ORIGINAL CONTRIBUTION

Simulated Car Crashes and Crash Predictors in Drivers With Alzheimer Disease

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Background: Alzheimer disease (AD) is the most common cause of dementia and can impair cognitive abilities crucial to the task of driving. Rational decisions about whether such impaired individuals should continue to drive require objective assessments of driver performance.

Objective: To measure relevant performance factors using high-fidelity driving simulation.

Design: We examined the effect of AD on driver collision avoidance using the Iowa Driving Simulator, which provided a high-fidelity, closely controlled environment in which to observe serious errors by at-risk drivers. We determined how such unsafe events are predicted by visual and cognitive factors sensitive to decline in aging and AD.

Setting: The University of Iowa Hospitals and Clinics, Iowa City, and the Iowa Driving Simulator.

Participants: Thirty-nine licensed drivers: 21 with AD and 18 controls without dementia.

Main Outcome Measures: We determined the number of crashes and related performance errors and analyzed how these occurrences were predicted by visual and cognitive factors.

Results: Six participants (29%) with AD experienced crashes vs 0 of 18 control participants ($P=.022$). Drivers with AD were more than twice as likely to experience close calls ($P=.042$). Plots of critical control factors in the moments preceding a crash revealed patterns of driver inattention and error. Strong predictors of crashes included visuospatial impairment, reduction in the useful field of view, and reduced perception of 3-dimensional structure-from-motion.

Conclusions: High-fidelity driving simulation provides a unique new source of performance parameters to standardize the assessment of driver fitness. Detailed observations of crashes and other safety errors provide unbiased evidence to aid in the difficult clinical decision of whether older or medically impaired individuals should continue to drive. The findings are complementary to evidence currently being gathered using techniques from epidemiology and cognitive neuroscience.

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CAR CRASHES pose a serious public health problem and result in great individual suffering and costs to society. Many fatal crashes are due to faulty driving by unfit operators, and special concerns have been raised about drivers who have Alzheimer disease (AD), the most common cause of dementia. The number of older people with AD is projected to increase sharply in the next several decades,[1] with clear implications for collision risk. Yet there still seems to be little agreement on how to advise these individuals about whether to keep driving.[2-5]

An international panel of experts convening in Borlänge, Sweden, agreed that decisions on the fitness to drive of at-risk drivers should be based on empirical observations of performance, because age or medical diagnosis alone are often unreliable criteria.[6] State road tests, however, are designed to ensure that novice drivers know and can apply the rules of the road, not to predict crash involvement in skilled drivers who may have become impaired. Also, the driving task may involve hidden strategic, tactical, and operational variables that are simply not measured by standard neuropsychological probes.[7] Recent studies[8,9] found that car crashes in large samples of older drivers were predicted by reductions in the useful field of view (UFOV) and occurred, in part, as a result of improper backing up or stopping, loss of control, failure to merge, and especially failure to yield right-of-way or notice other drivers at intersections. Yet real-life crashes are sporadic, uncontrolled events, and there are few critical observations. Personal accounts and even state crash records may be incomplete, and crashes are underreported. Therefore, it is desirable to observe serious driver errors in an environment that is challenging yet safe for the driver and tester, preferably under conditions of optimal stimulus and response control. For these reasons, we used the Iowa Driving Simulator (IDS) in experiments using high-fidelity collision avoidance scenarios. Our goals were the following: (1) to test the hypothesis that drivers with AD are more at risk for crashes than control participants without dementia of similar ages, (2) to determine what specific driver safety errors preceded a crash, and (3) to determine how such unsafe events are predicted by visual and cognitive factors sensitive to decline in aging and AD.

SUBJECTS AND METHODS

IOWA DRIVING SIMULATOR

The IDS is a realistic ground-vehicle simulator that uses recent technological innovations in computational dynamics, parallel computing, and image generation. The current configuration provides 190° in the forward field of view and 65° in the rear view. Multiple roadway types, traffic signals, traffic conditions, and vehicles can be displayed. These vehicles interact with the driver and each other according to a particular set of rules dictated by the experimental driving scenario. A large-payload, 6-*df* motion base provides excursions of ±112 cm with acceleration speeds up to 1.1g to produce a majority of the movement cues experienced during normal driving. Movement excites the vestibular organs to generate effects that cannot be reproduced in a static environment[10] and also reduces simulator discomfort encountered in static simulator environments by reducing visuovestibular mismatch. Washout algorithms permit movement of the car without commanding the motion base outside its limited envelope. The steering wheel, accelerator, brake pedal, and gear shift positions are read by a host computer to give feedback to the driver and to allow him or her to control the driving simulation. The speedometer, tachometer, indicator lights, and a motor on the steering column also provide feedback. The simulated environment is supplemented by realistic audio special effects providing accurate directional cues, including engine, wind, and road noise. Driver gaze position is assessed using unobtrusively mounted, charged, coupled device lipstick-size cameras. The IDS immerses the participant in the task of driving and allows investigators to examine, in detail, situations that cannot be safely evaluated in the field. Investigators are able to exercise control over the environment and vehicle being driven, replicate these conditions in different populations (including those with medical impairments), and acquire accurate measures of driver responses (**Figure 1**).

