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Which are the critical measures to assess the driving performance of drivers with brain pathologies?

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Abstract

Driving requires possessing cognitive, motor and visual skills and drivers need to have adequate motor strength, coordination and speed. More importantly, cognitive skills including concentration, attention, adequate visual perceptual skills, insight and memory must be present. The normal ageing process leads to declines in these motor and cognitive skills, and when combined with a brain pathology, it may significantly impair the person's driving performance, especially when unexpected incidents occur. The objective of this paper is to identify the critical driving performance measures in which drivers with cognitive impairments significantly deviate from the general population, through a driving simulator experiment. The brain pathologies considered concern Alzheimer's disease (AD), Parkinson's disease (PD) and Mild Cognitive Impairment (MCI). More analytically, a full neurological and neuropsychological assessment was carried out at the "ATTIKON" General Hospital in Athens, by neurologists and neuropsychologists of the UoA. Then, participants drove at the driving simulator of the NTUA. The driving tasks included driving in urban and rural road environment, while various unexpected incidents were scheduled to occur during the drives. The driving performance of 109 drivers with cognitive impairments (MCI, AD or PD) was compared to the driving performance of 31 healthy drivers of similar demographics. For each driver, the following driving performance measures were calculated and examined: speed, speed variability, lateral position, lateral position variability, headway, headway variability, and reaction time. All these parameters were compared to the range of "typical" values of the respective distribution of healthy drivers, and significant deviations from the "typical" distribution were identified. Results indicated that group of patients had various difficulties in driving performance compared with the control drivers. More specifically, more than 50% of the patients had extremely low mean speeds, and they often had lower speed variability (in 40% of the cases) than controls. Regarding the lateral position, the patients had difficulty in positioning the vehicle in the lane, and more than 1 out of 5 patients had very large variability in their lateral position. Also, 44% of the drivers with a brain pathology kept very large mean headways from the vehicle ahead. Finally, 50% of patients had very slow reaction times in unexpected incidents; in rural area 70% of the patients had reaction times larger than 2 seconds.

Keywords: brain pathologies; driving performance measures; driving simulator; reaction time

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1. Brain pathologies and driving performance - literature review

Driving is considered to be a complicated task that requires possessing sufficient cognitive, visual and motor skills and drivers must have highly cognitive skills such as speed, coordination, concentration, attention, adequate visual and perceptual skills, insight, judgement and memory. More importantly the task of driving requires the ability to receive sensory information, process the information, and to make proper, timely judgments and responses (Freund et al., 2005). Also, higher cortical functions required for driving include strategic and risk taking behavioral skills, including the ability to process multiple simultaneous environmental cues in order to make rapid, accurate and safe decisions. The ability for an individual to drive can be affected by various motor, visual, cognitive and perceptual deficits which are caused by normal ageing process or are related to neurologic/cerebral disorders. More specifically, physical aging, often accompanied by sensory and motor problems, along with some cognitive deceleration, may affect negatively someone's ability to drive efficiently (Ott & Daiello, 2010).

Diseases affecting a person's brain functioning (e.g. presence of specific brain pathology due to neurological diseases as Alzheimer's disease, Parkinson's disease, or Mild Cognitive Impairment, effect of pharmaceutical substances used for the treatment of various neurological disturbances) may significantly impair the person's driving behavior. These conditions have obvious impacts on driving behavior in mild cases but more importantly in the very early stages, they may be imperceptible in one's daily routine and driving ability. Taking into account that the percentage of the elderly in society is increasing (Baldock et al., 2007), while at the same time the level of motorization also increases (Yannis et al., 2011), the need to investigate the impact of these conditions on driving behaviour becomes quite critical.

Drivers who suffer from a brain pathology may have difficulties in their usual activities, including driving competence. However, scientists cannot agree to what extend mild cognitive impairment is affecting driving behaviour and road safety. The greater the dementia severity is, the greater is the likelihood of poor driving ability (Hunt et al. 1993). While it might be assumed that individuals with dementia would stop driving after onset of symptoms, it is estimated that around one-third of drivers with dementia continue to drive (Silverstein 2008). Most drivers are early in the disease process when cognitive deficits are generally mild (Adler & Kuskowski 2003) and changes to driving performance are minimal. Nonetheless, drivers with dementia are one of the groups considered at greatest risk for unsafe driving performance (Langford et al. 2007). Road accidents, while infrequent, are also of concern for drivers with dementia, whose crash risk is two to five times that of unimpaired older drivers (Charlton et al. 2003).

