Marshall S., Molnar, F. & Wilson, K. (2007). Systematic Review of Driving Risk and the Efficacy of Compensatory Strategies in Persons with Dementia. Journal of the American Geriatrics Society, 55, 878-884.
24. Uc, E. Y., & Rizzo, M. (2008). Driving and neurodegenerative diseases. Current Neurology and Neuroscience Reports, 8, 377–383.
25. Uitti, R. J. (2009). Parkinson's disease and issues related to driving. Parkinsonism Related Disorders, 15, 122–125.
26. Devlin A, McGillivray J, Charlton J, Lowndes G, Etienne V. (2012). Investigating driving behavior of older drivers with mild cognitive impairment using a portable driving simulator. Accident Analysis & Prevention, 49, 300-307.
27. Kawano N, Iwamoto K, Ebe K, Suzuki Y, Hasegawa J, Ukai K, Umegaki H, Iidaka T, Ozaki N. (2012). Effects of mild cognitive impairment on driving performance in older drivers. Journal of the American Geriatrics Society, 60(7), 1379-1381.
28. Caird, J.K., Horrey, W. Twelve practical and useful questions about driving simulation. In Fisher, D.L., Rizzo, M., Caird, J.K., & Lee, J.D. (Eds). (2011). Handbook of Driving Simulation for Engineering, Medicine, and Psychology. Boca Raton, FL:, 2011, CRC Press.

29. Papantoniou P., Papadimitriou E., Yannis G., (2015), “Assessment of Driving Simulator Studies on Driver Distraction”, Advances in Transportation Studies, Issue 35, pp. 129-144.