SUBJECTS

Subjects were 21 participants with AD (mean±SD age, 71.5±8.5 years) and 18 control participants without dementia (mean±SD age, 71.9±5.5 years). Participants with AD were recruited from a registry in the Alzheimer's Disease Research Center of the Department of Neurology, University of Iowa, Iowa City. The diagnosis relied on the recommendations made under the auspices of the Department of Health and Human Services Task Force on Alzheimer's Disease.[11] Computed tomographic and magnetic resonance imaging scans of the brain were obtained in all participants with dementia to help exclude destructive lesions due to cerebrovascular and neoplastic disease. Control participants were recruited from volunteers in the local community. All participants held a current, valid state driver's license, although some had reduced driving activity because of self- or family-imposed restrictions. Criteria for exclusion included alcoholism, stroke, depression, vestibular disease, and motion sickness. Informed consent was obtained in accord with institutional guidelines at the University of Iowa.

All participants were tested on the same batteries of cognitive and visual tasks. The AD group showed mild to moderate dementia reflected by poorer performance than control participants on a number of neuropsychological measures. There was no difference in visual acuity between the groups, although the AD group had a slight reduction in static spatial contrast sensitivity, measured with the Pelli-Robson chart ($P=.07$, rank sum test): the control group had a mean score of 1.89 and a median score of 1.95 while the AD group had a mean score of 1.73 and a median score of 1.73. The AD group also had a higher total UFOV loss (group mean, 66%) than the control group (group mean, 33%; $P=.0001$, Wilcoxon rank sum test).

DRIVING SCENARIO

Each participant drove approximately 29 km on a simulated rural 2-lane highway with interactive traffic. Four events associated with potential crashes were interspersed with uneventful highway segments (**Figure 2**). A warm-up and training phase lasting 15 to 20 minutes preceded the experimental drive. In this preparatory phase, each participant was escorted to the simulator bay and up a set of stairs leading into the dome and seated in the driver's seat of the car, a 1993 General Motors Saturn (Saturn, Spring Hill, Tenn). A research assistant seated in the front passenger seat helped familiarize the driver with the vehicle controls. The assistant was generally a registered nurse who measured the participant's vital signs and also monitored the participant for signs of discomfort or fatigue. Prior to beginning the experiment, each driver was familiarized with the simulator by driving on a segment of a simulated 2-lane highway. Microphones in the vehicle allowed an operator in the control room (located adjacent to the simulator bay) to monitor onboard activity, start and stop the simulation on demand, and inform the onboard research assistant via an earpiece of control room developments. The driver did not wear an earpiece and could not hear the control room operator.

MEASURES OF DRIVING PERFORMANCE

Experimental performance data were digitized at 30 Hz and reduced to means, SDs, or counts for each virtual road segment. Simulator output included steering wheel position (in radians or degrees), normalized accelerator and brake pedal position (ie, scale of pedal depression from

0%-100%), lateral and longitudinal acceleration (in terms of gravity), headway (distance to the lead vehicle in meters), time to collision (in seconds), and speed (in miles per hour). A crash detection algorithm was used to determine collisions. Each driver was permitted a maximum score of 1 crash per event or interevent interval. Following a crash, data were not analyzed until after the driver had regained control of the vehicle.

Driving performance was also recorded by videotape at 10 frames per second using miniature lipstick-size cameras mounted unobtrusively within and outside the vehicle. A forward camera recorded the scene observed by the driver and provided a backup record of the driver's lane tracking. Another camera directed at the driver allowed evaluation of a participant's gaze in regions of interest in the vehicle and on the virtual road. Synchronization of the digital and video data streams facilitated the inspection of artifacts and allowed for review of potential driver safety errors, including behavior in the moments preceding a crash.

Driver performance errors were classified into 1 of 3 possible categories: unplanned lane deviations, dangerously close headways, and abrupt braking. An unplanned lane deviation occurred when any part of the driver's vehicle crossed the center line (deviation to the left) or the right line of the lane of travel (deviation to the right). A dangerously close headway was defined as a headway of 0.6 seconds or less.[12] Each driver error was further classified by the environmental proximities of potential hazards. A near miss occurred when the driver had to take abrupt evasive action to avoid a collision (eg, depressing the brake pedal abruptly to avoid colliding with the lead vehicle or swerving to avoid a collision with oncoming traffic). The potential injury severity of each driver error was then assessed with a decision tool modified from Jahns.[13] This tool assigned a potential injury severity value based on the US National Highway Traffic Safety Administration General Estimates System,[14] taking into account the specific situation at the time of the driver error (eg, speed of the vehicle, type of roadway, etc).

