Translating cognitive neuroscience to the driver's operational environment: A neuroergonomic approach

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Neuroergonomics provides a multidisciplinary translational approach that merges elements of neuroscience, human factors, cognitive psychology, and ergonomics to study brain structure and function in everyday environments. Driving safety, particularly that of older drivers with cognitive impairments, is a fruitful application domain for neuroergonomics. Driving makes demands on multiple cognitive processes that are often studied in isolation and so presents a useful challenge in generalizing findings from controlled laboratory tasks to predict safety outcomes. Neurology and the cognitive sciences help explain the mechanisms of cognitive breakdowns that undermine driving safety. Ergonomics complements this explanation with the tools for systematically exploring the various layers of complexity that define the activity of driving. A variety of tools, such as part task simulators, driving simulators, and instrumented vehicles, provide a window into cognition in the natural settings needed to assess the generalizability of laboratory findings and can provide an array of potential interventions to increase driving safety.

Overview of neuroergonomics with respect to driving

Neuroergonomics is the study of brain and behavior at work (Parasuraman, 2003; Parasuraman & Rizzo, 2007). This multidisciplinary field merges the principles and practice of neuroscience and ergonomics to study brain structure and function in everyday environments. Whereas neuroscience and cognitive psychology have tended to focus on the neural structures and mental processes underlying cognition in controlled laboratory settings, ergonomics is more concerned with naturalistic behaviors. In each case, valuable information about how humans think and act in relation to the environment has been obtained. However, because cognition and behavior are often situational in context, laboratory findings—particularly with regard to decision making and related executive functions—may fail to predict behavior in complex and dynamic tasks that people confront in their daily lives. Thus, cognition must be considered in relation to actions and artifacts in the environment. Humans and computers make up joint cognitive systems that function in real-world settings. Consequently, neuro-

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ergonomics focuses on neural bases of perceptual and cognitive functions and actions in relation to actual technologies and settings, providing opportunities for translational research between neuroscience, human factors, ergonomics, medicine, engineering, computer science, and the social sciences.

Neuroergonomics can be applied to gain greater understanding of human behavior and performance in a wide range of settings at home, at work, and traveling in between. A key representative area where neuroergonomics can be applied is the study of outcomes and safety measures in automobile driving. This article takes a neuroergonomic approach in examining issues related to older drivers, who tend to be overrepresented in fatal crashes on a per-mile basis (Evans, 2004). The proportion of fatal crashes for drivers aged 65 and older is expected to increase because of demographic shifts in the population, with some researchers suggesting a 155% increase by 2030 (Lyman, Ferguson, Braver, & Williams, 2002; McGwin, Owsley, & Ball, 1998). Increased crash risk for older drivers stems from age- and disease-related declines in visual, cognitive, and attentional abilities (Ball & Owsley, 1993b; Owsley, Ball, Sloane, Roenker, & Bruni, 1991; Preusser, Williams, Ferguson, Ulmer, & Weinstein, 1998).

Several age-related declines have been reported in older drivers, such as diminished visual acuity and contrast sensitivity, diminished night vision, slower and less efficient eye movements, increased sensitivity to glare, diminished divided attention capacity in complex or cluttered environments, and reductions in the visual field of view (see Ball, Vance, Edwards, & Wadley, 2004; Dewar, 2007; Preusser et al., 1998). Such changes in visual and cognitive ability may decrease the ability of older drivers to extract and respond to information in the driving environment and may explain certain driving maneuver difficulties, such as detecting and understanding traffic control devices (e.g., failure to yield), driving at night, and navigating routes. In particular, this group of drivers has problems with complex traffic situations, including navigating intersections, making left turns across traffic, merging into traffic, and making lane changes (McGwin & Brown, 1999; National Highway Traffic Safety Administration [NHTSA], 2009; Preusser et al., 1998; Zhang, Fraser, Lindsay, Clarke, & Mao, 1998).

In many cases, increased risk for older drivers is probably due to medical factors that accompany aging rather than just age itself. Age-related disorders include mild cognitive impairment, Alzheimer's disease (AD) and associated disorders, stroke, cardiac disease, cancer, diabetes, and other systemic disorders that affect brain and body chemistry and produce encephalopathy, a broad term subsuming any kind of cognitive impairment (Filley, 2004). Diabetes provides a prototypical opportunity for linking physiology and behavior in naturalistic settings. Diabetes may chronically affect multiple organ systems (e.g., vision, kidneys, peripheral nerves), and a key effect is fluctuations of blood sugar, causing hypoglycemia (low blood sugar) or hyperglycemia (high blood sugar). Hypoglycemia produces acute cognitive impairments affecting alertness, judgment, and risk perception and is commonly caused by insulin, the mainstay of diabetes treatment. Strict control over glucose levels using insulin, intended to reduce chronic systemic complications of diabetes, can increase the likelihood of hypoglycemic episodes. Unfortunately, some diabetics are unaware of their hypoglycemia and fail to take appropriate steps to treat the problem and to modulate their behavior to mitigate the risk posed by driving while impaired. A neuroergonomic approach offers the opportunity to link somatic states associated with hypoglycemia to meaningful real-world outcomes such as driver errors. This approach can inform the design and application of countermeasures, such as real-time auditory and haptic feedback to hypoglycemic drivers, triggered by low glucose sensor readings from continuous glucose monitoring devices (McGarraugh, 2010).

