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Simulated Car Crashes at Intersections in Drivers With Alzheimer Disease

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Summary: Current evidence suggests that car crashes in cognitively impaired older drivers often occur because of failure to notice other drivers at intersections. We tested whether licensed drivers with mild to moderate cognitive impairment due to Alzheimer disease (AD) are at greater risk for intersection crashes. In this experiment, 30 participants drove on a virtual highway in a simulator scenario where the approach to within 3.6 seconds of an intersection triggered an illegal incursion by another vehicle. To avoid collision with the incurring vehicle, the driver had to perceive, attend to, and interpret the roadway situation; formulate an evasive plan; and then exert appropriate action on the accelerator, brake, or steering controls, all under pressure of time. The results showed that 6 of 18 drivers with AD (33%) experienced crashes versus none of 12 nondemented drivers of similar age. Use of a visual tool that plots control over steering wheel position, brake and accelerator pedals, vehicle speed, and vehicle position during the 5 seconds preceding a crash event showed inattention and control responses that were either inappropriate or too slow. The findings were combined with those in another recent study of collision avoidance in drivers with AD that focused on potential rear end collisions. Predictors of crashes in the combined studies included visuospatial impairment, disordered attention, reduced processing of visual motion cues, and overall cognitive decline. The results help to specify the linkage between decline in certain cognitive domains and increased crash risk in AD and also support the use of high-fidelity simulation and neuropsychologic assessment in an effort to standardize the assessment of fitness to drive in persons with medical impairments. **Key Words:** Human factors psychology—Motion perception—Neuroergonomics—Safety factors—Visual attention.

Safe operation of a motor vehicle requires a driver to monitor multiple objects and events despite being unsure of where critical hazards may lie. This challenging task requires adequate awareness, coding of inputs from central and peripheral vision and the other senses, and allocation of attention between onboard and roadway targets and distracters. It also requires memory of road rules, routes, vehicle operations, and other vehicle positions as well as effective decision making and execution. The driver must act rapidly on feedback of safety errors while also monitoring travel goals, vehicle integrity, and personal state for signs of fatigue or other incapacity that would compromise safety. Aging and neurologic disease can disrupt these functions, increasing the risk of driver safety errors that lead to vehicular crashes and resulting injuries.

The proportion of licensed older drivers is increasing in the general driving population (National Highway Traffic Safety Administration, 1994), and a rising number among this population are exhibiting a decline in cognitive functions critical to safe driving. Drivers aged

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65 to 69 years are twice as likely to be involved in fatal multivehicle crashes as drivers aged 40 to 49 years, and drivers aged 85 years and older are 11 times as likely as drivers aged 40 to 49 years to be involved in such crashes (National Highway Traffic Safety Administration, 1994). Drivers over the age of 65 years have the second highest fatality rate per mile traveled (the highest rate is held by drivers aged 15–24 years) even though they travel fewer miles per year than younger drivers. The fatality rate of drivers aged 80 years and older actually surpasses that of drivers younger than 24 years old (National Highway Traffic Safety Administration, 1991). An important step toward addressing this growing problem is to develop reliable criteria to predict risky versus safe driving.

Special concerns have been raised about driver safety associated with Alzheimer disease (AD) (Friedland et al., 1988; Lucas-Blaustein et al., 1988; Drachman and Swearer, 1993; Lundberg et al., 1997), the most common cause of abnormal cognitive decline in older adults (Roush, 1996). Johansson et al. (1997) analyzed brain autopsies in 98 older drivers who perished in single and multivehicle crashes. They found that 52 of 98 (53%) had sufficient neuritic plaques to fulfill Consortium to Establish a Registry for Alzheimer's Disease neuropathologic criteria suggesting (20%) or indicating (33%) AD. Yet, not one of these drivers carried a diagnosis of AD, and family members were often unaware that there was any problem (Lundberg et al., 1998), which raises the dramatic possibility that the first manifestation of AD may sometimes be a fatal crash. In deceased drivers over the age of 76 years, apolipoprotein E epsilon 4 allele (a risk factor for AD) was found more often than in age- and sex-matched paired controls. Further analyses indicated that preclinical AD increases the relative risk of fatal crashes in older drivers more than 10-fold (Johansson et al., 1998).

Safety errors committed by cognitively impaired drivers should increase in situations where information processing demands are high and rapid reactions are required as in response to sudden moves by other vehicles at roadway intersections (Ball et al., 1993; Brouwer and Ponds, 1994; Hakamies-Blomqvist, 1994). Such driver safety errors are best studied under conditions of optimal stimulus and response control in an environment that is challenging yet safe for both driver and tester (Rizzo et al., 1997). For these reasons, we used the Iowa Driving Simulator (IDS) in experiments using high-fidelity collision avoidance scenarios to examine driver response in intersection incursion by another vehicle. Our aims were (1) to test the hypothesis that older drivers with mild to moderate AD are at greater risk for crashes than older drivers without dementia; (2) to determine how such unsafe events may be predicted by visual and cognitive impairment in AD; (3) to determine what specific driver safety errors precede a crash; and (4) to compare and combine the results of this study with those of a prior study of older and cognitively impaired drivers performing in different collision avoidance scenarios implemented using the IDS (Rizzo et al., 1997).