After determining the number of crashes and other related performance errors, we analyzed how these unsafe occurrences were predicted by various cognitive, visual, and demographic measures. Specifically, we fit univariate logistic regression models using the exact methods available in LogXact (Cytel Corp, Cambridge, Mass). For ease of interpretation, all predictors were dichotomized and *P* values were based on the Fisher exact test.

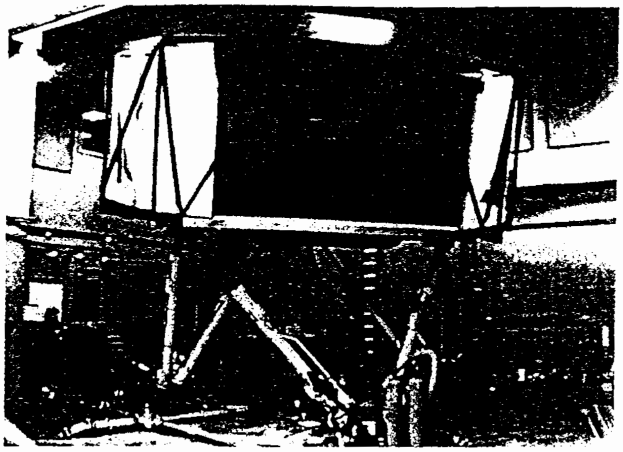
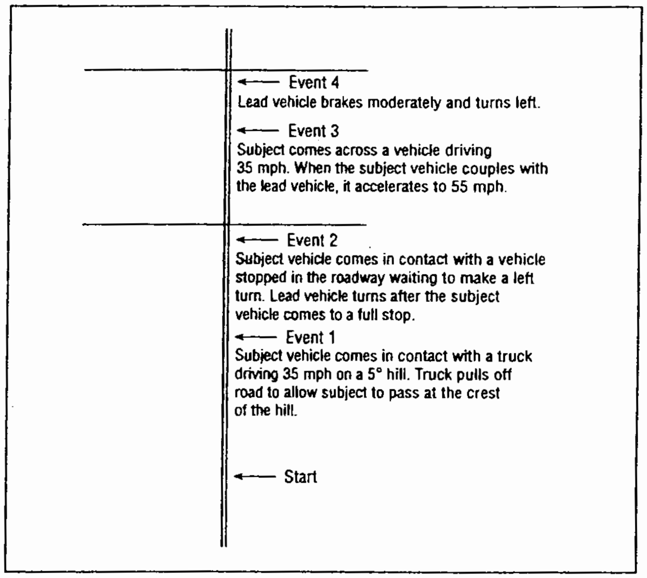


Figure 1. *The Iowa Driving Simulator consists of a vehicle cab and controls, a visual display, and a large-payload motion base. A dome with a 2.8-m radius is mounted on the motion base and contains a real car with the power train and suspension removed. Within the dome is projected a computer- generated scene depicting the roadway panorama and events. In this picture, the dome is laid open to reveal a Humvee (Chrysler Corp, Detroit, Mich) during cab changes between experiments. A 1993 General Motors Saturn (Saturn, Spring Hill, Tenn) was used for our study. The participants drove through the computer-controlled scripted scenario outlined in Figure 2.*



Event 4
Lead vehicle brakes moderately and turns left.

Event 3
Subject comes across a vehicle driving 35 mph. When the subject vehicle couples with the lead vehicle, it accelerates to 55 mph.

Event 2
Subject vehicle comes in contact with a vehicle stopped in the roadway waiting to make a left turn. Lead vehicle turns after the subject vehicle comes to a full stop.

Event 1
Subject vehicle comes in contact with a truck driving 35 mph on a 5° hill. Truck pulls off road to allow subject to pass at the crest of the hill.

