Driving Simulator Performance in Patients with Possible and Probable Alzheimer's Disease

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ABSTRACT - Drivers with more advanced stages of Alzheimer's disease (AD) have been previously associated with an increased rate of motor vehicle accidents. Drivers suffering from early AD are also involved in, and may even cause motor vehicle accidents with greater frequency than "normal" drivers. Consequently there is considerable public concern regarding traffic safety issues for those with AD and subsequently for society, but there has been little research in understanding whether deterioration in driving ability is progressive, or has a sudden onset once the disease has reached a certain severity. The purpose of this study was to identify possible degradation in simulated driving performance that may occur at the earliest stages of AD, and compare these decrements to a control group of normal drivers.

Using a single blind design, seventeen AD subjects, eight at a Clinical Dementia Rating (CDR) of 0.5 (possible AD) and nine at a CDR of 1 (probable AD), were compared to 63 cognitively normal, elderly controls. All subjects were trained to drive a computerized interactive driving simulator and then tested on a 19.3 km (12 mile) test course.

The AD subjects demonstrated impaired driving performance when compared to the controls. The simulated driving performance of the CDR 1 AD subjects was so degraded that it would be regarded as unsafe by standard assessment criteria. The CDR 0.5 subjects made similar errors, suggesting that driving impairment may occur at the earliest stages of the disease. Further work will be necessary to determine the significance of these findings.

INTRODUCTION

Generally, in North America the risk of automobile collisions rises with the age of the driver. However, in older drivers this increase is related to the number of miles traveled by the driver (a measure of exposure) with decreasing annual mileage resulting in an increased probability of collision involvement. [Cerrelli, 1989; Langford, Methorst. Hakamies-Blomqvist., 2006] Perceptions by the general public that older drivers, especially those with Alzheimer's disease (AD), do not drive safely are based primarily on anecdotal reports in the press [Suroff, 1997]. Increased demand for legislative control of driving by impaired elders has resulted from these perceptions. Extensive research has determined standard driving criteria for individuals under the influence of alcohol [Allen, Jex, McRuer, et al., 1975], however, similar criteria have not been clearly defined for older, potentially impaired, drivers.

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Advancing age is the single greatest risk factor for Alzheimer's disease [NIH, 1998], and it is well established that individuals with AD drive long after the diagnosis has been made [Dubinsky, Williamson, Gray et al., 1992, Hunt, Morris, Edwards, et al, 1993; Odenheimer, 1993]. Lack of a meaningful, exposure based collision rate is one limitation to the study of older drivers collision involvement. Additionally, the nature of the driving errors committed by older, impaired individuals, such as those affected by AD, has only begun to be explored. The older driving population in the United States is increasing as 'baby boomers' reach old age making the understanding of any potential differences in normally aging and AD impaired older drivers of increasing importance.

To assist clinicians with AD patients in counseling patients and their families, the American Academy of Neurology has developed, and subsequently updated a Practice Parameter for Driving and AD used to assist clinicians in treating patients with dementia. In reviewing the literature related to driving and AD a striking finding was the limited research of AD drivers at a Clinical Dementia Rating (CDR) of 0.5, while there was significant research for drivers with CDR 1 [Dubinsky, Stein, Lyons, 2000; Iverson, Gronseth, Reger et al., 2010].

On-the-road tests provide the most realistic method of examining driving behavior and performance, yet there are inherent risks to the subject, the examiner, and the general driving public [Odenheimer, Beaudet, Jette, 1994; Sivak, 1981]. It would appear that the best possible method for testing a subject's ability to drive under their *usual* conditions is to observe the person driving their own vehicle in their neighborhood. While seemingly more realistic, there are many problems this type of on-the-road test may not address. First, the data collected are subjective, and there may be biases or differences introduced by different examiners. Also, as many accidents involving elders occur when they are lost and become confused [Fitten, Perryman, Wilkinson et al., 1995], driving in one's neighborhood eliminates the possibility of a confusion-based error.

