Driver route-following and safety errors in early Alzheimer disease

E.Y. Uc, MD; M. Rizzo, MD; S.W. Anderson, PhD; Q. Shi, MS; and J.D. Dawson, ScD

Abstract—*Objective:* To assess navigation and safety errors during a route-following task in drivers with Alzheimer disease (AD). *Design/Methods:* Thirty-two subjects with probable AD (by National Institute of Neurological and Communicative Disorders criteria) of mild severity and 136 neurologically normal older adults were tested on a battery of visual and cognitive tests of abilities that are critical to safe automobile driving. Each driver also performed a route-finding task administered on the road in an instrumented vehicle. Main outcome variables were number of 1) incorrect turns; 2) times lost; and 3) at-fault safety errors. *Results:* The drivers with mild AD made significantly more incorrect turns, got lost more often, and made more at-fault safety errors than control subjects, although their basic vehicular control abilities were normal. The navigational and safety errors were predicted using scores on standardized tests sensitive to visual and cognitive decline in early AD. *Conclusions:* Drivers with Alzheimer disease made more errors than neurologically normal drivers on a route-following task that placed demands on driver memory, attention, and perception. The demands of following route directions probably increased the cognitive load during driving, which might explain the higher number of safety errors.

NEUROLOGY 2004;63:832–837

Getting lost is a common problem for those with Alzheimer disease (AD).[1-5] First these patients become disoriented in unfamiliar surroundings, but later they even have difficulty navigating on familiar routes.[2-5] Drivers with neurologic disorders including AD are more likely to get lost because of topographic disorientation from declines of spatial, verbal, and topographic memory.[1,6,7]

This study tested the hypothesis that patients with early AD commit navigation errors on a route-following task (RFT) that resembles the real-world situation in which a driver must follow verbal directions to a destination. This RFT was implemented in an instrumented vehicle designed to record driver speed, steering, braking, and acceleration and to assess driver errors.[8,9] An additional goal was to establish whether drivers with AD, under the influence of the cognitive load imposed by the RFT, commit more safety errors that could place them at greater risk for a potential crash. We also tested whether navigation and safety errors could be predicted by visual and cognitive measures sensitive to decline in early AD.

Additional material related to this article can be found on the *Neurology* Web site. Go to www.neurology.org and scroll down the Table of Contents for the September 14 issue to find the link for this article.

Methods. *Subjects.* Subjects were 32 participants (27 men and 5 women) with mild AD (mean Mini-Mental State Examination [MMSE] score ± SD, 26.3 ± 2.9; range, 18 to 30) and 136 neurologically normal control participants (67 men and 69 women). Both groups had comparable years of education (mean ± SD, 15.3 ± 3.2 in AD and 15.6 ± 2.5 in normal control subjects). The AD subjects were somewhat older (mean age ± SD, 75.9 ± 6.2 years for AD and 64.0 ± 11.4 years for control subjects; $p < 0.0001$, Wilcoxon rank sum). The male predominance in the AD group might reflect that women in this age group had not traditionally been the main driver in the family and more readily relinquished their driving privileges once they developed AD. Subjects with neurologic disorders other than AD were excluded. No subject had acute, confounding medical or psychiatric conditions. Participants with AD were recruited from a registry in the Department of Neurology. The diagnosis of probable AD relied on the National Institute of Neurological and Communication Disorders and Stroke/Alzheimer's Disease and Related Disorders Association criteria.[10] Accordingly, all AD patients had symptoms of memory impairment and related cognitive complaints that interfered with their social or occupational life. MMSE screening reflected mild early cognitive decline in these still licensed drivers. Impairments on memory and other cognitive domains on a standardized battery of neuropsychological tests (table 1) were consistent with early AD.[11] CT and MRI scans of the brain excluded destructive lesions caused by cerebrovascular and neoplastic disease. Control participants were recruited from volunteers in the local community. All participants held a current, valid state driver's license and were still driving, although some had reduced driving activity because of self- or family-imposed restrictions. Exclusion criteria included alcoholism, stroke, depression, vestibular disease, and motion sickness. Informed consent was obtained in accord with institutional and federal guidelines for human subjects' safety and confidentiality.