SUBJECTS AND METHODS

Subjects

Participants included 18 drivers with probable AD (mean age = 73 years; SD = 7 years) and 12 control subjects without dementia (mean age = 70 years; SD = 4.7 years). The AD patients were recruited from a registry in the Alzheimer's Disease Research Center in the Department of Neurology. The diagnosis of AD relied on the recommendations of the National Institute of Neurological Communicative Disorders and Stroke–Alzheimer's Disease and Related Disorders Association Work Group under the auspices of the Health and Human Services Task Force on AD (McKhann et al., 1984). Magnetic resonance imaging or computed tomography of the brain was obtained in all patients to help exclude destructive lesions due to stroke, neoplasm, or other causes. Control subjects were recruited from volunteers in the local community. All subjects held a current valid state driver's license, although some had reduced driving activity as a result 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.

Visual and Cognitive Performance

All participants performed on a battery of visual and cognitive tests administered by trained technicians who were not apprised of experimental hypotheses. The results of static visual acuity tests showed no significant differences (Wilcoxon two-sample test) between participants with and without AD; visual acuity was measured using standard Sloan letters presented at near (20/27.2 [12.9] vs. 20/27.1 [7.8]; $p = 0.320$) and far (20/31.4 [23.4] vs. 20/26.3 [7.6], $p = 0.899$) locations. Results of static spatial contrast sensitivity tests measured using a Pelli-Robson chart (Pelli et al., 1988) likewise showed no significant difference (1.78 [0.24] vs. 1.88 [0.120], $p = 0.330$). On a measure known as the useful field of view (UFOV), however, the group with AD demonstrated more than twice the total loss compared with controls (69.4% [SD = 22.3%] vs. 32.1% loss [SD =

9.3%]; $p < 0.001$). The UFOV measure depends on visual processing speed and attention skills (Ball et al., 1988, 1990, 1993; Owsley et al., 1991). Participants with AD also showed lower true sensitivity (d′) than control subjects on a test of sustained visual attention known as the Starry Night test (d′ = 0.18 [1.48] vs. 2.25 [1.03]; $p < 0.001$) (Rizzo and Robin, 1990, 1996; Rizzo et al., 2000).

All subjects also participated in a battery of standardized neuropsychologic tests aimed at assessing a range of cognitive functions (Eslinger et al., 1984, 1985; Tranel, 1996). The neuropsychologic battery included (1) Temporal Orientation (Benton et al., 1983); (2) Information subtest from the Wechsler Adult Intelligence Scale–Revised (WAIS-R) (Wechsler, 1981); (3) Controlled Oral Word Association (COWA) (Benton and Hamsher, 1978); (4) Digit Span subtest from the WAIS-R; (5) Rey-Osterrieth Complex Figure Test (CFT), copy version; (6) Facial Recognition Test (FRT) (Benton et al., 1983); (7) Benton Visual Retention Test (BVRT) (Sivan, 1992); (8) Block Design subtest from the WAIS-R (Wechsler, 1981); and (9) Trail Making Test (TMT) parts A and B (Reitan and Davison, 1974).

The AD group showed greater variability and performed significantly worse than the controls on most indices (one-sided *p* values: Temporal Orientation (<0.001), Information subtest (0.005), COWA (0.008), Digit Span subtest (0.075), CFT (0.006), FRT (0.010), BVRT (<0.001), Block Design subtest (<0.001), TMT-A (0.009), and TMT-B (<0.001). Mean scores in the AD group fell within the range of mild to moderate impairment. To gauge overall cognitive impairment, standard T-scores (mean = 50; SD = 10) were assigned to each of nine tests from the cognitive assessment battery (only part B was used on the TMT). This allowed us to generate an equally weighted composite score (termed *ADSTAT*) based on the homogeneity of variance of each test score (Rizzo and Nawrot, 1998).

As expected, the participants with AD taken as a group had worse (lower) ADSTAT scores, indicating worse cognitive status (ADSTAT = 412 [59] vs. 501 [23]; $p < 0.001$).

Iowa Driving Simulator

The IDS is a realistic ground-vehicle simulator that incorporates technologic innovations in computational dynamics, parallel computing, and image generation. The current configuration provides 190 degrees in the forward field of view and 65 degrees in the rear view.

It is possible to display multiple roadway types, traffic signals, traffic conditions, and vehicles that interact with the driver and each other according to the particular set of rules established for each experimental driving scenario. Hidden cameras and microphones in the car allow an operator in a control room 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 developments in the control room. The driver cannot hear the control room operator. A large-payload, six-degree motion base provides excursions of ±44 in, with acceleration speeds of up to 1.1*g* to simulate most of the movement cues experienced during normal driving. Movement generates effects that cannot be reproduced in a static environment (Lyons and Simpson, 1989) and reduces the discomfort encountered in static simulator environments by reducing visual-vestibular mismatch. "Washout" algorithms allow the car to move without commanding the motion base beyond its boundaries. The steering wheel, accelerator, brake, and gearshift positions are read by a host computer, and feedback is relayed to the driver so that the subject may 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 special audio effects that provide accurate directional cues, including engine, wind, and road noise.