One method for overcoming the shortfalls of on-the-road examination is testing in a computerized, interactive driving simulator. These simulators have been used extensively to investigate the performance of both normal and impaired drivers. The advantages of driving simulators include standardization of the course, vehicle handling, road conditions, traffic density, and ambient light. Additionally, simulators allow the staging of potential collisions without risk to the subject, the examiner, or the driving public. While simulators do not have the realism of on-the-road testing, they are realistic enough that most subjects report a sensation of movement, and driving performance has been shown to be the same when driving simulator performance is compared with driving performance in an instrumented vehicle on a closed course [Stein, Allen 1987; Allen, et al., 1975].

As reported above, most previous studies have studied individuals at CDR 1, and little research has been conducted in those individuals at CDR 0.5. This research examined the driving behavior of a small group of patients with mild cognitive impairment, determined by a significant change in memory performance after multiple, yearly evaluations of cognitive performance (CDR 0.5), and compared their performance to both drivers with CDR 1 and cognitively normal elder controls.

METHODS

All subjects were participants in a longitudinal study of AD and healthy aging as part of the University of Kansas Alzheimer's Core Center's research. The primary study group included eight subjects identified as having recent onset of minimal cognitive impairment. This was established by having normal cognition the year prior to testing, but exhibiting clinically significant memory impairment (CDR score equal to 0.5; [Morris, 1993]) at the time of their driving performance evaluation. These individuals were chosen specifically for the presence of earliest detectable cognitive impairment. It is significant that many of these individuals would be identified as cognitively unimpaired by routine medical evaluations.

This group was compared to a group of nine subjects previously diagnosed with a CDR score equal to 1.0. Both groups were compared to a "normal" sample of 64 cognitively unimpaired, age and gender matched control subjects (CDR = 0). Each control subject underwent extensive neuropsychological testing and was free of measurable cognitive impairment.

Participation in the study required a valid driver's license and the subject to be currently driving without the use of assistive devices (glasses and hearing aids were allowed). These minimal requirements, combined with the need to obtain subjects in a timely manner proved to be a significant stumbling block in obtaining both CDR 0.5 and 1.0 subjects.

In our recruitment pool of subjects most of the CDR 1.0 subjects had given up driving. The CDR 0.5 group came from subjects who were initially considered "normally aging", but who were discovered to have developed minimal cognitive impairment over the previous year. Both groups were small to begin with, and became even smaller when potential subjects declined participation.

As a result of difficulty in obtaining the study group, we were unable to match groups for current driving experience. When recruited for the study, subjects were informed that their simulator performance would not be used to make a decision about fitness to drive, nor would it be reported to any governmental agency. The Human Subjects Committee of the University of Kansas Medical Center approved this study.

Neuropsychological Testing

All subjects were administered the Mattis Dementia Rating Scale [Shay, Duke, Conboy, et al., 1991] and the Mini Mental State Examination (MMSE) [Folstein, Folstein, McHugh, 1975] as part of their annual visit to the Alzheimer's Disease Clinic. These tests were required to have been administered within three months of participation in this study.

The CDR stage was based on the clinical impression, using a standardized protocol [Morris, 1993] at visits to the University of Kansas Alzheimer's Disease Clinic administered before entering the driving study. The investigators administering the driving training and testing were blinded to the subject's CDR score as well as their scores on the neuropsychological tests.

Driving Simulator

The driving performance data were gathered in a fully interactive, fixed-base driving simulator installed in a cut down mid-sized sedan, described in Allen, Stein, Aponso, et al. (1990). The simulator was located in a windowless room adjacent to the Alzheimer's Disease Center at the University of Kansas Medical Center. This type of simulator has been used extensively for the testing of driving behavior and has been validated against on-the-road driving performance as previously discussed in the Introduction. All interior controls and displays are intact. The simulator display is placed outside the cab so the roadway scene of a two-lane highway and horizon is presented in the driver's line of sight.