See Commentary, page 765

From the Division of Neuroergonomics, Department of Neurology, College of Medicine (Drs. Uc, Rizzo, Anderson, and Dawson, Q. Shi), Department of Mechanical and Industrial Engineering (Dr. Rizzo), Public Policy Center (Dr. Rizzo), and Department of Biostatistics, College of Public Health (Dr. Dawson, Q. Shi), University of Iowa, Iowa City, IA.

Supported by grants NIA AG 17717 and NIA AG 15071.

Received August 14, 2003. Accepted in final form May 7, 2004.

Address correspondence and reprint requests to Dr. Matthew Rizzo, Department of Neurology, University of Iowa Hospitals and Clinics, 200 Hawkins Drive, Iowa City, IA 52242; e-mail: matthew-rizzo@uiowa.edu

Table 1 Characteristics of Alzheimer disease and normal control groups

	AD (n = 32)	Normal (n = 136)	*p* Values	
Demographics				
Age, y	75.9 (6.2)	64.0 (11.4)	<0.0001	
Education, y	15.3 (3.2)	15.6 (2.5)	0.4844	
Cognitive tests			Crude	Age-adjusted
MMSE	26.3 ± 2.9			
COGSTAT	300.4 (45.4)	405.4 (45.2)	<0.0001	<0.0001
AVLT-RECALL	3.2 (2.6)	10.5 (3.0)	<0.0001	<0.0001
BVRT	9.2 (3.2)	4.4 (2.5)	<0.0001	<0.0001
CFT-RECALL	9.2 (4.5)	15.7 (5.7)	<0.0001	<0.0001
JLO	23.6 (4.1)	26.1 (3.6)	0.0005	0.0208
BLOCKS	23.9 (10.0)	40.5 (10.8)	<0.0001	<0.0001
CFT-COPY	29.0 (3.9)	32.0 (3.3)	<0.0001	0.0003
TMT-B	154.5 (72.4)	78.1 (38.8)	<0.0001	<0.0001
COWA	34.3 (11.0)	39.5 (10.7)	0.0132	0.0921
Visual tests				
NVA	0.052 (0.064)	0.018 (0.037)	<0.0001	<0.0001
FVA	0.024 (0.109)	−0.099 (0.116)	<0.0001	<0.0001
CS	1.64 (0.17)	1.86 (0.13)	<0.0001	<0.0001
SFM	13.0 (7.04)	10.3 (2.85)	0.1055	0.0047
UFOVTOT	1,262 (221)	610 (233)	<0.0001	<0.0001

Values expressed as mean (SD). Groups were compared using Wilcoxon rank sum.

AD = Alzheimer disease; MMSE = Mini Mental State Examination; COGSTAT = composite measure of cognitive impairment; AVLT-RECALL = Auditory Verbal Learning Test-Recall; BVRT = Benton Visual Retention Test; CFT-RECALL = Complex Figure Test-Recall; JLO = Judgment of Line Orientation; BLOCKS = Block Design subtest; CFT-COPY = Complex Figure Test-Copy; TMT-B = Trail-Making Test subtest B; COWA = Controlled Oral Word Association; NVA = near visual acuity; FVA = far visual acuity; CS = contrast sensitivity; SFM = structure from motion; UFOVTOT = total of subtests of the Useful Field of view task.