Driver gaze position is assessed using inconspicuous miniature cameras. The IDS immerses the driver in the task of driving and allows researchers to examine in detail situations that cannot be safely evaluated in the field.

Driving Scenario

Each subject drove approximately 15 miles on a simulated rural two-lane highway with interactive traffic. The scenario culminated with the driver's approach to an intersection, which triggered an illegal incursion by another vehicle (Fig. 1). A 15- to 20-minute "warm-up and training" phase preceded the experimental drive. In this preparatory phase, each subject was escorted to the simulator bay (up a set of stairs leading into the dome) and seated in the driver's seat of the car, a 1993 General Motors Saturn. A research assistant (who was also a registered nurse) sat in the front passenger seat to help familiarize the driver with the vehicle controls, take the driver's vital signs, and monitor the driver for signs of discomfort or fatigue. Before beginning the experiment, each driver was familiarized with the simulator by driving on a segment of simulated two-lane highway.

The 5-mile practice drive began from the roadway shoulder. After two vehicles had passed from behind, the driver was instructed to merge and practice steering and braking. This gave the driver experience in controlling

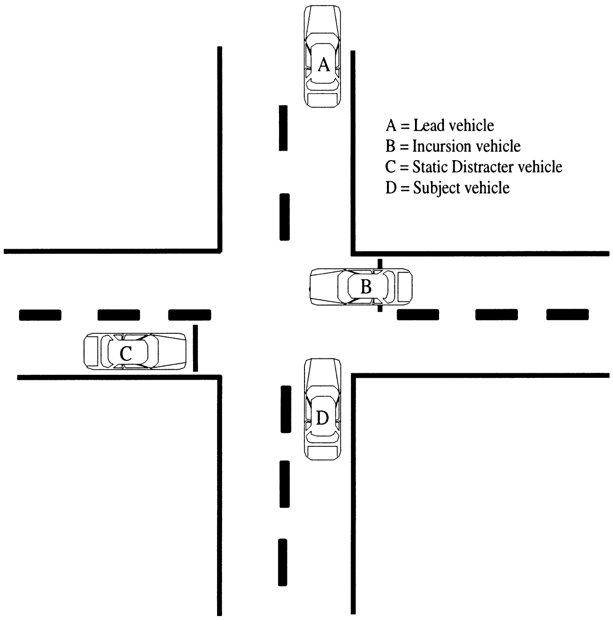

FIG. 1. Schematic depiction of a simulated intersection incursion. The incurring vehicle began on the subject's right side with its front bumper 48.5 ft from the yellow centerline, and accelerated at 13.8 ft/sec^2 for 2.31 seconds. It decelerated and stopped with its front bumper on the yellow centerline 3 seconds after beginning the incursion. This completely blocked the subject's lane (see text).

the vehicle before the intersection incursion. Generic oncoming traffic was spaced at six vehicles per mile to constrain passing. The speed limit was 55 miles per hour (mph) throughout. No traffic followed. After a distance of 7 miles, the driver came up on a truck traveling 40 mph. The dense oncoming traffic hindered passing. Once the driver had reduced speed to match or go slower than the truck, the truck accelerated away, slowed to 25 mph to climb a hill, and pulled off of the roadway just beyond the hill crest. These interactions gave the driver further practice adjusting speed, braking, and interacting with simulated vehicles.

After the driver had passed the truck, a car going 40 mph appeared 400 ft ahead. As the gap between the cars closed, the lead car accelerated and maintained a 6-second headway. Two seconds before entering the intersection (located 1.5 miles beyond the crest of the hill), the lead car accelerated away subtly (at 3 ft/sec^2) to ensure that it was no obstacle to the driver's passage through the intersection.

The intersection had a pickup truck positioned in one crossing lane and a Buick sedan in the opposing lane, both waiting to cross perpendicular to the driver. Safe passage of the lead car implied that the upcoming intersection was not a four-way stop and that the two stopped vehicles were aware of cross-traffic and would continue to wait for the driver to pass. As the driver approached to within 3.60 seconds of the intersection, the Buick pulled out in front of the driver. This illegal incursion blocked the driver's path across the entire lane (see Fig. 1).

This surprise event required immediate decision making and action by the subject to avert a crash. Optimal response involved releasing the accelerator, applying the brake, and making steering corrections as needed to remain within the lane (safe avoidance). It was also possible to avoid a collision with suboptimal responses by swerving onto the shoulder of the road or into the left lane (unsafe avoidance). Here, the occurrence of obstacles or oncoming traffic would create the potential for a near miss (Jahns, 1994) or an injury in a secondary collision.