Furthermore, driving skills predictably worsen and will ultimately require individuals with dementia to stop driving (Adler et al. 2005). Driving decisions need to be made not on diagnosis but on an assessment of the dementia's progress and the disease's effects on functional abilities (Duchek et al. 2003, Eby et al. 2009, Eby & Molnar 2010). A typical approach to assessing driving skills in individuals with dementia uses a driving simulator. Learning to use a simulator, however, can be difficult for drivers with dementia even when given time to adapt to the setting (Cox et al. 1998). Owsley et al. (1991) developed the "useful field of view" (UFOV) that captures both speed of visual attention and ability to focus visual attention despite distractions. In two prospective studies, UFOV was found to predict crashes over a three year time period (Ball et al. 1993, Owsley et al. 1991) in a sample of older adults. Other cognitive measures, including memory scores, did not further predict driving performance. In a recent meta-analysis of the relationship between performance on neuropsychological tests and on-road driving ability in patients with dementia and elderly controls, measures of visuospatial abilities were more strongly associated with driving than were other cognitive domains (Reger et al. 2004).

Overall, international literature indicates that drivers with brain pathologies, namely dementia, AD, MCI or PD, may have difficulties in several driving performance indexes. The presence of a brain pathology leads to severe deterioration of the driving behaviour, regarding several longitudinal and lateral control measures, and road safety control measures such as the reaction time, which can lead to high accident risk (Pavlou et al., 2015).

2. Objectives

This paper aims to identify the driving performance measures in which drivers with cognitive impairments caused by brain pathologies significantly deviate from the general population. The driving performance of 109 drivers with cognitive impairments, (59 drivers with Mild Cognitive Impairment (MCI), 25 drivers with Alzheimer's Disease (AD)

and 25 drivers with Parkinson's Disease (PD)), was compared to the driving performance of 31 healthy drivers of similar demographics, through a driving simulator experiment. For each driver, the following driving performance measures were calculated and examined: a) mean speed, b) mean speed variability, c) time headway, d) time headway variability, e) lateral position, f) lateral position variability, and g) reaction time at incidents. All these driving indexes were compared to the range of "typical" values of the respective distribution of healthy drivers. In particular, we hypothesized that the presence of a brain pathology has a negative effect on the driving performance measures of PD, AD and MCI patients as compared to cognitive intact individuals of similar age, education and driving experience. Thus, we expected that the group of patients significantly deviate from the range of "typical values" of the control group, in most cases.

3. Methodology

3.1. Overview of the experiment

Road safety research often makes use of driving simulators, as they allow for the examination of a range of driving performance measures in a controlled, relatively realistic and safe driving environment. Driving simulators, however, vary substantially in their characteristics, and this can affect their realism and the validity of the results obtained. Despite these limitations, driving simulators are an increasingly popular tool for measuring and analyzing driver distraction, and numerous studies have been conducted, particularly in the last decade.

This study was carried out within the framework of two research projects: DriverBrain and Distract research project. They were carried out by an interdisciplinary research team of transportation engineers, neurologists and neuropsychologists (Yannis et al. 2013, Pavlou et al. 2014). According to the objectives of the analysis, the experiment included three types of assessment: a) a neurological assessment which concerned the administration of a full clinical medical, ophthalmological and neurological evaluation, in order to well document the characteristics of each of these disorders (e.g. MCI, AD, PD, as well as other related parameters of potential impact on driving (i.e. use of medication affecting the Central Nervous System), b) a neuropsychological assessment which concerned the administration of a series of neuropsychological tests and psychological-behavioural questionnaires to the participants. The tests carried out covered 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) a "driving at the simulator assessment"; after clustering our sample scheme in four categories by the neuropsychological and the neurological teams (group of PD, group of AD, group of MCI and group of healthy controls) all participants moved on to the third type of assessment. The third type of assessment concerned the programming of a set of driving tasks into the driving simulator for different driving scenarios. The driving simulator experiment took place at the Department of Transportation Planning and Engineering of the National Technical University of Athens, where the FOERST Driving Simulator is located. 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. Research evidence from on-road testing supports the validity properties of the driving simulator that was applied in the current study (Yannis et al., 2015).