Cognitive and visual battery. All participants were tested on a battery of cognitive and visual tasks (see table 1). The Rey–Osterrieth Complex Figure Test Copy version (CFT-COPY) requires participants to copy a complex geometric figure, which provides an index of visuoconstructional ability. In the CFT-RECALL version, a good measure of nonverbal anterograde memory, the subject is asked to draw the figure from memory 30 minutes after copying the CFT. The Block Design subtest (BLOCKS) from the Wechsler Adult Intelligence Scale-Revised provides an additional measure of visuoconstructional ability that correlates with performance IQ. The Benton Visual Retention Test (BVRT) stresses working memory, a key executive function. The Trail-Making Test subtest B (TMT-B) also places demands on executive functions, including working memory and attentional set shifting. Rey Auditory Verbal Learning Test (AVLT) measures anterograde verbal memory. Judgment of Line Orientation (JLO) assesses visuospatial perception by requiring matching lines of different orientation to target. Controlled Oral Word Association (COWA) Test requires subjects, within a 1-minute time limit, to generate as many words as possible that begin with a certain letter of the alphabet. These tasks are described in detail elsewhere.[12,13] We calculated a composite measure of cognitive impairment (COGSTAT) by assigning standard *T* scores (mean = 50, SD = 10) to each of the eight tests from the neuropsychological assessment battery (COWA, CFT-COPY, CFT-RECALL, AVLT-RECALL, BVRT, BLOCKS, JLO, and TMT-B) as in our previous work.[14,15]

The Useful Field of View (UFOV) task (Visual Attention Analyzer, Visual Resources Inc., Chicago, IL) measures speed (in ms) of visual processing, divided attention, and selective attention.[16,17] UFOV loss correlates with increased crash risk in simulated driving scenarios and real-life crashes.[16,17] We used the sum of four subtests of the UFOV task (UFOVTOT) in our analyses. Contrast sensitivity (CS) was assessed using the Pelli–Robson chart.[18] The best corrected visual acuity was measured using the Early Treatment Diabetic Retinopathy Study chart[19] for far visual acuity (FVA) and reduced Snellen chart for near visual acuity (NVA), both expressed as logarithm of the minimum angle of resolution, with 0 representing 20/20 vision. Perception of three-dimensional structure from motion (SFM) and of motion direction was tested using computer-generated animation sequences.[15]

ARGOS. The experimental drive was conducted aboard an instrumented vehicle known as ARGOS (the Automobile for Research in Ergonomics and Safety), a mid-sized 1995 Ford Taurus station wagon with an automatic transmission and hidden instrumentation and sensors.[8,9] Experimental performance data (e.g., steering wheel position, normalized accelerator and brake pedal position, lateral and longitudinal acceleration, and vehicle speed) were digitized at 10 Hz and reduced to mean, SD, or count. Driver's lane tracking and visual scanning activity of the environment were recorded by videotape at 30 frames/s using miniature lipstick-sized cameras mounted unobtrusively within the vehicle. Control of speed[20] and lane position[21] are critical aspects of driving, and unplanned lane deviations occur with degradation of driving performance.[22]

Administering the road test in ARGOS. The road test in ARGOS was administered within 1 week of cognitive and visual testing, sometimes on the same day. Order of testing (cognitive and visual vs ARGOS) was random. The subjects were seated comfortably in the driver's seat. The experimenter sat in the front passenger seat to score the on-road performance and operate the dual controls, if needed. The experimenter gave standard instructions to the drivers on operating ARGOS. The experimental drive lasted ~45 minutes and started after the driver acclimated to

ARGOS on a short test drive. The experimental drive consisted of "on-task" (e.g., while performing RFT) and "no-task" segments. Road testing was carried out only during the day (usually between 9:00 AM and 4:00 PM) on specific roads surrounding Iowa City. Drivers were not tested in inclement weather that might cause poor visibility or road conditions. The assessment incorporated several essential maneuvers such as turns, stopping at a stop sign, and maintaining vehicle control.

Route-following task. Route following was tested as part of a sequence of on-road tasks administered in ARGOS. Drivers were given verbal instructions to follow a route (see figure E-1 on the *Neurology* Web site at www.neurology.org). The instructions (i.e., 1. From the main hospital entrance, turn left onto Hawkins Drive, 2. Right onto Melrose Avenue, 3. Left on Koser Avenue, and 4. Left on George Street) were read to the subject just before beginning the experimental drive and were repeated with corrections until the driver recited the instructions correctly twice in a row. Each segment was ~0.2 miles long. Driver familiarity with the section of town where the RFT was administered was assessed and incorporated into analyses. After a turn error, subjects were allowed to drive one additional block before the experimenter disclosed the error to the subject. After identification of an error, the subject was given the opportunity to correct the error. If the driver failed to correct the error, the experimenter redirected the driver to the proper route. Dependent measures were number of 1) incorrect turns, defined as turning too soon, too late, or in the wrong direction (maximum 4); 2) times lost, defined as incorrect turns after which the driver did not recognize and correct the error; and 3) at-fault safety errors, such as erratic steering, lane deviation, shoulder incursion, stopping or slowing in unsafe circumstances, and unsafe intersection behavior.