The roadway and background are displayed on a computer monitor presenting a 50-degree x 40-degree field of view. The displayed roadway is interactive with the driver's control inputs so that, for example, when the driver depresses the accelerator or brakes it appears as if the vehicle is accelerating or slowing, the driver's steering inputs result in the vehicle changing direction, etc. The driver's inputs are processed through a simplified set of vehicle equations of motion providing appropriate acceleration, braking, steering, and time delay responses for a mid-sized car with vehicle response characteristics appropriate to its type and size [Allen, et al., 1990]. The simulator includes realistic sound representations of the interior of the car, including drive train, exhaust, and wind noises, and the shift points of an automatic transmission.

The subject was presented with curves, obstacles, and traffic signal events at specific locations on the driving course. The driver's impression was that of a rural roadway. Periodically the driver needed to negotiate a curve, obey a traffic signal, drive through an uncontrolled intersection, or control the vehicle in a section of roadway appearing to have gusty winds.

The simulator has been extensively validated against both closed course and real world driving, and has been found to be robust in its realism and fidelity. [Allen, Mitchell, Stein, et al., 1991]

Driving Tasks

The workload for the driver was designed to be typical for a rural drive, with a task encountered on an average of once every 30 seconds. The driving tasks were presented to the subjects in a pseudorandom order and starting points were counterbalanced to prevent learning.

Discrete driving tasks included:

Intersections with a tri-light traffic signal set for one of three decision making conditions: *Must go*: the signal stayed green until after the subject entered the intersection; m*ust stop*: the signal changed from green to yellow seven seconds before the vehicle arrived at the intersection; and, *should stop*: the signal indication changed from green to yellow five seconds before the vehicle arrived at the intersection (derived from the minimum yellow light change interval timing found in [FHWA, 2003]). Signal timing for the yellow light was based on the vehicle's velocity 152 meters (500 ft) before the intersection.

In addition, if the driver stopped for the red light, data were obtained for their reaction time to the fresh green light.

Uncontrolled intersections with and without cross traffic, and with and without pedestrians. Intersections were presented without signals or stop signs; and either without cross traffic, or with cross traffic that required the subject to either speed up or slow down to avoid a collision; or either without a pedestrian, or with a pedestrian that required the driver to slow down to avoid a collision.

Curve negotiation. Curves of 122 and 914 meters (400 and 3000 ft) radius signed with a speed limit advisory of 65 km/hr (40 mph).

Speed control. The speed limit was 90 km/hr (55 mph) except for a 6.0 km (3.75 mi) segment at the end of the first one-third of the drive where the speed limit was reduced to 70 km/hr (45 mph). If the posted speed was exceeded by 5 km/hr (3 mph) a 'speed exceedance' was recorded. If a police officer was present on the course at that time the driver also received a speeding ticket.

As part of the overall driving task, vehicles approaching in the opposing lane were included in the driving scenario. If the subject drifted into the opposing lane and struck the approaching vehicle a collision occurred.

During the entire drive, data were collected on total run time (seconds), accidents (running off the road), collisions (striking either another vehicle or pedestrian), speed exceedances (the number of times the speed limit was exceeded by more than 5 km/hr [3 mph]), speeding tickets (the number of times the speed limit was exceeded by more than 5 km/hr (3 mph) *and* the traffic officer was present), and stop light tickets. An investigator manually recorded the subjects' response at each stoplight based on the 'must go, must stop, and should stop' timing.

In addition to the above discrete driving tasks, two 1.22 km (4000 ft) straight sections of roadway appearing to have random wind gusts were used to assess the subjects' vehicle control capabilities. The random wind gusts are presented in the visual representation of the roadway, and are a fixed-instability tracking task introduced into the steering feedback loop in the vehicle dynamics equations of motion. To the driver it appears as if the vehicle is being moved by an external force (wind), and a steering input is required to correct the movement.

A divided attention task was presented during the first wind gust section. During the divided attention task, subjects were required to respond to horn or turn signal icons displayed in the upper corners of the display monitor. The subjects had 5 seconds to respond to the task before the icon was removed from the display. This task is a visual vigilance task similar to the drivers' need to periodically check the side- and rear-view mirrors and was displayed eight times during the divided attention drive [Stein, 1987].