3.2. Driving simulator experiment - Rural and Urban Sessions

The driving simulator experiment began with one practice drive (usually 15-20 minutes), until the participant fully familiarized with the simulation environment. Afterwards, all participants continued to the two sessions. Each session corresponds to a different road environment (Figure 1): a) rural route that is 2.1km long, single carriageway and the lane width is 3m, with zero gradient and mild horizontal curves, b) an urban route that is 1.7km long, at its bigger part dual carriageway, separated by guardrails, and the lane width is 3.5m. Moreover, narrow sidewalks, commercial uses and parking are available at the roadsides. During each trial, 2 unexpected incidents were scheduled to occur at fixed points along the drive. More specifically, incidents in rural area concerned the sudden appearance of an animal (deer or donkey) on the roadway, and incidents in urban areas concerned the 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.

Regarding the time point that the hazard appears, it depends on the speed and the time to collision in order to have identical conditions for all participants to react, either they drove fast or slowly. Thus, there was no possibility for the incident to appear closely or more suddenly to a participant than to another.

Fig. 1. The two plans of the driving routes (rural and urban) and two screenshots for each driving environment

3.3. Ethical issues

The study was approved by the Ethics Committee of the University General Hospital "ATTIKON". Informed consent was obtained from all individuals studied; it was explained to them that participation was on a voluntary basis 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.

4. Participants

For the purpose of this paper 274 participants have, at least, started the driving simulator experiment that was described analytically in the above chapters. 49 participants were eliminated from the study because they had simulator sickness issues from the very beginning of the driving simulator experiment. Thus, 225 individuals (both patients with cerebral diseases and "healthy controls") went through the whole experiment procedure. 25 participants had a brain pathology which was beyond the purpose of this paper and thus, they were eliminated from the analyses. Finally, 60 participants were of younger age (<55 years old) and they were eliminated from this study too, in order not to have age as a parameter that may affects the results, but only their cerebral condition.

Summarizing the above, 140 participants of more than 55 years of age went through the whole experimental procedure. More specifically, our sample scheme consists of 109 patients with cerebral diseases (69.0 years of age on average, 80 males) and 31 healthy controls (64.5 years of age on average, 20 males). The group of patients includes 25 AD patients (75.4 years of age on average), 59 MCI patients (70.1 years of age on average) and 25 PD patients (66.1 years of age on average). In Table 1, the between-group comparisons in age, driving experience, driving exposure (number of days driven per week and kilometers per week), and in the number of years of education are presented. The difference in age between the two groups was not statistically significant at the 0.05 level (p=0.316); the groups were not statistically different in terms of gender, driving experience, frequency of driving (number of days and kilometers they drive per week), years of education (Table 1). The similarities in demographic characteristics within the participants are significant and the sampling scheme can be safely considered to be representative.

Table 1. Comparison of patients with brain pathologies and of a Control group without neurological history on various demographics with the use of the Wilcoxon Rank Sum Test

	Group of patients	Control group	P-values
Age, y, mean±SD	69.0±7.4	64.5±7.8	0.316
Gender, n, M/F	109, 80/29	31, 20/11	1.000
Driving experience, y, mean±SD	39.8±4.8	35.9±3.7	0.298
Days/week, median (range)	4 (2-7)	5 (2-7)	0.589
Education, y, mean±SD	11.9±3.4	14.5±2.4	0.853

The following inclusion criteria were required for participation in the current study: a) valid driving license, b) more than 3 years of driving experience, c) driving more than 2500km during the last year, d) driving at least 10km/week during the last year, e) no history of psychosis, f) absence of any significant kinetic disorder that prevents them from basic driving movements, g) absence of dizziness or nausea while driving, either as a driver or as a passenger, h) absence of alcohol or any other drug addiction, i) absence of any significant eye disorder that prevents them from driving safely.