Causes of incorrect turns were classified as perception/attention or memory errors based on driver self-report, questionnaires, and video analyses. Perception/attention errors included failure to look for, identify, or read the street sign. Memory errors included inability to remember the street name, turn direction, or turn sequence.

Statistical analysis. We made crude and age-adjusted comparisons between groups with respect to demographic, visual, and cognitive measures. We used Fisher's exact test to compare the proportion of drivers in each group who made incorrect turns, at-fault safety errors, and got lost. We used the Wilcoxon rank sum test to compare the outcome measures of the RFT and the cognitive and visual tests. We used regression models to adjust these comparisons for age, gender, visual acuity, and previous familiarity with the route. We calculated Spearman correlation coefficients for the outcome measures with the cognitive and visual tests. We identified predictors of the main outcomes in the RFT using stepwise logistic regression for incorrect turns and memory errors and ordinal logistic regression for at-fault safety errors. The modeling for cognitive and visual predictors was done in two ways. First, the individual components of COGSTAT were used to model for cognitive predictors, followed by modeling for visual variables (CS, UFOVTOT, NVA, FVA, SFM) that was adjusted for general cognitive performance by using COGSTAT in the model. This allowed us to see the overall effect of the main two classes (cognitive and visual) of variables. Second, all cognitive and visual variables were modeled together without the intermediate role of the derived composite measure of cognition (COGSTAT) to see the direct effects of each variable in the model.

Results. The proportion of subjects who made incorrect turns, got lost, or made at-fault safety errors was significantly higher in the AD group (figure). Drivers with AD made more incorrect turns, got lost more often, and committed more at-fault safety errors than the neurologically normal control subjects (table 2). These safety errors mainly comprised illegal lane boundary crossings of varying magnitude. However, there was no difference between the groups in the basic vehicular control (as measured by steering wheel position, number of large changes in steering wheel position/min, and speed variation) on a straight segment of the drive during which no secondary task such as RFT was administered (see table E-1 on the *Neurology* Web site at www.neurology.org). Drivers with AD required more trials to learn the route correctly, took longer time to finish the route, and made more perception/attention and memory related errors than the controls. Some incorrect turns were the result of perception/attention and memory errors. The difference between the RFT outcome measures in the AD patients and control groups persisted after adjusting for familiarity with the neighborhood, age, FVA and NVA, gender, and all covariates together except times lost and memory errors (see table 2). Adjustment for familiarity with the neighborhood and FVA made the group difference in times lost insignificant. Adjustment for all covariates together had a similar effect on times lost and memory errors (see table 2).

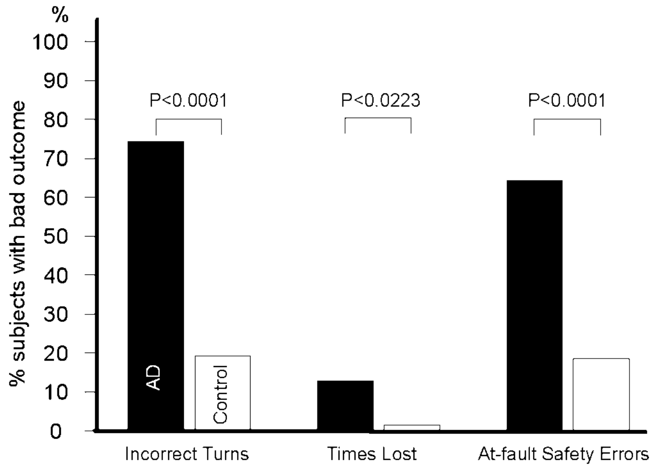

Figure. Proportion of subjects with "bad" outcomes on the route following task in patients with Alzheimer disease (AD) and normal control group. The bad outcomes are defined as making at least one incorrect turn, getting lost at least once, and making ≥2 at-fault safety errors, all significantly higher in the AD group (Fisher's exact test).