The vehicle control data collected during the performance blocks included: mean and standard deviation of lane position, mean and standard deviation of velocity, and divided attention task results. Data included the mean and standard deviation of the response time, and correctness of the response

Research has shown every driver displays an amount of lane tracking instability or wobble. As their lane position approaches their predetermined limit, the driver will correct and return towards the middle of the lane. This correction occurs well before the driver approaches the lane boundaries and is typically 0.3 m (1 ft) or less [Stein, Allen, 1987]. The average lane position is much the same among drivers. The standard deviation of lane position is the measurement of the amount tracking instability or wobble from the average lane position. When the standard deviation of lane position approaches 0.6 m (2 ft) the edges of the driver's car will cross the lane boundaries. A collision will occur if another vehicle is present or if an obstacle is present on the shoulder of the road.

Similarly, while the average velocity gives an overall measurement of speed control, the standard deviation of velocity measures the variability in the driver's ability to control velocity. The more variable the driver's standard deviation of lane position and standard deviation of velocity, the greater their likelihood of being involved in an accident.

Increased standard deviation of lane position and standard deviation of velocity are commonly seen with driving impairment due to alcohol, fatigue, diazepam, and antihistamines [Stein, 1987, Allen, Stein, Jex, 1981, O'Hanlon, Ramaekers, 1995a, O'Hanlon, Vermecren, Uiterwijk, et al., 1995b]. In many instances impaired drivers will "trade off" between steering control and speed control, thus as the standard deviation of one improves the other deteriorates.

Subjects completed seven training drives ranging in distance from 2.0 to 3.0 km (1.25 mi to 1.75 mi). Each training drive focused on specific tasks (e.g., traffic lights) that the subject had to master before advancing to the next training drive.

Simulator training took approximately 90 minutes for each subject. After a ten minute break the subjects were given a final set of instructions before starting the test drive.

Reward-Penalty Structure

A reward-penalty scheme was used to encourage real-world driving [Cook, Allen, Stein, 1981]. As part of the reward, subjects were paid a fixed amount for their participation in the project. They were also monetarily rewarded for finishing the drive within a predefined reference time (simulating driving with the flow of traffic), and for responding both quickly and accurately to the divided attention task (simulating appropriately dividing their attention between the primary speed and steering control tasks and the requirement to be aware of surrounding traffic).

Monetary penalties were assessed for accidents (running off the road) and collisions, speeding and signal light tickets, and for not responding to the divided attention task or for responding incorrectly. The subjects were also made aware that the traffic officer who issued speeding and signal light tickets would only be on the course a small percentage of the time.

The rewards and penalties were scaled to represent the real world contingencies of the reward or penalty. For example collisions were assessed at a higher rate than tickets.

Data analysis was performed using a one-way ANOVA with the Student-Newman-Keuls test used for post hoc comparison.

RESULTS

Demographic and neuropsychological test results for the CDR 0.5 group, CDR 1 group and Normal Controls (CDR 0) are summarized in Table 1. As a group, the age, sex distribution, and driving exposure of the three control groups were similar. One of the 64 control subjects was unable to complete the training on the simulator due to motion sickness. The seventeen drivers at CDR 0.5 and CDR 1, and the remaining 63 controls were able to complete the simulator training and the test.

Table 1. - Subject Demographics and Neuropsychological Test Results

	CDR 1	CDR 0.5	Controls	p
N	9	8	64	
Male/Female	5/4	5/3	35/29	
Age	71.2 ±8.7	74.3±12.2	73.5±6.9	.6728
Km/yr driven	14914	14001	14912	.1583
(range)	(1000-29000)	(3900-39000)	(300-39000)	
Mattis Dementia Rating	112.1±16[a]	128.1±8[b]	138.0±5[c]	<.0001
MMSE Score	22.6 ±3.2[a]	26.5 ±3.5[b]	29.3 ±0.9[c]	<.0001

Means with the same letter are not significantly different from each other at $p \leq 0.05$

Overall Driving Performance

Significant differences in overall driving performance were found between the three groups and is summarized in Table 2. The drivers with CDR 0.5 and CDR 1 had more accidents (running off the road) and collisions (striking an object) than the controls. The drivers with CDR 1 struck more pedestrians (7 collisions for 9 drivers) than the controls (one collision for 63 drivers) or the drivers with CDR 0.5 (none). The drivers with CDR 0.5 and the drivers with CDR 1 took longer to complete the drive and had more errors of judgment at traffic lights, but not at uncontrolled intersections. The subjects' traffic light mistakes were generally too conservative (i.e., slowing down or stopping for a green light). There were no differences between the groups in the number of speed exceedances or the reaction time to a fresh green light.