Note that the time-to-intersection (TTI) of 3.60 seconds in this experiment was guided by results of normative studies ($n = 120$) that tested three TTIs (2.85, 3.60, and 4.35 seconds) and found that most normal drivers could avoid a collision with a TTI of 3.60 seconds (McGehee et al., 1996). A second pilot study found that three drivers with AD could all avoid an intersection crash at the longest TTI (4.35 seconds). The 3.60-second TTI was therefore chosen as the most appropriate TTI value.

Analysis 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 position (i.e., scale of pedal depression ranging from 0–100%, as shown in Fig. 2), lateral and longitudinal acceleration (measured as acceleration due to gravity), headway (distance to the lead vehicle in meters or feet), time to collision (in seconds), and speed (in mph or kilometers per hour). A crash detection algorithm was used to help identify crashes.

Driving performance was also recorded on videotape at 30 frames per second using miniature "lipstick" cameras mounted unobtrusively within 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 the subject's gaze in regions of interest in the car and on the virtual road. Synchronization of digital and video data streams facilitated the inspection of artifacts and allowed review of potential driver safety errors in the moments preceding a crash.

After determining the number of crashes, we analyzed how these unsafe events were predicted by cognitive, visual, and demographic measures. Also, we compared the data gathered with results from a recent study of 39 older drivers with cognitive impairment due to AD ($n =$

TABLE 1. *Summary of outcome of driver response to intersection incursion*

Safety outcome	Number of Alzheimer disease patients	Number of controls
Collision	6 (33.3%)	0
Unsafe avoidance	4 (22.2%)	2 (16.7%)
Safe avoidance	8 (44.4%)	10 (83.3%)

21) and without dementia ($n = 18$). This earlier study used different simulated driving scenarios (Rizzo et al., 1997; see Fig. 1) to probe drivers' avoidance of rear end vehicular collisions. In each study, the Fisher exact method was used to test whether individual risk factors were associated with collisions. Odds ratios (ORs) and 95% confidence intervals (CIs) were calculated using simple logistic regression. The data from the two studies were combined using a multiple logistic regression procedure to model the log odds of collision as a simultaneous function of the scenario itself and of each risk factor of interest. Hence, we were able to find probability values, ORs, and CIs for the effect of each risk factor, adjusted for scenario. These two-predictor models implicitly assume that the underlying effect of each risk factor was the same in each of the two scenarios. To test this assumption, an interaction term was added to each multiple logistic regression model, and probability values were reported (see section on combined analysis). The Fisher exact tests were calculated in Stata (Stata Corp., College Station, TX), and all logistic regression models were fitted using the exact permutation-based procedures available in LogXact (Cytel Corp., Cambridge, MA). To test further the ability of predictive measures to discriminate between drivers with and without a crash, receiver-operator characteristic curves were calculated.

RESULTS

Vehicle Control

Driving on the road segments preceding the intersection showed no safety errors related to lane crossings, shoulder crossings, speeding, or tailgating. These findings indicated that all drivers had mastered control of the simulator vehicle and were able to follow the rules of the road before entering the intersection. Measures of lateral and longitudinal vehicular control on these relatively uneventful segments before the intersection varied within restricted ranges and did not differ significantly between the group of drivers with AD and the 12 control subjects.

Crashes

Six of 18 subjects with AD (33%) experienced crashes during the intersection incursion versus none of 12 older drivers without AD ($p = 0.057$; Table 1). Several factors were predictive ($p < 0.05$) of crashes, namely, the Rey-Osterrieth CFT (copy version), WAIS-R Block Design, TMT, motion perception, COWA, and overall cognitive status (ADSTAT).

To investigate how each crash occurred, we used a visual tool that plots control over steering wheel position, brake and accelerator pedals, vehicle speed, and vehicle position during the 5 seconds preceding a crash event (Figs. 2 and 3). We were thus able to identify several types of crashes. Table 2 summarizes driver reactions in the final moments before a crash. In one type of crash, the driver was looking directly out the front windscreen but took no action (S4).

Such "looking without seeing" (Rizzo and Hurtig, 1987) has been reported in patients with lesions of the dorsolateral visual association cortex due to stroke or AD (Hof et al., 1990; Mendez et al., 1990; Rizzo, 1993) and has also been observed in other drivers with AD (Rizzo et al., 1997; see Fig. 3A). Additional crash types involved subjects who either reacted inappropriately or too late to avoid a collision. Taking into account vehicle speed using the General Estimates System (National Highway Traffic Safety Administration, 1991), analysis of crash circumstances showed that the crashes in this study would likely have resulted in serious injury or death. Figure 2B shows a successful response to the incurring vehicle at the intersection.