The AD group performed worse than the control group on several neuropsychological and visual tests, showing mild dementia and visual perception and processing deficits (see table 1). Measures of verbal (AVLT-RECALL) and nonverbal memory (CFT-RECALL and BVRT), executive function (TMT-B and COWA), visual perception (FVA, NVA, CS, and JLO), visual attention (UFOVTOT), visuoconstructional abilities (CFT-COPY, BLOCKS), and overall cognitive function (COGSTAT) correlated significantly (Spearman coefficients) with the outcome measures of the RFT (see table E-2 on the *Neurology* Web site at www.neurology.org). Using regression analyses on multivariate models for the cognitive and visual off-road tests as described previously, we identified AVLT-RECALL and UFOVTOT as important predictors of incorrect turns and times lost and AVLT-RECALL, CFT-COPY, and CS for at-fault safety errors (table 3).

We analyzed the effect of RFT on commission of at-fault safety errors between the groups. The group difference persisted ($p < 0.001$) when we compared the "on-task" errors (i.e., errors committed during the cognitive load imposed by the RFT) after adjusting for "off-task" errors (i.e., errors committed during segments of drive where no tasks were administered), indicating that the cognitive burden of the RFT increased the likelihood of errors.

Discussion. The findings in this study support our hypothesis that drivers with AD make more naviga-

Table 2 Main and secondary outcome measures of the route-following task expressed as means (SD) in Alzheimer disease (AD) and normal control group, compared using Wilcoxon rank sum

	AD	Normal	*p* Values						
Sample size	32	136	Crude	Adjustments					
Outcomes				Familiarity	Age	NVA	FVA	Gender	All covariates
Main outcomes									
Incorrect turns	0.97 (0.86)	0.21 (0.45)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0004
Times lost	0.22 (0.75)	0.02 (0.15)	<0.0159	0.1087	0.0425	0.0181	0.0796	0.0168	0.1508
At-fault safety errors	3.06 (2.95)	0.80 (1.10)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Secondary outcomes									
Learning to criterion	5.4 (2.9)	2.7 (0.8)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Perception/attention errors	0.63 (0.55)	0.18 (0.38)	<0.0001	0.0003	0.0007	<0.0001	<0.0001	<0.0001	0.0110
Memory errors	0.44 (1.08)	0.02 (0.19)	0.0005	0.0275	0.0042	0.0011	0.0254	0.0011	0.1887
Time to finish, s	275.0 (103.7)	174.9 (73.4)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0004

Forty-four percent of AD subjects and 74% of the normal control subjects were familiar with the neighborhood before the experiment. Note that adjustment for "familiarity" with the neighborhood, and neighborhood and FVA, as well as all covariates together, rendered the difference in the "times lost" insignificant. Difference in "memory errors" was rendered insignificant after adjusting for all covariates together. All other outcome measures remained significant after adjusting for individual and all covariates. Adjustments were made using linear regression for at-fault safety errors and time to finish; ordinal logistic regression for incorrect turns, times lost, and perception/attention errors; and exact logistic regression for memory errors. NVA = near visual acuity; FVA = far visual acuity.

tional errors than neurologically normal drivers on an RFT that places demands on driver memory, attention, and perception. These demands probably increased the cognitive load during driving, which might explain the higher number of at-fault safety errors we measured in these drivers who have limited cognitive resources. These group differences could not be explained by the older age or predominantly male gender of the AD subjects because significant differences between groups in RFT outcome measures persisted after adjustment for age and gender (see table 2).