In addition, we found the CDR 0.5 and CDR 1 drivers' consistently exhibited an unexpected and inappropriate driving behavior: they stopped for the yellow, diamond shaped symbol sign. that displayed a graphic representation of a tri-light traffic signal with all three lights showing. This sign was not seen during the training session. The actual intersection and stoplight were not visible until after the driver had passed the warning sign. The drivers with CDR 1 made this error twice as often as the drivers with CDR 0.5, and the CDR 0.5 group made the error five times more often than the control group.

During both 1.2 km (4000 foot) vehicle control segments the three groups had similar performance on average lane position and average speed. On the segment without the divided attention task the standard deviation of lane position (SDLP) of the CDR 1 drivers approached 0.6 m (2 ft), while the SDLP of the drivers with CDR 0.5 and the control groups were nearly identical. Also, the drivers with CDR 1 had significantly greater standard deviation of velocity (SDv) than did the normal drivers. The drivers with CDR 0.5 fell between the two other groups on this variable, and were not significantly different than either.

Table 2 – Overall Driving Performance

	CDR 1	CDR 0.5	Controls	p
Accidents (run off road)	3.67 ±3.32[a]	2.25 ±2.19[a]	0.58 ±0.87[b]	<.0001
Collisions	3.1 ±2.6[a]	3.0 ±1.6[a]	0.8 ±1[b]	<.0001
Ped. Collisions	0.67 ±1.0[a]	0 ±0[b]	0.06 ±0.3[b]	.0005
Run time (secs.)	1787 ±362[a]	1687 ±511[a]	1361 ±157[b]	<.0001
Traffic light errors	2.89 ±1.69[a]	1.87 ±1.55[a]	.051 ±1.05[b]	<.0001
Mean traffic light reaction time	1.08 ±0.57	1.2 ±0.3	1.05 ±0.51	.6117
"Signal Ahead" sign errors	0.78 ±1.09[a]	.038 ±1.06[a,b]	0.079 ±0.27[b]	.001
Intersection errors	1.44 ±0.88	1.25 ±1.0	1.13 ±0.91	.6073
Speed exceedances	9.56 ±4.25	9.13 ±6.17	9.21 ±6.86	.9877

Means with the same letter are not significantly different from each other at p≤0.05

When the divided attention task was presented during the segment, the drivers with CDR 0.5 and CDR 1 missed most of the divided attention tasks while the normal drivers responded correctly to most of the divided attention tasks. For all groups, the data on both standard deviation of lane position and standard deviation of velocity was similar to their no divided attention segment. Table 3 summarizes the above findings.

Table 3 – Performance During the Vehicle Control Segments

	CDR 1	CDR 0.5	Controls	p
Without Divided Attention Task				
SDLP (m)	0.56 ±0.36[a]	.032 ±0.13[b]	0.32 ±0.10[b]	.0001
Mean velocity (km/hr)	79.37 ±14.5	78.68 ±21.71	84.17 ±5.91	.1747
SDv (km/hr)	6.63 ±4.30[a]	4.07 ±2.93[a, b]	2.56 ±2.11[b]	.0001
With Divided Attention (DA)				
Correct DA responses	1.33 ±2.18[a]	2.75 ±3.33[a]	5.37 ±2.21[b]	<.0001
SDLP	0.54 ±.026[a]	0.36 ±0.09[b]	0.38 ±.013[b]	.0116
Mean velocity	74.67 ±13.18	77.62 ±14.03	81.55 ±10.38	.1734
SDv	11.49 ±11.22[a]	6.55 ±5.91[a, b]	5.60 ±5.66[b]	.0441

Means with the same letter are not significantly different from each other at p≤0.05

Comparison by 2 x 2 ANOVA showed that the standard deviation of lane position and standard deviation of velocity increased significantly ($p = .0029$ for standard deviation of lane position and $p = .0001$ for standard deviation of velocity) for the control group when comparing performance on the two divided attention conditions. However, the standard deviation of lane position and standard deviation of velocity did not significantly change for the drivers with CDR 0.5 or CDR 1 between these conditions ($p > .05$). In both cases, the standard deviation of lane position and of velocity for the CDR 0.5 and CDR 1 drivers was worse than that of the controls.