5. Results

The objective of this paper is to identify the driving performance measures in which drivers with cognitive impairments significantly deviate from the general population. For that reason, 7 key driving performance measures were examined, which correspond to both longitudinal and lateral driving control measures, in rural and urban areas, and are presented below:

- **Mean speed** - refers to the mean speed of the driver along the route, excluding the small sections in which incidents occurred, and excluding junction areas.
- **Mean speed variability** - refers to the variability (standard deviation) of the mean speed
- **Time headway** - refers to the time space between the simulator vehicle and the vehicle ahead
- **Time headway variability** - refers to the variability (standard deviation) of the time headway
- **Lateral position** - refers to the distance between the simulator vehicle and the middle of the road
- **Lateral position variability** - refers to the variability (standard deviation) of the lateral position of the vehicle
- **Reaction time** - refers to the time between the first appearance of the event - "obstacle" on the road and the moment the driver starts to brake.

In Table 2, the between-group comparisons in the 7 key driving performance indexes are presented for rural and urban driving environment. There were significant differences between the group of patients and the control group in several driving measures, namely mean speed in both driving areas, headway in rural area, and reaction time. Overall in seemed that patients with brain pathologies drove at much lower speeds, had less variability in their mean speed, they kept larger headways and had significantly worse reaction times than their cognitively intact counterparts.

Table 2. Comparison of patients with brain pathologies and of a Control group without neurological history on the 7 driving measures in rural and urban area, with the use of the Wilcoxon Rank Sum Test

	Group of patients	Control group	P-values
Mean Speed - Rural	36.5±8.0	44.3±7.5	0.010
Mean Speed - Urban	25.8±5.6	29.7±5.2	0.041
Mean Speed Variability - Rural	10.3±3.3	12.4±3.3	0.071
Mean Speed Variability - Urban	10.1±2.7	11.9±2.8	0.113
Time Headway - Rural	63.9±42.8	39.1±23.6	0.021
Time Headway - Urban	42.9±21.4	40.6±30.0	0.090
Time Headway Variability - Rural	179.8±117.1	170.0±102.5	0.113
Time Headway Variability - Urban	248.7±136.6	249.2±168.8	0.467
Lateral Position - Rural	1.5±0.2	1.5±0.1	1.000
Lateral Position - Urban	3.4±0.6	3.1±0.6	0.545
Lateral Position Variability -Rural	0.3±0.1	0.3±0.1	1.000
Lateral Position Variability - Urban	1.9±0.5	1.6±0.6	0.189
Reaction Time - Rural	2207.2±728.8	1644.4±531.5	0.001
Reaction Time - Urban	1618.2±361.9	1360.6±418.9	0.001

The two groups had differences in a majority of driving performance measures, but the objective of this study is to examine the individual driving performance of each participant with a brain pathology. For that reason, all 7 key measures were analyzed by a descriptive statistics technique which is described below: control groups' mean values minus one standard deviation and plus one standard deviation include 68.26% of the values of healthy controls (according to the normal distribution). For the purpose of this study, this area is defined by our research team as the

"typical area" (Figure 2). The individual driving indexes of all participants with cerebral diseases were compared to the "typical area" of the control group, in rural and urban driving environment and the results are presented in the next sections.

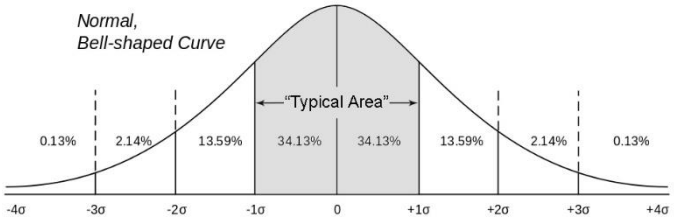

Fig. 2. Normal distribution - "typical area" of this study:
Control groups' mean values minus one standard deviation and plus one standard deviation

5.1. Mean speed

In Figures 3 and 4, the mean speed profiles and the mean speed variability profiles of patients with cerebral diseases are compared to the control's "typical area" (blue box represents the "typical area" in the rural area, whereas the brown box represents the "typical area" in the urban area) and several significant results were extracted; overall, 51% of the patients had extremely low mean speeds (below the lower limit of the control's "typical area"). Especially the group of AD patients drove significantly slower than the controls at the 68% of the cases. As expected, the speed was lower in urban area for all participants. Then, only 6% of the patients with cerebral diseases drove too fast, compared to the healthy controls. Regarding the mean speed of the PD and AD group, only the 35% of these drivers were inside the "typical area". Finally, drivers with a brain pathology had significantly lower speed variability (43% of the cases) than the group of controls. It is notable that 11% of PD drivers had significantly high speed variability in rural area.