Impaired navigating or way-finding (i.e., topographic disorientation)[6,7] may be an early complication in AD.[1-5] Patients with AD get lost easily, first in unfamiliar places, but later also in familiar surroundings.[2-5] Navigational and visuospatial abilities in these drivers

*Table 3 Predictors of the main outcome measures using forward stepwise logistic regression or ordinal logistic regression**

A	Predictor variables	Interval for modeling	OR	(95% CI)	*p* Values
Incorrect turns	AVLT-RECALL	1 unit decrease	1.27	(1.16, 1.40)	<0.0001
	UFOVTOT	100 units increase	1.26	(1.08, 1.47)	0.0027
Times lost	AVLT-RECALL	1 unit decrease	1.28	(1.06, 1.59)	0.0112
At-fault safety errors*	CS	0.3 unit decrease	2.08	(1.12, 3.85)	0.0191
	CFT-COPY	1 unit decrease	1.14	(1.04, 1.23)	0.0026
	AVLT-RECALL	1 unit decrease	1.10	(1.02, 1.18)	0.0120

B	Predictor variables	Interval for modeling	OR	(95% CI)	*p* Values
Incorrect turns	UFOVTOT	100 units increase	1.26	(1.10, 1.44)	0.0009
	AVLT-RECALL	1 unit decrease	1.14	(1.02, 1.27)	0.0207
Times lost	UFOVTOT	100 units increase	1.41	(1.13, 1.75)	0.0024
At-fault safety errors*	CS	0.3 units decrease	2.63	(1.52, 4.55)	0.0006
	CFT-COPY	1 unit decrease	1.14	(1.04, 1.23)	0.0026

A. Cognitive variables (COWA, CFT-COPY, CFT-RECALL, AVLT-RECALL, BVRT, BLOCKS, JLO, and TMT-B) and visual variables (CS, UFOVT, NVA, and FVA) were modeled separately. The modeling for visual variables was adjusted for general cognitive performance by using COGSTAT in the model. B. Cognitive and visual variables were modeled together.

OR = odds ratio; AVLT-RECALL = Auditory Verbal Learning Test-Recall; UFOVTOT = total of subtests of the Useful Field of View task; CS = contrast sensitivity; CFT-COPY = Complex Figure Test-Copy; COWA = Controlled Oral Word Association; BVRT = Benton Visual Retention Test; BLOCKS = Block Design subtest; JLO = Judgment of Line Orientation; TMT-B = Trail-Making Test subtest B.

have generally been tested indirectly using a variety of neuropsychologic tests[4,5,15,23-26] or walking on a trail.[2,3] To our knowledge, no study has tested route following in patients with AD during actual driving as in our study.

Our navigation task is route based (rather than map based[7]) and resembles the common situation, in which a driver receives verbal instructions that describe a sequence of steps to a destination. The RFT engages anterograde verbal memory, visual perception and attention, recognition of landmarks such as street signs, and visuospatial abilities (such as right/left discrimination and executing remembered turns in the correct direction). The RFT also requires drivers to monitor their navigation errors and correct them to resume the proper route. Self-monitoring and correction require executive functions, mental rotation of imagined space, recognition of recently encountered landmarks from an altered perspective, and comparison with the mental model developed from the initial sequence of verbal instructions. In line with these information procession demands of the RFT, measures of verbal and visual memory, executive function, visual perception, visual attention, visuoconstructional abilities, and overall cognitive function correlated significantly with the RFT outcome measures (see table E-2 on the *Neurology* Web site).

Although RFT outcomes correlated with NVA and FVA showing the role of basic vision in route finding, visual acuity is unlikely to be the primary determinant of RFT because NVA and FVA did not predict the RFT outcomes (see table 3), and statistical correction for them did not render the group differences insignificant (see table 2). However, emergence of UFOVTOT as a predictor of RFT (see table 3) and strong correlation of BLOCKS and BVRT with RFT outcomes (see table E-2 on the *Neurology* Web site) underscored the critical contribution of higher order visual and attentional processes and visuospatial abilities to route finding. Our findings are consistent with the literature that visual attention,[27-29] reading, route finding,[2,3] object localization and recognition,[5,30-32] and visuospatial abilities[4,27,33] are impaired even in early AD.[14,15,27,28,32,34-37]

AVLT-RECALL predicted incorrect turns, times lost, and at-fault safety errors consistent with anterograde verbal memory demands of RFT (see table 3). UFOVTOT predicted incorrect turns and times lost, consistent with the RFT's visual attention demands. CS and CFT-COPY predicted at-fault safety errors, underscoring the role of visual perception and visuospatial abilities in safe driving (see table 3). UFOVTOT, a predictor for crashes in elderly persons and patients with AD,[16,17] also predicted poor outcomes in two of three main RFT outcomes, indicating its importance in driver evaluation. Correlation of verbal and nonverbal abilities with RFT outcomes indicates that RFT depends on neuroanatomic substrates in both hemispheres.