Since we were not able to match control drivers with test drivers on the basis of annual mileage, we investigated the possibility that differences in driving performance were partially explained by differences in driving exposure. We examined this by both dividing the subjects into two groups either above or below the median miles per year, or dividing the population into three mileage groups. No correlation was found between driving exposure and simulator performance.

DISCUSSION

This study examined simulated driving performance of individuals with clinically possible (CDR 0.5) and clinically probable (CDR 1) AD. Overall driving performance was significantly impaired for both CDR groups, although the CDR 0.5 group performed better, on average, than did the CDR 1 group. The mistakes made by the drivers with CDR 0.5 and CDR 1 are best characterized as (1) inattention manifested as missed divided attention responses and impaired vehicle control (increased standard deviation of lane position and increased standard deviation of velocity), (2) judgmental errors (accidents, collisions, pedestrian collisions, stop light errors, misperception of the signal ahead advisory signs), and (3) driving too conservatively (increased total run time, tendency to drive slower during the vehicle control segments). While many of these errors in driving performance are similar to driver behavior reported in the limited survey studies of drivers at CDR 0.5, this research studied objective driving behavior in a group of patients who had the very earliest signs of cognitive impairment as identified by repeated yearly cognitive evaluations [Dubinsky, Stein, Lyons, 2000; Iverson, Gronseth, Reger et al., 2010].

Driver Inattention

The CDR 0.5 and CDR 1 groups missed most of the divided attention tasks. This task is analogous to looking at the side and rear view mirrors as part of the driver's surveillance of traffic, and locating and using navigational landmarks as a component of route finding [Stein, 1987, Stein, Allen, 1987]. Getting lost is a direct consequence of inattention to route finding.

The mild, yet significant increase in the standard deviation of lane position and standard deviation of velocity of the control group, when distracted by the divided attention task, is typical driving performance for an unimpaired driver [Allen, Stein, 1987]. The standard deviation of lane position and the standard deviation of velocity did not change for the CDR 0.5 and CDR 1 groups when they were distracted by the divided attention task. This is most likely because both of these groups responded to relatively few of the divided attention tasks. It appears that these drivers were working at capacity during the no divided attention segment to simply maintain their vehicle heading and speed. They appeared to have little cognitive processing reserve to detect and react to the divided attention task. Thus there was no change in their standard deviation of lane position and standard deviation of velocity between the two segments. The poor performance of the drivers with CDR 0.5 and CDR 1 on the divided attention task corresponds to the problems with AD drivers becoming lost reported by other investigators [Friedland, Koss, Kumar, et al, 1988, Gilley, Wilson, Bennett, et al., 1991] and their poor maintenance of lane position is consistent with impaired lane control as reported by Rizzo, Reinach, McGehee, et al. (1997).

The findings of Rizzo, et al., are similar to ours, in that the drivers with CDR 1 not only had more crashes but also had significantly more lane deviations (crossing over the yellow line into the oncoming traffic lane or crossing over the white line onto the shoulder of the highway). By measuring the standard deviation of lane position we provide a continuous measurement of the lane tracking instability of drivers, demonstrating that the drivers with CDR 1 have a significant lane tracking instability and that the drivers with CDR

0.5 have similar problems, though to a lesser degree.

Difficulty in maintaining speed or lane position can lead to driver inattention, and is typical of an impaired driver. This behavior is consistent with several theories of driving behavior which state that drivers will attend to the higher order tasks of lane position and speed maintenance before attending to other driving tasks [Allen, et al., 1991, Allen, Stein, 1989, Bellenkes, 1997].