Mean Speed		below lower limit	inside the "typical area"	higher than upper limit
Rural Area	PD	57%	36%	7%
	AD	67%	33%	0%
	MCI	43%	54%	3%
Urban Area	PD	43%	46%	11%
	AD	69%	25%	6%
	MCI	27%	64%	9%

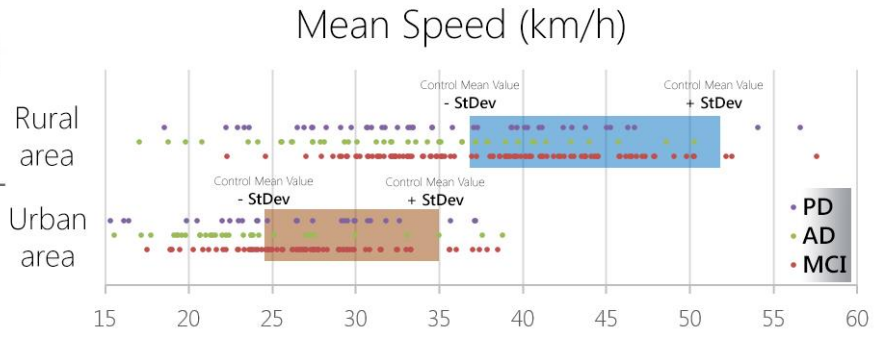

Fig. 3. Mean speed profiles of patients with brain pathologies

StDev of Mean Speed		below lower limit	inside the "typical area"	higher than upper limit
Rural Area	PD	50%	39%	11%
	AD	49%	42%	9%
	MCI	37%	55%	8%
Urban Area	PD	32%	61%	7%
	AD	59%	38%	3%
	MCI	32%	65%	3%

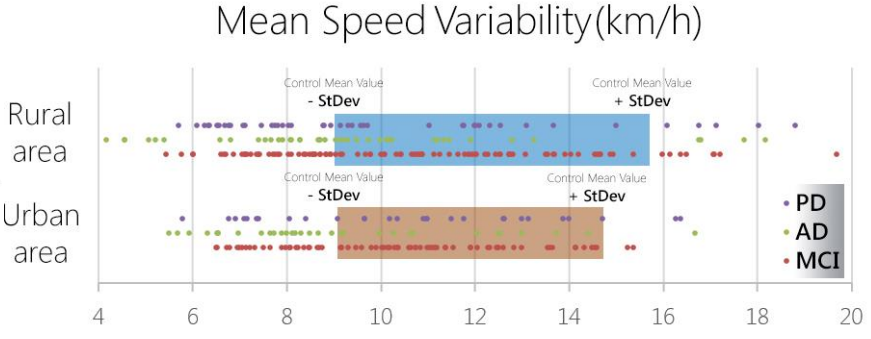

Fig. 4. Mean speed variability profiles of patients with brain pathologies

5.2. Time headway

In Figures 5 and 6, the time headway and the time headway variability profiles of patients with cerebral diseases are compared to the control's "typical area" (blue box represents the "typical area" in the rural area, whereas the brown box represents the "typical area" in the urban area) and several significant results were extracted; 44% of the drivers with a brain pathology in rural area have kept very large time headways, but in urban area this percentage was significantly lower (12%). No AD or PD patient kept a headway which was below the lower limit of the "typical area". Also, 20% of the patients had very large variability in their time headways whereas 12% of drivers with a brain pathology had significantly lower. It is important to mention, though, that regarding the variability of time headway in all groups of patients, at least 6 drivers out of 10 were inside the "typical area".