Figure 2. *Iowa Driving Simulator map of simulated 2-lane highway and scenarios. Event 1, The participant drove at 55 mph and encountered a slower moving tractor-trailer truck traveling uphill at 35 mph. Event 2, The participant suddenly encountered a lead vehicle stopped at a 4-way intersection waiting to turn left. Event 3, The participant, driving at 55 mph, encountered a slower-moving lead vehicle traveling at 35 mph along a flat segment of highway; the participant had to couple with the lead vehicle for 2 seconds before the lead vehicle increased its speed to 55 mph. Event 4, The participant encountered the same lead vehicle slowing down to turn left at a 4-way intersection.*

RESULTS

CRASHES

Six (29%) of 21 participants with AD experienced crashes vs none of the 18 control participants ($P=.022$). Several factors were strong predictors ($P<.001$) of crashes (**Table**), namely results of the Rey-Osterreith Complex Figure Test copy version, the Block Design subtest from the Wechsler Adult Intelligence Scale–Revised (WAIS-R), the Benton-Van Allen Facial Recognition Test, the Trail-Making Test,[15,16] and the perception of 3-dimensional structure-from-motion.[17,18] The Rey-Osterreith Complex Figure Test required participants to copy a complex geometric figure, which provides a reliable index of visuoconstructional ability. The Trail-Making Test is a sensitive mea-

Odds Ratio (OR) Estimates, 95% Confidence Intervals (CIs), and Exact *P* Values of Predictors of Crashes

Predictor Variable*	OR Estimate (95% CI)	Fisher Exact Test *P* (Dichotomous Predictors)
Rey-Osterreith CFT-Copy <20	57.61 (6.88-∞)	≤.001
3-D SFM >15	44.94 (5.50-∞)	≤.001
Trail-Making Test (Part B) <3†	30.19 (3.81-∞)	≤.001
WAIS-R Block Design <6‡	40.78 (3.29-2441.41)	≤.001
BVRT Correct <4	12.30 (1.41-∞)	.01
UFOV total loss ≥50%	18.13 (2.34-∞)	.002
Faces <40§	58.53 (4.32-3784.18)	≤.001
WAIS-R Digit Span <10‡	10.04 (1.31-∞)	.02
Temporal orientation <0	20.14 (1.82-1098.63)	.004
WAIS-R information <10	24.56 (2.16-1373.29)	.002
Starry Night (d′) <1	29.83 (2.53-1708.98)	.001
COWA <30§	24.56 (2.16-1373.29)	.002
Alzheimer disease	8.91 (1.17-∞)	.02
Age >70 y	0.74 (0.09-6.41)	>.99
Sex, M	3.17 (0.30-165.94)	.39

**CFT indicates Complex Figure Test; 3-D SFM, 3-dimensional structure-from-motion; BVRT, Benton Visual Retention Test; UFOV, useful field of view; Faces, Benton-Van Allen Facial Recognition Test; WAIS-R, Wechsler Adult Intelligence Scale–Revised; and COWA, Controlled oral word association.*

†For the Trail-Making Test, the scaled score equivalent of a test raw score is reported.

‡Age-scaled scores reported.

§Scores are corrected for age and education level.

sure of executive functions. The Block Design subtest from the WAIS-R provides a reliable measure of nonverbal intellect that correlates with the performance IQ. The Benton-Van Allen Facial Recognition Test measures visuoperceptual capacity. These tasks are described in detail elsewhere.[15,16] Perception of 3-dimensional structure-from-motion and of motion direction were tested using computer-generated animation sequences.[19,20] Correlation of reduced 3-dimensional structure-from-motion with crashes supports computational theories on the perception of egomotion. These computational theories assert that structure-from-motion allows the detection of potential crashes.[21] The perception of motion cues is diminished in people with AD.[22]

Other predictors of crashes ($P<.05$) included UFOV total loss, results of the Benton Visual Retention Test and the Starry Night Test, digit span (backward), WAIS-R information, temporal orientation, Controlled Oral Word Association, and AD. The Starry Night Test depends on visual sensory function and attention over a spatial array over time.[23] The dependent measure (d′) is calculated from percentage of correct and false-positive scores using signal detection theory. Some of these factors are thought to predict the ability to pass a road test and to drive safely in patients with neurologic deficits.[24,25] Among the 15 participants with total UFOV loss of 50% or greater, 6 (40%) had at least 1 crash, while none of the 23 participants with total UFOV loss less than 50% had any crashes ($P=.002$, Fisher exact test). The UFOV task (Visual Attention Analyzer, Visual Resources Inc, Bowling Green, Ky) uses 3 subtests (speed of visual processing, divided attention, and selective attention). Deficits are expressed in terms of percentage reduction (0%-90%) of a maximum 35°-radius field; older drivers with UFOV loss (40% and greater) had more crashes than unaffected drivers.[8,9] The correlation of UFOV loss with increased crash risk in a simulated driving scenario resembles the relationship between UFOV loss and real-life crashes as documented in state records.[8,9]

We performed a forward stepwise selection procedure to attempt to build a multivariate model. After the model was adjusted in the first step for results of the Rey-Osterreith Complex Figure Test (the most statistically significant among all the risk factors in the Table), no other factors were significant. This was likely because of the combination of a small sample size and a high correlation among the predicting factors.