We found that drivers with AD committed more at-fault safety errors during the RFT even after adjusting for the safety errors performed during no-task driving segments. There also was no group difference in vehicular control when no secondary task was administered (see table E-1 on the *Neurology* Web site). Thus, the greater number of safety errors in drivers with AD probably results from increased cognitive load caused by performing the RFT rather than differences in basic vehicular control.

Familiarity with the neighborhood was a mitigating factor in this study. Drivers who reported previous familiarity with the area of town where the RFT was conducted did not get lost (see table 2). Drivers with early AD may have trouble learning new routes yet continue to navigate accurately on familiar old routes. This finding suggests that graded licensure policies that allow driving in a familiar neighborhood can be considered for drivers with mild dementia.

A number of drivers with AD did not make turn errors, did not get lost, and drove safely (see figure), suggesting that some individuals with mild dementia remain fit drivers and should be allowed to continue to drive.[38]

The current findings indicate that the approach to assessments of driver fitness in at-risk drivers with cognitive impairment can benefit from introducing controlled challenges of vision, perception, memory, and attention during driving scenarios implemented in an instrumented vehicle. Future work in this area must address the relationship between relatively high-frequency low-severity safety errors, such as we measured in ARGOS, and low-frequency high-severity incidents, such as injurious crashes, in epidemiologic records.

References

1. Barrash J. A historical review of topographical disorientation and its neuroanatomical correlates. J Clin Exp Neuropsychol 1998;20:807–827.
2. Cherrier MM, Mendez M, Perryman K. Route learning performance in Alzheimer disease patients. Neuropsychiatry Neuropsychol Behav Neurol 2001;14:159–168.
3. Passini R, Rainville C, Marchand N, Joanette Y. Wayfinding in dementia of the Alzheimer type: planning abilities. J Clin Exp Neuropsychol 1995;17:820–832.
4. Henderson VW, Mack W, Williams BW. Spatial disorientation in Alzheimer's disease. Arch Neurol 1989;46:391–394.
5. Tetewsky SJ, Duffy CJ. Visual loss and getting lost in Alzheimer's disease. Neurology 1999;52:958–965.
6. Barrash J, Damasio H, Adolphs R, Tranel D. The neuroanatomical correlates of route learning impairment. Neuropsychologia 2000;38:820–836.
7. Aguirre GK, D'Esposito M. Topographical disorientation: a synthesis and taxonomy. Brain 1999;122:1613–1628.
8. Barry CJ, Smith D, Lennarson P, et al. The effect of wearing a restrictive neck brace on driver performance. Neurosurgery 2003;53:98–102.
9. Rizzo M, McGehee D, Petersen AD, Dingus TA. Development of an unobtrusively instrumented field research vehicle for objective assessments of driving performance. In: Rothengatter T, Carbonnel VE, eds. Traffic and Transport Psychology: Theory and Application. New York: Pergamon, 1997:203–208.
10. 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.
11. Salmon DP, Thomas RG, Pay MM, et al. Alzheimer's disease can be accurately diagnosed in very mildly impaired individuals. Neurology 2002;59:1022–1028.
12. Lezak MD. Neuropsychological Assessment, 3rd ed. New York: Oxford University Press Inc, 1995.