Time Headway		below lower limit	inside the "typical area"	higher than upper limit
Rural Area	PD	0%	48%	52%
	AD	0%	51%	49%
	MCI	5%	63%	32%
Urban Area	PD	0%	93%	7%
	AD	0%	75%	25%
	MCI	1%	95%	4%

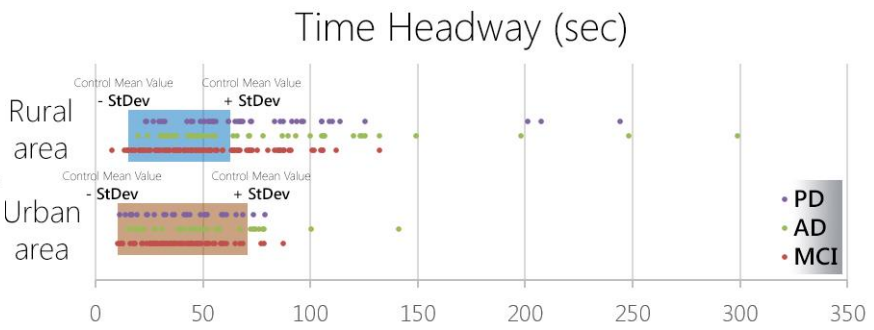

Fig. 5. Time headway profiles of patients with brain pathologies

StDev of Time Headway		below lower limit	inside the "typical area"	higher than upper limit
Rural Area	PD	7%	64%	30%
	AD	19%	65%	16%
	MCI	10%	71%	19%
Urban Area	PD	14%	79%	7%
	AD	6%	78%	16%
	MCI	13%	75%	12%

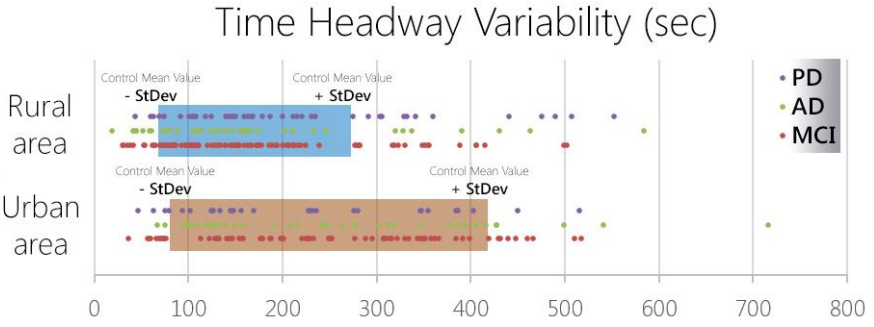

Fig. 6. Time headway variability profiles of patients with brain pathologies

5.3. Lateral position

In Figures 7 and 8, the lateral position and the lateral position variability profiles of patients with cerebral diseases are compared to the control's "typical area" (blue box represents the "typical area" in the rural area, whereas the brown box represents the "typical area" in the urban area) and several significant results were extracted; 32% of patients in urban area drove closer to the right border of the road (positive lateral position values indicate longer distance from the central axis of the road). Overall, 40% of drivers with cerebral disease were out of the "typical area", regarding the lateral position of the vehicle. Also, more than 1 out of 5 patients had very high variability in their lateral position. Especially for the group of AD in rural roads, 30% of this particular group had extremely high lateral position variability, despite the fact that the lane was narrow in rural area. It is important to mention that the rural route was single carriageway and the lane width was 3m, whereas the urban route was (at its bigger part) dual carriageway, and the lane width is 3.5m. Thus, the positioning of the vehicle cannot be compared between the two road environments. Overall, at least 30% of the patients group were outside the "typical area" regarding lateral position variability.

Lateral Position		below lower limit	inside the "typical area"	higher than upper limit
Rural Area	PD	30%	61%	9%
	AD	14%	67%	19%
	MCI	15%	66%	19%
Urban Area	PD	14%	57%	29%
	AD	3%	69%	28%
	MCI	8%	52%	40%

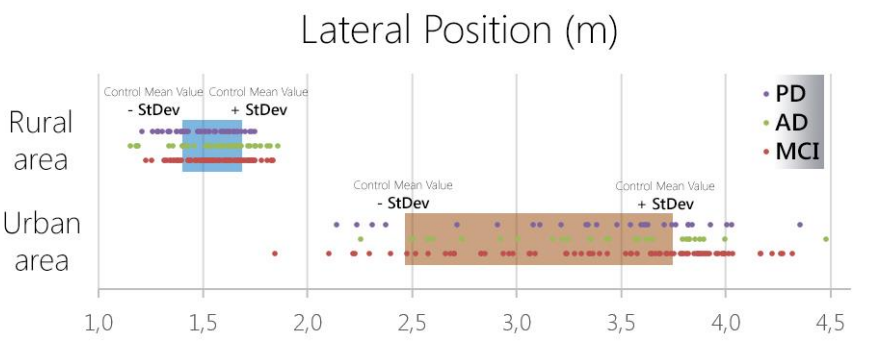

Fig. 7. Lateral position profiles of patients with brain pathologies

StDev of Lateral Position		below lower limit	inside the "typical area"	higher than upper limit
Rural Area	PD	7%	77%	16%
	AD	7%	63%	30%
	MCI	7%	81%	12%
Urban Area	PD	14%	57%	29%
	AD	9%	75%	16%
	MCI	8%	71%	21%