To investigate how each crash occurred, we developed a visual tool that plotted control over steering wheel position, position of brake and accelerator pedals, vehicle speed, vehicle position, and eye position during the 5 seconds preceding a crash event (**Figure 3**). We were thus able to identify several types of crashes. In 1 type the driver was looking directly out the front windshield but took no action. Such "looking without seeing" has been reported in patients with lesions of the dorsolateral visual association cortex, due to stroke or AD.[26-29] Other crash types involved participants who reacted too late or evaded a primary hazard only to experience a secondary collision. Only 1 crash occurred on a straightaway segment, and in this case, the driver may have lost control of the vehicle while distracted. Analysis of crash circumstances, taking into account vehicle speed using the General Estimates System,[14] showed that several of the crashes in this study (15 of 21) would likely have been fatal occurrences.

NEAR MISSES

The analysis of close calls (or near misses) provides another index of driver safety. This analysis was possible in 36 drivers. Near misses and other driver performance errors far outnumber traffic fatalities, just as occupational safety errors outnumber major safety-related injuries.[13,30] In this study, 14 (74%) of the 19 participants with AD experienced 1 or more near misses compared with 6 (35%) of the 17 control participants ($P=.042$). In a manner similar to that represented in the Table, we examined which factors predicted at least 1 near miss. In addition to AD, we found that digit span, 3-dimensional structure-from-motion, results of the Starry Night Test, WAIS-R information, and Controlled Oral Word Association were all statistically significant ($P<.05$, data not shown). Furthermore, 5 (25%) of 20 participants who had 1 or more near misses had 1 or more crashes, while none of the drivers without near misses had any crashes ($P=.053$). Other performance factors predicting 1 or more crashes were a higher number of lane deviations ($P=.001$) and number of lateral accelerations greater than 0.1g ($P=.001$, Wilcoxon rank sum test). The former events (lane deviations) can occur with no other vehicles present and hence are not necessarily associated with near miss events; the latter events (lateral accelerations) are not necessarily even associated with deviations from the lane. With a sufficient number of observations, it may be possible, even in the absence of