TABLE 2. *Driver reactions in the final seconds preceding a crash*

Driver	Accelerator pedal	Brake pedal	Steering wheel	Impact speed
S4	None	None	None	>60 mph
S6	Released >3 s TTI	Pumping >3 s TTI	L-R-L 1 s TTI	<20 mph
S9	Released >3 s TTI	1 s TTI	L 1 s TTI	~35 mph
S51	Released 1 s TTI	<1 s TTI	L 1 s TTI	~40 mph
S52	Released >2 s TTI	1 s TTI	L-R 1 s TTI	~40 mph
S58	Released >2 s TTI	1 s TTI	L 1 s TTI	~40 mph

TTI, time to intersection midpoint; s, second; L, left; R, right; mph, miles per hour.

FIG. 2. Left column: S52, a patient with Alzheimer disease. **Right column:** SIO5, a control subject. Views during the simulated intersection incursion. **Top**: Views of drivers' faces/superimposed steering readout. **Middle**: View of drivers' feet. **Bottom:** Roadway views show vehicle incursion from right just before crash (DTI = distance to the intersection midpoint). Note: Objects look closer in simulator. S52 crashed at 40 miles per hour into incurring vehicle. In the final moments, she made ineffective brake and steering adjustments. Her gaze was directed forward, suggesting she should have seen the vehicle ahead (see Fig. 3A). S105 stopped in time. This subject used both feet to operate the control pedals (see Fig. 3B).

Combined Analysis

Factors predictive of crashes at intersections in "at risk" drivers with cognitive impairments in the current study were all also predictive of crashes in the earlier collision avoidance study (McKhann et al., 1984). Yet, several other factors predictive of crashes in the earlier study were only marginally predictive in the current study (e.g., Temporal Orientation [$p = 0.072$]; Tables 3 and 4). One explanation for these differences is that the

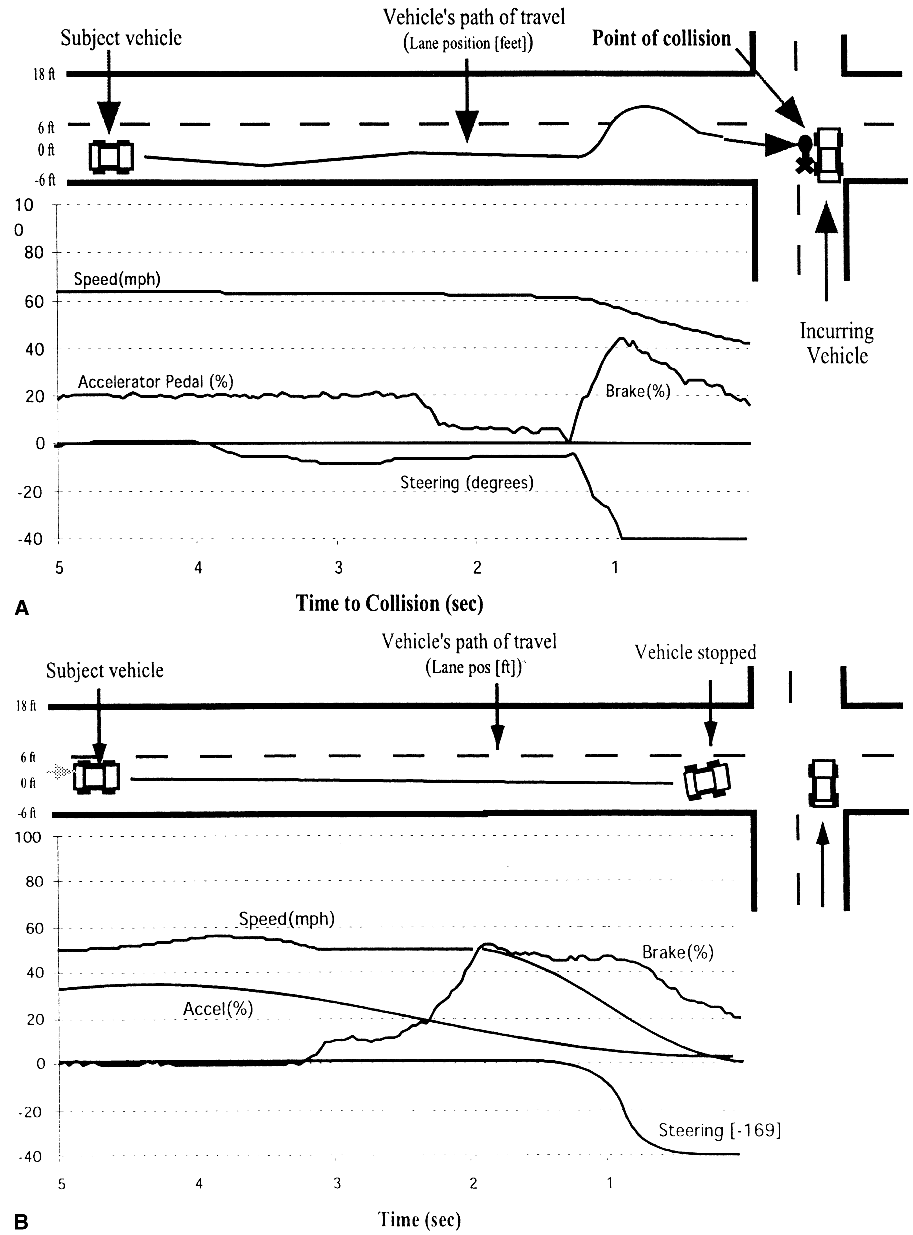

FIG. 3. Plots of driver control in the simulated intersection incursion. Common ordinate scale shows vehicle speed, percentage of pedal application for accelerator and brake, and steering wheel rotations in degrees (upward deflections are CCW rotations). Path and lane positions of driver and other vehicles are depicted to scale at top. (**A**) S52, a patient with Alzheimer disease. (**B**) S105, a control subject. The control subject began braking immediately after letting off the accelerator.