13. Spreen O, Strauss E. A Compendium of Neuropsychological Tests. New York: Oxford University Press Inc, 1991.
14. Rizzo M, McGehee DV, Dawson JD, Anderson SN. Simulated car crashes at intersections in drivers with Alzheimer disease. Alzheimer Dis Assoc Disord 2001;15:10–20.
15. Rizzo M, Nawrot M. Perception of movement and shape in Alzheimer's disease. Brain 1998;121:2259–2270.
16. 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.
17. 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.
18. Pelli DG, Robson JG, Wilkins AJ. The design of a new letter chart for measuring contrast sensitivity. Vision Res 1988;2:187–199.
19. Ferris FL III, Kassoff A, Bresnick GH, Bailey I. New visual acuity charts for clinical research. Am J Ophthalmol 1982;94:91–96.
20. Monty RW. Eye Movements and Driver Performance with Automotive Displays [master's thesis]. Blacksburg, VA: Virginia Polytechnic Institute and State University, 1984.
21. Godthelp H. Vehicle control during curve driving. Hum Factors 1986; 28:211–221.
22. Dingus TA, Antin JF, Hulse MC, Wierwille WW. Attentional demand requirements of an automobile moving-map navigation system. Transportation Res 1989;4:301–315.
23. Kavcic V, Duffy CJ. Attentional dynamics and visual perception: mechanisms of spatial disorientation in Alzheimer's disease. Brain 2003;126: 1173–1181.
24. Rainville C, Marchand N, Passini R. Performances of patients with a dementia of the Alzheimer type in the Standardized Road-Map test of Direction Sense. Neuropsychologia 2002;40:567–573.
25. O'Brien HL, Tetewsky SJ, Avery LM, Cushman LA, Makous W, Duffy CJ. Visual mechanisms of spatial disorientation in Alzheimer's disease. Cereb Cortex 2001;11:1083–1092.
26. Cronin-Golomb A, Corkin S, Rizzo JF, Cohen J, Growdon JH, Banks KS. Visual dysfunction in Alzheimer's disease: relation to normal aging. Ann Neurol 1991;29:41–52.
27. Rizzo M, Anderson SW, Dawson J, Nawrot M. Vision and cognition in Alzheimer's disease. Neuropsychologia 2000;38:1157–1169.
28. Rizzo M, Anderson SW, Dawson J, Myers R, Ball K. Visual attention impairments in Alzheimer's disease. Neurology 2000;54:1954–1959.
29. Parasuraman R, Greenwood PM, Haxby JV, Grady CL. Visuospatial attention in dementia of the Alzheimer type. Brain 1992;115:711–733.
30. Kurylo DD, Corkin S, Rizzo III, Growdon JH. Greater relative impairment of object recognition than of visuospatial abilities in Alzheimer's disease. Neuropsychology 1996;10:74–81.
31. Mendola JD, Cronin-Golomb A, Corkin S, Growdon JH. Prevalence of visual deficits in Alzheimer's disease. Optom Vis Sci 1995;72:155–167.
32. Giannakopoulos P, Gold G, Duc M, Michel JP, Hof PR, Bouras C. Neuroanatomic correlates of visual agnosia in Alzheimer's disease: a clinicopathologic study. Neurology 1999;52:71–77.
33. Kaskie B, Storandt M. Visuospatial deficit in dementia of the Alzheimer type. Arch Neurol 1995;52:422–425.
34. Duchek JM, Hunt L, Ball K, Buckles V, Morris JC. Attention and driving performance in Alzheimer's disease. J Gerontol B Psychol Sci Soc Sci 1998;53:130–141.
35. Reinach SJ, Rizzo M, McGehee DV. Driving with Alzheimer disease: the anatomy of a crash. Alzheimer Dis Assoc Disord 1997;11(suppl 1):21–27.
36. Rizzo M, Reinach S, McGehee D, Dawson J. Simulated car crashes and crash predictors in drivers with Alzheimer disease. Arch Neurol 1997; 54:545–551.
37. Pantel J. Alzheimer's disease presenting as slowly progressive aphasia and slowly progressive visual agnosia: two early reports. Arch Neurol 1995;52:10.
38. Lundberg C, Johansson K, Ball K, et al. Dementia and driving: an attempt at consensus. Alzheimer Dis Assoc Disord 1997;11:28–37.