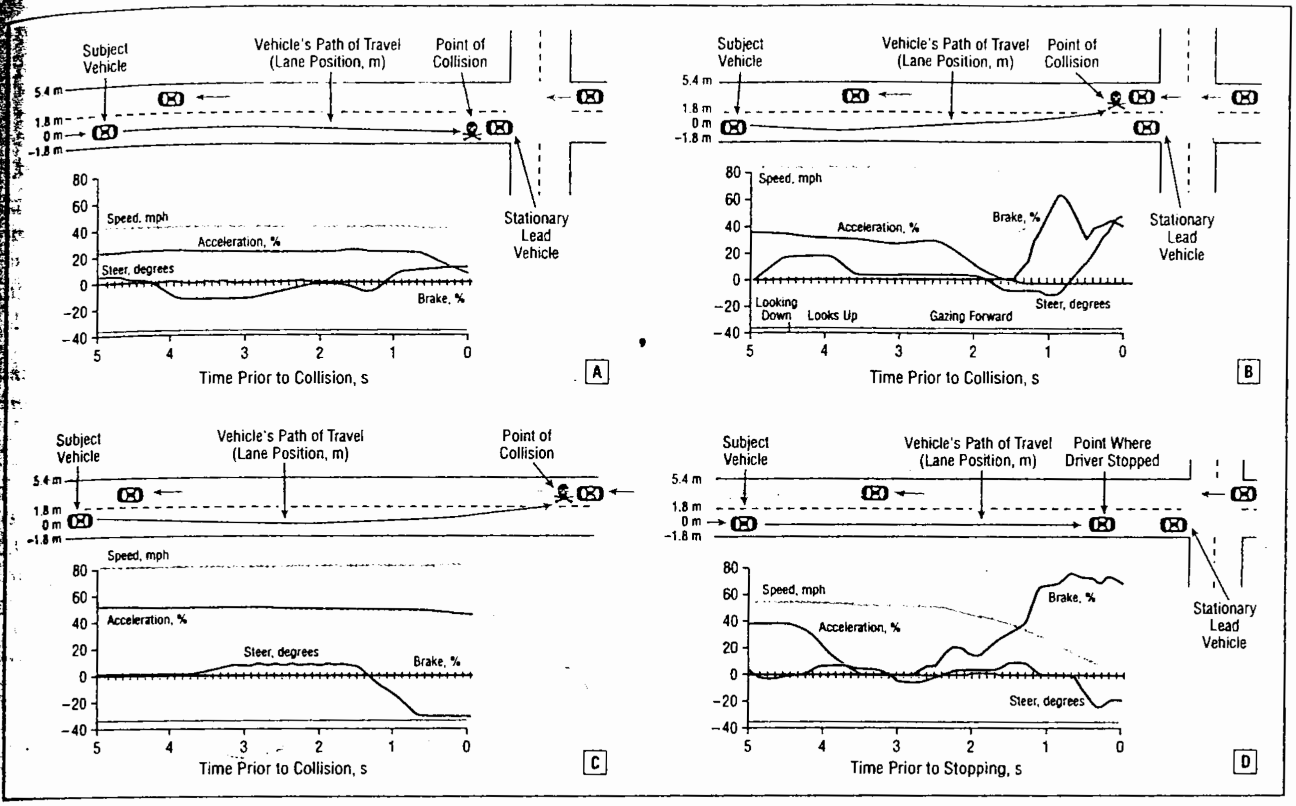


Figure 3. *Plotting different channels from the video and electronic data streams from the Iowa Driving Simulator provides a window on participants' behavior in critical portions of the simulation. The common ordinate scale shows vehicle speed in miles per hour (yellow), percentage of pedal application for the accelerator (green) and brake (blue), and steering wheel rotations in degrees (red, where upward deflections are counterclockwise rotations). The path (and lane position in meters from the center of the lane) of the driver and other vehicles is depicted to scale at the top of each panel. In panels A through C, different safety errors in 3 drivers with AD led to crashes that would have been fatal. Panel A, Participant 31 with AD drove at 40 mph into the back of a stopped vehicle in event 2 (see Figure 2). In the final second he made small and ineffective brake pedal and steering adjustments that may or may not be in response to the impending crash. The participant's eye gaze was directed forward, suggesting he should have seen the vehicle ahead. Panel B, Participant 35 with AD was speeding at 80 mph and in the final 2 seconds braked and swerved into the left lane to avoid the stopped vehicle in event 2, but collided with oncoming traffic. Panel C, Participant 75 with AD became distracted and swerved into oncoming traffic during uneventful driving; braking in the final second was ineffective. Panel D, Participant 23, an older driver without dementia, slowed from the legal speed limit, 55 mph, to a full stop behind a lead vehicle in event 2. The participant eased off the accelerator pedal (4 seconds) and began braking (3 seconds) with time to spare. There was a modest clockwise steering rotation in the last half second.*

a crash, to accurately estimate relative crash risk through the assessment of measurable safety errors.

COMMENT

Safe driving depends on the conscious registration of sensory input, attention and perception, language and memory, and decision making and execution. We find that neurologic disease and aging can alter these abilities with consequences for driver risk that can be evaluated safely and efficiently in simulation. It is possible to create information flows to the driver that are unattainable in the real world and to identify specific driver reactions in a crash scenario, a line of inquiry that is dangerous and unethical on the road.

In simulation, a multidimensional real-life task is reduced to a lower dimension approximation. One theory is that transfer between the simulated and real-life tasks will occur to the extent that they share common components. More relevant, perhaps, is the level of psychological fidelity or functional equivalence of the simulation.[31-33] Early simulators created video game–like scenarios and some participants experienced uneasiness, possibly because low microprocessor speeds introduce coupling delays between visual motion and driver performance.[34] Despite this modest degree of realism, such simulations show the driver in the loop, operating hand and foot controls. Successful demonstrations include performance profiles in sleep apnea, drowsiness, alcohol intoxication, old age, and the study of basic aspects of cognition in drivers with brain lesions.[35-41]

Modern microelectronic, sensor, communication, and control technology allows more extensive automation of the evaluation of human-machine interactions. The same technology that has led to the development of the glass cockpit, which uses multiple computer-run displays to assist aircraft pilots to fly safely, can now be applied to human factors of driver behavior and collision avoidance research.[42,43] This technology was used in our current study of at-risk drivers on the IDS. By increasing the exposure of older drivers and drivers with dementia in high-fidelity simulated collision avoidance scenarios, we were able to infer crash risk through direct observation of events that might have taken months to infer from real-life events. Detailed analyses of the events preceding crashes, as in the crash diagrams in Figure 3, provide demonstrations of driver behavior that cannot be obtained any other way. The simulator record can be compared with that of the black box flight recorder from a downed aircraft, yet no one is injured.