two collision avoidance studies differed in terms of the types of demands placed on the drivers. A second explanation points to the smaller sample size of the current study and is supported for two reasons. First, for most risk factors, the estimated ORs in the current study are greater than 1; thus, the data are consistent with the hypothesized associations. Second, there is considerable overlap of the OR CIs across the two studies, and only one risk factor (FRT) showed significant interaction with the study. This implies that the data are consistent between the studies, with similar associations between most risk factors and the occurrence of crashes. For the FRT, there seems to be a predictive effect for the first study but not for the second. This suggests the hypothesis that collision avoidance cues in the first study, which included the rear taillights and grille of a car, are processed using the same detailed visuoperceptual abilities required to perform the FRT.

The ADSTAT score predicted crashes, and each 100-point decrease in ADSTAT corresponded to an OR of 5.54 (CI, 1.34–30.40; $p = 0.017$).

Comparing the crash rate of drivers with an ADSTAT less than 400 versus an ADSTAT greater than or equal to 400 gave an OR of 6.39 ($p = 0.151$) in this study and

TABLE 3. *Intersection incursion study: odds ratio estimates, 95% confidence intervals, and exact probability values of predictors of crashes*

Predictor variable	Odds ratio estimate (95% confidence interval)	Fisher exact test probability value
Temporal Orientation <1	7.77 (0.71, 419.62)	0.072
WAIS-R information <10	4.58 (0.52, 61.75)	0.156
COWA <30	41.68 (3.02, 2,716.06)	0.001
WAIS-R Digit Span <10	6.58 (0.60, 354.77)	0.169
Rey-Osterrieth CFT, copy <20	9.70 (0.79, 164.99)	0.041
FRT <40	1.24 (0.09, 11.74)	1.000
BVRT correct <4	1.95 (0.21, 18.18)	0.641
WAIS-R Block Design <6	9.27 (0.75, 157.83)	0.046
Trail Making Test (Part B) <3	13.47 (1.19, 747.68)	0.016
UFOV total loss >50%	3.20 (0.37, 42.20)	0.360
Starry Night (d′) <1	3.81 (0.44, 50.78)	0.184
Three-dimensional SFM >15	4.67 (0.46, 50.31)	0.120
MDD >30	12.21 (1.20, 194.55)	0.016
Alzheimer disease	7.24 (0.91, ∞)	0.057
Age >70 years	0.51 (0.05, 4.72)	0.641
Male gender	1.00 (0.11, 9.06)	1.000

WAIS-R, Wechsler Adult Intelligence Scale–Revised; COWA, Controlled Oral Word Association; CFT, Complex Figure Test; FRT, Facial Recognition Test; BVRT, Benton Visual Retention Test; UFOV, useful field of view; SFM, structure from motion; MDD, motion direction discrimination.

57.61 ($p < 0.001$) in our earlier study of collision avoidance. These ORs are not statistically different between studies ($p = 0.249$), allowing both data sets to be pooled together to give an adjusted OR of 23.48 (CI, 4.40–179.29; $p < 0.001$).

Figure 4 shows the receiver-operator characteristic curve for the ADSTAT predictor variable. Receive-operator characteristic curves represent the relation between proportions of hits (i.e., predicting a crash in drivers who did crash; *y* axis) and false alarms (predicting a crash in drivers who did not crash; *x* axis) for a range of criterion levels for each independent variable. The false alarm rate, hit rate, and d′ were calculated at each criterion level. The highest d′ value for the ADSTAT variable in the combined studies was 2.32. The highest d′ value for other predictor variables was 1.96 for CFT, 1.64 for UFOV, and 1.23 for BVRT. The ADSTAT variable (at a cutoff level of 385) showed better balance of sensitivity

TABLE 4. *Combined studies: odds radio estimates, 95% confidence intervals, and exact probabiity values of predictors of crashes*