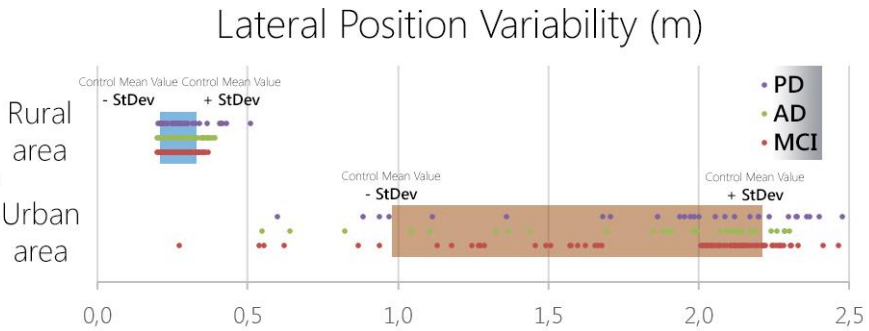

Fig. 8. Lateral position variability profiles of patients with brain pathologies

5.4. Reaction time

In Figure 9, the reaction time profiles of patients with cerebral diseases are compared to the control's "typical area" (blue box represents the "typical area" in the rural area, whereas the brown box represents the "typical area" in the urban area) and several significant results were extracted; the group of patients significantly deviated from the reaction time of the control group. More than 50% of participants with a brain pathology in rural area and 26% in urban area had significantly larger reaction times than the control group. In rural area 70% of the patients with cerebral diseases had reaction times larger than 2 seconds. Especially for the AD and the PD groups, the 42% of these participants were above the upper limit of the "typical area" in both rural and urban driving environments. It is important to mention that the reaction times of the rural area cannot be compared of the reaction times in urban area because all participants drove firstly in rural area and then in urban area for reasons that we presented in chapter 3. Finally, no patient was below the lower limit of the "typical area", regarding the reaction time.

Rection Time		below lower limit	inside the "typical area"	higher than upper limit
Rural Area	PD	0%	57%	43%
	AD	0%	40%	60%
	MCI	0%	69%	31%
Urban Area	PD	0%	74%	26%
	AD	0%	60%	40%
	MCI	0%	87%	13%

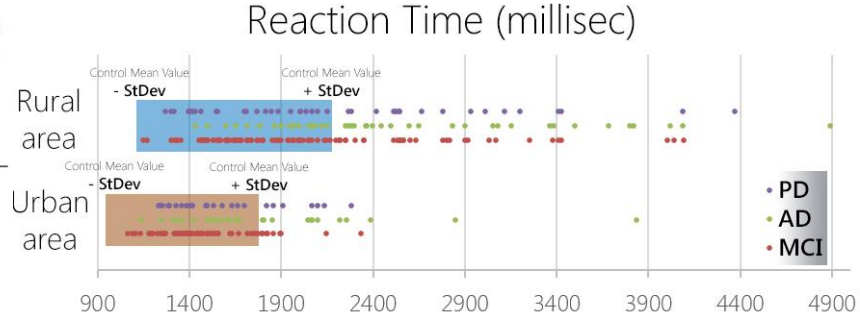

Fig. 9. Reaction time profiles of patients with brain pathologies

5. Discussion - Conclusions

This paper aimed to identify the driving performance measures in which drivers with brain pathologies significantly deviate from the general population. Relatively few studies exist analyzing the effect of a specific pathology on driving performance, and even fewer studies comparing different pathologies. The majority of these studies indicate serious deterioration in driving performance of drivers with a cerebral disease compared to healthy drivers.