Some drivers with mild dementia were prone to crash in our simulations and these crashes were predicted by visual and cognitive test scores. A set of these off-road tools (eg, UFOV, Rey-Osterreith Complex Figure Test, 3-dimensional structure-from-motion, Trail-Making Test, and WAIS-R Block Design) might aid licensing authorities in deciding whether to recertify impaired drivers. Moreover, use of these tools may also prevent what amounts to discrimination against aging or illness. Our results show that most drivers with AD (15 of 21) did not crash and exhibited fair vehicular control, compatible with the idea that some individuals with mild dementia remain fit drivers and should be allowed to continue to drive.[6]

Clearly, this study simulates a vehicle with control characteristics that differ from the driver's. We sought to minimize potential effects of unfamiliarity by including an antecedent warm-up and training session. Another potential concern is that as long as subjects are aware they are participating in a simulation, the reward and penalty structure for the simulated act will likely differ from real life. The safety of simulated driving should engender less fear of the consequences of a crash, without life or license at stake. However, a road test situation likewise alters naturalistic driving, as when a person drives in an unfamiliar way or place (eg, under the intrusive eye of an observer) or in someone else's vehicle (eg, a test car equipped for safety with dual controls). Admittedly, we exposed drivers to traffic situations that they might attempt to avoid in real life. We suggest, however, that a licensed driver should reasonably be expected to recognize and negotiate commonly encountered road hazards caused by external events or actions, such as a short stop or intersection incursion by another vehicle, in which a potential crash can be avoided in most cases by most drivers. These common hazards are best tested in simulation.

In short, high-fidelity driving simulation can provide a unique new source of specific parameters to standardize the assessment of driver fitness from direct observations of crashes and other serious safety errors. Our findings are especially useful as a complement to evidence now being gathered in older and medically impaired populations using techniques from epidemiology, psychophysics, cognitive science, and human factors research. Future research in simulation can address rehabilitation and the decision for patients to resume driving following an acute illness, the implementation of collision warning and avoidance systems, and the testing of practical strategies for avoiding crashes by impaired or negligent operators. Such safety suggestions include leaving a greater space cushion from the lead vehicle, avoiding night driving, and keeping to the right for those who drive slower than surrounding traffic.[14] Effective scenarios and data tiles from advanced simulators, such as the IDS or its successor, the National Advanced Driving Simulator, might be transferred to lower cost, standardized, static-base simulators for greater public use and benefit.

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REFERENCES

1. Marx J. Searching for drugs that combat Alzheimer's. *Science.* 1996;273:50-53.
2. Friedland RP, Koss E, Kumar A, et al. Motor vehicle crashes in dementia of the Alzheimer type. *Ann Neurol.* 1988;24:782-786.
3. Lucas-Blaustein MJ, Filipp L, Dungan C, Tune L. Driving in patients with dementia. *J Am Geriatr Soc.* 1988;36:1087-1091.
4. Drachman DA, Swearer JM. Driving and Alzheimer's disease: the risk of crashes. *Neurology.* 1993;43:2448-2456.
5. Rizzo M, Dingus T. Driving in neurological disease. *Neurologist.* 1996;2:140-160.
6. Lundberg C, Johannson K, and the Borlänge Consensus Group. Dementia in driving: an attempt at consensus. *Alzheimer Dis Assoc Disord.* 1997;11:28-37.
7. Michon JA. Quoted by: Van Zomeran AH, Brouwer WH, Minderhoud JM. Acquired brain damage and driving: a review. *Arch Phys Med Rehabil.* 1987;68:697-705.
8. Owsley C, Ball K, Sloane ME, Roenker DL, Bruni JR. Visual/cognitive correlates of vehicle accidents in older drivers. *Psychol Aging.* 1991;6:403-415.
9. Ball K, Owsley C, Sloane ME, Roenker DL, Bruni JR. Visual attention problems as a predictor of vehicle crashes in older drivers. *Invest Ophthalmol Vis Sci.* 1993;34:3110-3123.
10. Lyons TJ, Simpson CG. The giant hand phenomenon. *Aviat Space Environ Med.* 1989;60:64-66.
11. McKhann G, Drachman D, Folstein M, Katzman R, Price D, Stadlan EM. Clinical diagnosis of Alzheimer's disease: report of the NINCDS-ADRDA Work Group under the auspices of Department of Health and Human Services Task Force on Alzheimer's Disease. *Neurology.* 1984;34:939-944.
12. Ohta H. Individual differences in driving distance headway. In: Gale AG, Brown ID, Haslegrave CM, Kruysse HW, Taylor SP, eds. *Vision in Vehicles IV.* New York, NY: Elsevier Science Inc; 1993:91-100.
13. Jahns S. *A Methodology for Near Miss Assessments While Driving.* Iowa City: University of Iowa; 1994. Thesis.
14. US National Highway Traffic Safety Administration General Estimates System. Washington, DC: National Highway Traffic Safety Administration; 1991.
15. Lezak MD. *Neuropsychological Assessment.* 3rd ed. New York, NY: Oxford University Press Inc; 1995.