Predictor variable	Odds ratio estimate (95% confidence interval)/probability value	Interaction probability value
Temporal Orientation <0	13.26 (2.39, 140.67)/<0.001	1.000
WAIS-R information <10	10.21 (2.15, 67.23)/0.002	0.639
COWA <30	32.05 (5.40, 361.44)/<0.001	1.000
WAIS-R Digit Span <10	14.36 (1.88, 656.13)/0.004	1.000
Rey-Osterrieth CFT, copy <20	32.85 (5.41, 370.03)/<0.001	0.431
FRT <40	7.15 (1.55, 36.42)/0.009	0.037
WAIS-R Block Design <6	19.28 (3.65, 138.28)/<0.001	0.856
BVRT correct <4	5.28 (1.05, 35.52)/0.042	0.325
Trail Making Test (Part B) <3	35.90 (4.57, 1,663.21)/<0.001	0.902
UFOV total loss >50%	9.76 (1.84, 99.66)/0.003	0.376
Starry Night (d′) <1	10.34 (2.13, 70.10)/0.002	0.447
Three-dimensional SFM >15	16.88 (3.37, 118.26)/<0.001	0.213
MDD >30	7.75 (1.69, 43.51)/0.006	1.000
Alzheimer disease	16.91 (2.61, ∞)/0.001	1.000
Age >70 years	0.62 (0.15, 2.63)/0.652	1.000
Male gender	1.63 (0.38, 8.37)/0.682	0.935

WAIS-R, Wechsler Adult Intelligence Scale–Revised; COWA, Controlled Oral Word Association; CFT, Complex Figure Test; FRT, Facial Recognition Test; BVRT, Benton Visual Retention Test; UFOV, useful field of view; SFM, structure from motion; MDD, motion direction discrimination.

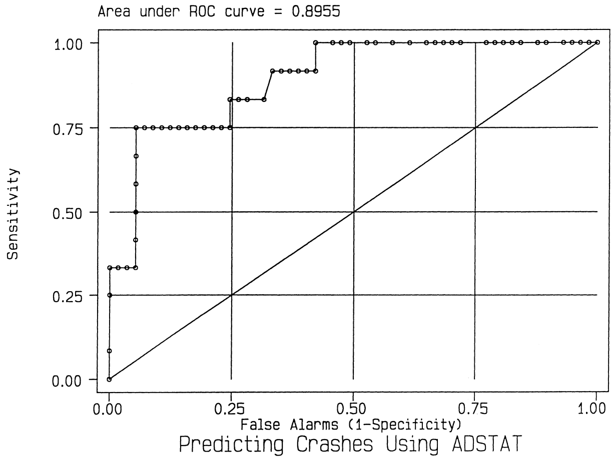

FIG. 4. Receiver-operator characteristic curves were plotted to test the ability of cognitive measures to discriminate between drivers who did and did not crash in the combined studies. Results for the equally weighted composite score (ADSTAT) predictor variable are shown. Receive-operator characteristic curves represent the relation between proportions of hits (*y* axis) and false alarms (*x* axis) for different levels of the independent predictor variables. A hit corresponds to predicting a crash in a driver who actually crashed. A false-positive result (false alarm) corresponds to predicting a crash in a driver who did not crash. Specificity is equivalent to 1-P (false alarm). The highest d′ value for the ADSTAT variable was 2.32 (see text).

(75%) and specificity (94.7%) than the other independent predictor variables.

DISCUSSION

In the current study, 6 of 18 drivers with AD (33%) experienced crashes when the driver's approach to an intersection triggered an illegal incursion by another vehicle versus none of 12 nondemented drivers of similar age. The findings are similar to those of an earlier study using rearend collision avoidance scenarios implemented on the IDS (Rizzo et al., 1997), where 6 of 21 cognitively impaired individuals with AD (29%) experienced crashes versus none of 18 controls. The results are compatible with our hypothesis that older drivers with mild to moderate AD are at greater risk for crashes than older drivers without dementia.

Relations between driver performance factors and safety errors can be represented by an imaginary triangle (Heinrich et al., 1980) or "iceberg" (Maycock, 1997). Visible safety errors (above the "waterline") include car crashes resulting in fatality, serious injury, mild injury, or, most commonly, property damage only. Crash events are relatively infrequent and tend to follow a Poisson distribution (Siskind, 1996; Thomas, 1996). Submerged below the "waterline" are several behavioral variables that are theoretically related to crashes and occur more frequently.

As the frequency of events increases, the relevance to serious driver safety errors and crashes decreases. With a sufficient number of observations, it should be possible to accurately estimate the risk of a crash (a low-frequency, high-severity event) through the assessment of measurable safety errors (high-frequency, low-severity events).

Figure 5 depicts an information processing model for understanding driver errors that can lead to a crash. The risk of human error in complex systems (such as a driver operating a motor vehicle) increases with deficits of attention, perception, response selection (which depends on memory and decision making) and response implementation (Norman, 1981, 1988; Reason, 1984, 1990; Wickens, 1992). Psychomotor factors and general mobility are also important (Marottoli et al., 1994). Individuals with defects in these abilities, as indexed by scores on cognitive tests administered in our research, seem to be more likely than normal drivers to commit the kind of errors that cause motor vehicle crashes. Some errors are detected when drivers who normally monitor their own performance receive feedback on their driving that fails to match expectations based on correctly formulated intentions: the discrepancy is thus detected "online" (Wickens, 1992). Cognitively impaired drivers are less likely to realize their errors. In short, cognitive abilities and impairments determine specific driver behaviors and safety errors, which, in turn, predict crashes.