In this research, the driving performance of 109 drivers with cognitive impairments (AD, PD and MCI) was compared to the driving performance of 31 cognitively intact healthy individuals with similar demographics, through a large driving simulator experiment. For each driver, the following 7 driving performance measures were calculated and examined, namely the mean speed, the mean speed variability, the time headway, the time headway variability, the lateral position, the lateral position variability, and the reaction time at incidents. All these driving indexes were compared to the range of "typical" values of the respective distribution of healthy drivers. The main research hypotheses were that a) the presence of a brain pathology has a negative effect on the driving performance measures of PD, AD and MCI patients as compared to cognitive intact individuals of similar age, education and driving experience, and b) the group of patients significantly deviate from the range of "typical values" of the control group, in most cases.

Summarizing the results, drivers with cerebral diseases were found to drive at lower speeds compared to the healthy control group drivers. Especially the group of AD patients drive significantly slower than the controls at the 68% of the cases. Regarding the mean speed of the PD and AD group, only the 35% of these drivers were inside the "typical area". Moreover, patients had significantly lower speed variability (43% of the cases) than the group of controls. As would be expected, this reduced speed had as a result, increased headways, in both rural and urban roads. Comparing the 3 groups of patients, it seemed that group of MCI drove slightly faster than the other 2 groups. The low mean speed of the group of patients and the low variability of the mean speed, indicates conservative driving behaviour and sometimes self-regulation of their driving behaviour caused by the self-awareness of their degraded driving performance. We conclude that drivers who significantly deviate from the "typical area" (below the lower limit), regarding mean speed, mean time headway and their variabilities, cannot be considered as "safe" drivers. This is a very strong indication, though, for degraded driving performance and should be taken into consideration combined with other driving performance indexes. Thus, these 4 measures can be considered as critical in order to assess driving performance of patients with cerebral diseases but only in combination with the following driving performance measures.

The following driving performance indexes analysed were the lateral control measures and it was observed that 32% of patients in urban area drove closer to the right border of the road. Overall, 40% of drivers with cerebral diseases were out of the "typical area", regarding the lateral position of the vehicle. Also, more than 25% of patients had very large variability in their lateral position (above the upper limit). Especially for the group of AD in rural roads, 30% of this particular group had extremely high lateral position variability, despite the fact that the lane was narrow in this area. It seems that the more complex is, the driving environment the more the patients have difficulty in maintaining the position of the vehicle in the lane. Thus, the variability of the lateral position is considered to be a critical driving performance index.

Analyzing the reaction times of the patients at unexpected incidents, it was observed that participants with brain pathologies had significantly longer reaction times in both rural and urban areas in comparison to the control group. Compared with each other, drivers with MCI seemed to have slightly better reaction times than the groups of AD and PD in most cases. It was impressive that in rural area 70% of the patients with cerebral diseases had reaction times larger than 2 seconds, and no patient was below the lower limit of the "typical area", whereas 42% of participants with AD or PD were above the upper limit of the "typical area" in both rural and urban driving environments. All these very large reaction times, are findings of great significance if we take into consideration the low mean speeds and low variabilities of the mean speeds that the groups of patients had. Hence, the reaction time is considered to be a critical driving performance and road safety parameter, in which the majority of the participants with cerebral diseases significantly deviated from the cognitively intact participants of similar demographic characteristics. The fact that these "not typical" findings that concern reaction time, are combined with "not typical" indexes in the other driving performance measures (like this study) is of great significance.

In conclusion, the take-home message of the current work is that some of the drivers with brain pathologies had serious difficulties in their driving performance in comparison with the healthy controls and their driving indexes deviated significantly from the "typical area" of the healthy controls. The presence of a brain pathology, such as AD, PD and in a lesser extend MCI, seems to lead to severe deterioration of the driving behaviour, regarding several longitudinal and lateral control measures, and road safety control measures such as the reaction time, which can lead to high accident probability. The critical measures to assess the driving performance of drivers with cerebral diseases are the mean speed (and its variability), the lateral position variability and the reaction time, but more importantly the critical measure is the combined assessment of all these parameters, in order to have a driving performance profile of each driver with a brain pathology.

Overall, all these observations that were extracted from the present study could have considerable practical importance; they provide quite useful information for the formulation of efficient driving recommendations which have the capacity to reduce the accident probability, and thus to reduce road fatalities in a sensitive group of car drivers, such that of drivers with MCI, AD or PD.

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