16. Spreen O, Strauss E. *A Compendium of Neuropsychological Tests.* New York, NY: Oxford University Press Inc; 1991.
17. Gibson JJ. *The Perception of the Visual World.* Boston, Mass: Houghton Mifflin Co; 1950.
18. Nakayama K. Biological image motion processing: a review. *Vision Res.* 1985; 25:625-660.
19. Nawrot M, Rizzo M. Motion perception deficits from midline cerebellar lesions in humans. *Vision Res.* 1995;35:723-731.
20. Rizzo M, Nawrot M, Zihl J. Motion and shape perception in cerebral akinetopsia. *Brain.* 1995;118:1105-1128.
21. Fermuller C, Aloimonos Y. Direct perception of three-dimensional motion from patterns of visual motion. *Science.* 1995;270:1973-1976.
22. Gilmore GC, Wenk HE, Naylor LA, Koss E. Motion perception and Alzheimer's disease. *J Gerontol.* 1994;49:52-57.
23. Rizzo M, Robin D. Bilateral effects of unilateral occipital lobe lesions in humans. *Brain.* 1996;119:951-963.
24. Cushman LA. *The Impact of Cognitive Decline and Dementia in Older Adults.* Washington, DC: AAA Foundation for Traffic Safety; 1992.
25. Van Zomeren AH, Brouwer WH, Rothengatter JM, Snoek JW. Fitness to drive a car after recovery from head injury. *Arch Phys Med Rehabil.* 1988;69:90-96.
26. Rizzo M, Hurtig R. Looking but not seeing: attention, perception, and eye movements in simultanagnosia. *Neurology.* 1987;37:1642-1648.
27. Hof PR, Bouras C, Constantinidis J, et al. Selective disconnection of specific visual association pathways in cases of Alzheimer's disease presenting with Balint's syndrome. *J Neuropathol Exp Neurol.* 1990;49:168-184.
28. Mendez MF, Mendez MA, Martin R, et al. Complex visual disturbances in Alzheimer's disease. *Neurology.* 1990;40:439-443.
29. Rizzo M. 'Balint's Syndrome' and associated visuospatial disorders. *Baillieres Clin Neurol.* 1993;2:415-437.
30. Heinrich HW, Petersen D, Roos N. *Industrial Accident Prevention.* New York, NY: McGraw-Hill Book Co; 1980.
31. Alessi SM. Simulation fidelity. *J Comput Based Instr.* 1988;15:40-47.
32. Lintern G, Roscoe SN, Koonce JM, Segal LD. Transfer of landing skills in beginning flight training. *Hum Factors.* 1990;32:319-327.
33. Lintern G. An informational perspective on skill transfer in human-machine systems. *Hum Factors.* 1991;33:251-266.
34. Frank LH, Casali JG, Wierwille WW. Effects of visual display and motion system delays on operator performance and uneasiness in a driving simulator. *Hum Factors.* 1988;30:201-217.
35. Haraldsson P-E, Carenfelt C, Laurell H, Tornros J. Driving simulator vigilance test. *Acta Otolaryngol (Stockh).* 1990;110:136-140.
36. Dingus TA, Hardee HL, Wierwille WW. Development of models for on-board detection of driver impairment. *Accid Anal Prev.* 1987;19:271-283.
37. McMillen DL, Wells-Parker E. The effect of alcohol consumption on risk-taking while driving. *Addict Behav.* 1987;12:241-247.
38. Brouwer WH, Ponds RWHM, van Wolffelaar PC, Van Zomeren AH. Divided attention 5 to 10 years after severe closed head injury. *Cortex.* 1989;25:219-230.
39. DeWaard D, Brookhuis KA, van der Hulst M, van der Laan JD. Behaviour comparator prototype test in a driving simulator. In: Report 2009/DETER/ Deliverable 10 (321B). Haren, the Netherlands: Traffic Research Centre, University of Groningen; 1994.
40. Katz RT, Golden RS, Butter J, et al. Driving safely after brain damage: follow-up of twenty-two patients with matched controls. *Arch Phys Med Rehabil.* 1990;71:133-137.
41. Guerrier JH, Manivannan P, Pacheco A, Wilkie F. The relationship of age and cognitive characteristics of drivers to performance of driving tasks on an interactive driving simulator. In: Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting; San Diego, Calif; 1995:172-176.
42. Sheridan TS. *Human Factors of Driver Vehicle Interaction in the IVHS Environment.* Cambridge: Massachusetts Institute of Technology Center for Transportation Studies; 1990.
43. Allen RW, Weir DH. *Analysis of Man-in-the-Loop Performance Measurement Technology for Crash Avoidance Research.* Washington, DC: National Highway Traffic Safety Administration; 1984. NHTSA Department of Transportation publication B06-x718.
44. Janke MK. Mature driver improvement program in California. *Transportation Res Rec.* 1994;1438:77-83.