Errors Of Judgment

Several of our drivers with Alzheimer's disease stopped inappropriately at a sign warning of an upcoming stoplight. Brashear, Unverzagt, Kuhn, et. al. (1998) reported that drivers with early Alzheimer's disease had difficulty identifying the 10 international traffic signs that are presented as part of the written driver's licensing examination.

While, on the surface, not understanding the meaning of an advance warning sign may appear to be a benign error, it actually can have significant traffic safety implications. If a driver is being followed by someone who understands the meaning of the advanced warning sign, and the driver ahead stops for the sign and not at the intersection (especially if the signal is visible and green), the following driver runs a risk of rear-ending the errant driver. Since the rear-ending driver is usually found at fault, the judgmental error may never come to light, and appropriate assessment of the offending driver may never occur.

Driving Too Conservatively

Drivers plan and execute components of the driving task based upon their prediction of the actions of the other drivers on the roadway. When a driver is too conservative (e.g. driving well under the speed of surrounding traffic or waiting excessively to make a turn) other drivers may incorrectly predict their behavior leading to an accident. The drivers with CDR 0.5 and CDR 1 drove in a conservative fashion apparently because they had already reached their maximum processing capacity and they had no cognitive reserves to devote to the increased level of cognitive demands of driving at the speed limit. The only accommodation that they could make to their driving performance was to slow down, thus increasing the time available for their processing capacity. This solution did not provide adequate compensation as shown by the increased number of errors on the part of the drivers with CDR 0.5 and CDR 1.

This research, as well as the research of others have shown that driving by those with CDR 1 poses a traffic safety problem. The impairments in their driving abilities include an increase in the accident rate, frequently getting lost (even in familiar territory), causing accidents or near accidents, misinterpreting or not responding to traffic signs, and impaired ability to maintain their vehicle at an appropriate speed and position on the roadway.

In this study, by examining drivers at the very earliest stages of AD, we have shown that they make many of the same errors and have the same difficulties with driving performance as drivers with CDR 1. While accident rates of those with CDR 0.5 and CDR 1 are no more than what is tolerated by our society in beginning drivers, driving performance by drivers with early AD is likely to degrade over time. The data presented here suggest that driving performance begins to degrade at the earliest stages of AD.

Further work will be necessary to determine the significance of these findings. For example, comparing the simulator performance of our subjects with actual driving records may provide insight into the reliability of conducting simulator research on this population of subjects. Replication of this study with a larger subject population will allow validation of the results presented herein. The inclusion of additional performance measures, such as unobtrusive eye tracking, may result in the ability to understand why certain errors are committed. Finally, we have developed some hypotheses on the use of "low tech" solutions to overcome some of the errant driving behaviors in both CDR groups.

LIMITATIONS

There were limitations to the study, which were due to the limited funding and time available for completion of the research.

First, the populations of CDR 0.5 and 1.0 subjects were limited. Thus, any findings in this study may not generalize to the larger population of these drivers. However, it should be noted that this research found results similar in nature to those of others studying driving in these populations. [eg., Duchek, Hunt, Carr, et al., 2003]. It should also be noted that finding drivers in this population is a significant challenge.

Many of these patients have given up driving, and therefore will not qualify for this type of research. The difficulty in recruiting subjects in the CDR population also resulted in an inability to match subjects for driving experience.

The second limitation comes from the use of simulation to test the drivers. While workloads are kept consistent with the type of drive desired (i.e., rural, urban, etc.) the tasks themselves are designed to result in higher accident probabilities than are experienced in the real world. This is an unfortunate requirement of conducting this type of research, as we need to be able to gather appropriate and relevant data in a reasonable time period. As discussed earlier, the collision rates of the subjects presented herein - six collisions per hour of driving for CDR and nearly two collisions per hour for controls – is unrealistically high and would certainly result in loss of driving privileges in the real world. It is not clear if the unrealistically rigorous driving environment we designed exacerbates the performance differences between the control and CDR groups, and thus it is possible that in an on-road driving situation where more normal accident rates are experienced the CDR and normal control subject's performance might be similar.

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