Mitigation of performance errors in AD is linked to the general issue of self-awareness of acquired impairments (Anderson and Tranel, 1989). Individuals with AD rarely refer themselves for evaluation and tend to be unaware of their acquired cognitive impairments. Certain motorists with cognitive decline curtail their driving activity to some extent because of self- or family-imposed driving restrictions, yet others have impaired awareness of acquired cognitive defects (known in the neurologic literature as anosognosia). Anosognosia falls under the rubric of executive function defects and can greatly exacerbate the functional consequences of impairments in other cognitive domains (Anderson and Tranel, 1989). Individuals with impaired awareness of their compromised cognitive condition fail to take steps that might compensate for their impairments and are liable to continue to drive regardless of risk.

The crashes measured in this study and in its predecessor were predicted by performance scores on cognitive tests sensitive to declines in aging and AD. Neuropsychologic screening might help licensing authorities to decide whether to recertify impaired drivers (Cushman, 1992; O'Neill et al., 1992; Carr, 1993; Hunt et al., 1993; Fitten et al., 1995; Johansson et al., 1996). It may be

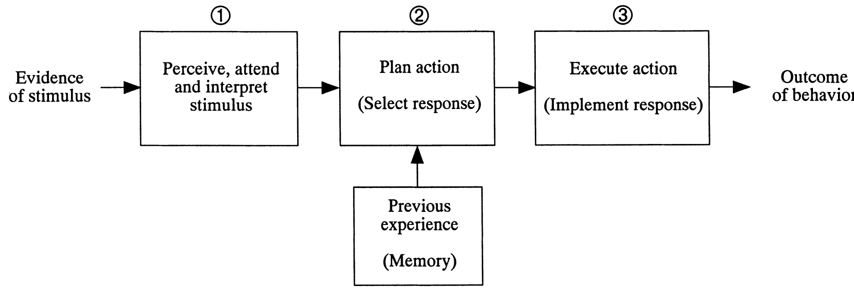

FIG. 5. An information processing model for understanding driver error. In this simple heuristic framework, (1) the driver perceives and attends stimulus evidence (e.g., through vision, audition, vestibular, and proprioceptive inputs) and interprets the situation on the road; (2) the driver formulates a plan based on the particular driving situation and relevant previous experience or memory; and (3) the driver executes an action (e.g., by applying the accelerator, brake, or steering controls as in Fig. 3). The driver's behavioral response is either safe or unsafe as a result of errors at one or more stages in the driving task. The outcome of the behavior provides a source of potential feedback for the driver to take subsequent action. The relations between low-frequency (high-severity) driver performance errors that lead to crashes and high-frequency (low-severity) driver performance errors are best studied in simulation (see text).

useful in helping to prevent what amounts to discrimination against those who are aging or ill. Our results show that most AD drivers did not crash and exhibited fair vehicular control (15 of 21 subjects in the first study and 12 of 18 subjects in the intersection incursion scenario). This suggests that some individuals with mild dementia remain fit drivers and should be allowed to continue to drive until their cognitive impairment progresses to a degree predictive of unsafe driving.

It should be noted that no driver in this study of AD committed a safety error while driving on the relatively uneventful segments of simulated highway preceding the intersection incursion. Unless the experimental driving task poses a sufficient challenge, the likelihood of observing meaningful safety errors for predicting driver fitness is low. This is probably why state road tests (in which operating conditions must be constrained to minimize threat of injury) fail to predict crashes in experienced drivers whose risk of a crash in real life is unacceptably high (e.g., drivers with cognitive decline).

By manipulating task demands in a safe and controlled experimental environment, it is possible to stress a particular information processing stage or stream in driving and to create traffic situations in which driver errors of one type or another (e.g., perception vs. planning) are more likely to occur. This is important in terms of localizing errors in the driving task for drivers who have impairment in certain cognitive domains (measured by off-road neuropsychologic tasks) and are hypothesized to fail under certain conditions. In a simulated environment, it is possible to create information flows to the driver that are unattainable in the real world and that identify specific driver reactions and safety errors in crash avoidance scenarios, a line of inquiry which is hazardous and unethical on the road (Rizzo et al., 1997). By increasing the "exposure" of cognitively impaired drivers, it is possible to infer crash risk through direct observation of events that might take months to infer from real-life events (Table 5).

TABLE 5. *Crash risk with equally weighted composite score (ADSTAT) less than 400: odds ratio estimates, 95% confidence intervals, and exact probability values*

Study	Odds ratio	Confidence interval	Probability value
Rear end	57.61	(6.88–∞)	<0.001
Intersection incursion	6.39	(0.59–77.72)	0.151
Combined (crude)	23.44	(3.43–173.59)	<0.001
Combined (adjusted)	23.48	(4.40–179.21)	<0.001

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