Another example in which the neuroergonomic approach linking behavior and physiology in operational settings can be helpful is in the case of excessive daytime sleepiness, which can be due to a variety of causes, including sleep-disordered breathing associated with obstructive sleep apnea. Obstructive sleep apnea impairs vigilance (Tippin, Rizzo, Sparks, & Boyle, 2007) and causes microsleeps (reductions a few seconds long in the background alpha [8–11 Hz] brain rhythms in alert people that can be objectively determined by analyses of electroencephalographic data) and related changes in vehicle steering (Boyle, Tippin, Paul, & Rizzo, 2008).

It is possible to evaluate brain activity in driving-like tasks implemented in a functional magnetic resonance imaging scanner (cf. Calhoun, McGinty, Pekar, Watson, & Pearlson, 2001; Calhoun, McGinty, Watson, & Pearlson, 2000; Graydon et al., 2005). The metabolic changes in specific brain areas can be related to visuospatial and motor aspects of driving. Older people with neurodegenerative impairment have reductions in the activity in posterior parietal and frontal regions (Peters et al., 2009) that are activated during information processing related to the driving task, underscoring the potential utility of relating measures of brain metabolism with components of driving task performance in older drivers. The brain lesion method provides unique evidence that complements the findings from functional brain imaging and electrophysiologic techniques. The lesion method shows which brain structures are necessary for a certain function (Rorden & Karnath, 2004). This method successfully addresses the nature of mental representations and the organization of brain processes (psychoanatomy) in animals and humans with brain lesions and is highly relevant to understanding the organization of cognition in drivers with lesions in different cerebral areas caused by various medical conditions (e.g., traumatic brain injury, stroke, tumors). For example, certain decrements might be predicted or expected given the examination of magnetic resonance imaging of a driver with frontal lobe damage, such as that illustrated in Figure 1. Given that the frontal lobes have been implicated in attention and working memory, and knowing that these cognitive functions are important for executing complex tasks such as driving, it could be predicted that a patient sustaining extensive damage to the frontal lobe would show impaired driving performance in judging hazards. Identifying and evaluating drivers with various brain lesions offers a means to better understand the processes involved in driving.

A number of tools are effective for assessing the cognitive and neurological mechanisms of failure in populations known to have elevated crash risk. Figure 2 provides a range of methods and tools for examining driver performance, ranging from standardized neuropsychological tests, which are capable of measuring levels of cognitive performance in health or disease but may be less sensitive to impairment in driving performance; to computer-based tests that may use photographs or video of complex scenes (e.g., change blindness [CB] and hazard perception [HP] tasks); to various types of simulators (task focused, non–motion based, or motion based); to driving a car in controlled situations (on a test track, on a state road test, or on public roads); and naturalistic driving (in the driver's own car, over extended time frames that follow no set protocol). Complex computer tasks such as the useful field of view (UFOV), CB, and HP represent

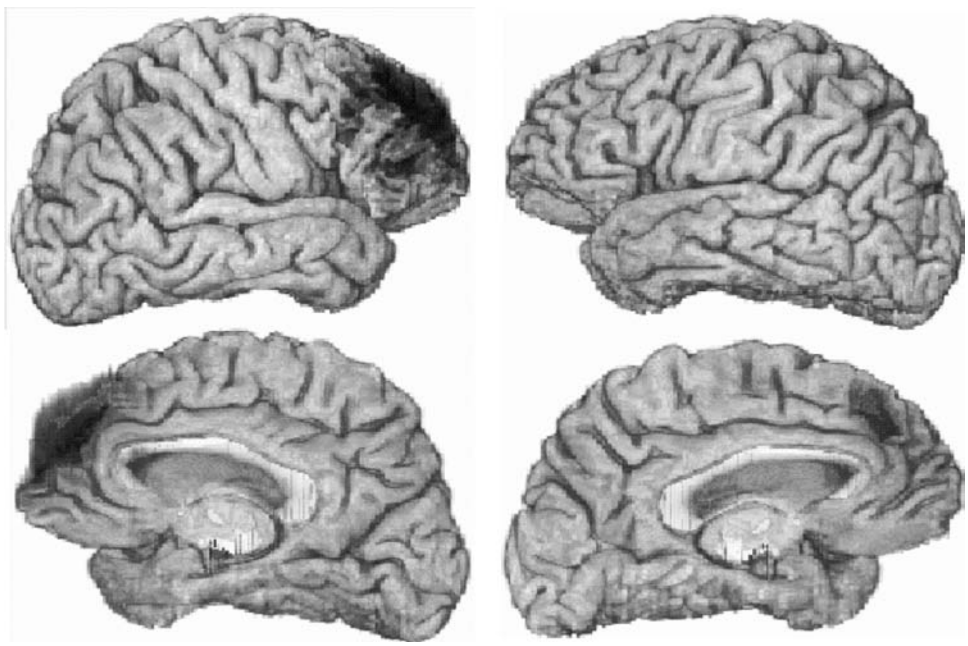

FIGURE 1. 3D magnetic resonance imaging depicts the brain surface of a person with frontal lobe damage (dark areas) and executive dysfunction (which includes impairments of decision making and implementations)

neuropsychological tasks that allow researchers to examine various levels of functioning. For example, CB tasks have been used to assess aspects of working memory and attention in drivers with brain disorders and neurodegenerative disease and to examine the effects of normal aging (Rizzo et al., 2009; Summers, 2006). HP tasks represent a more global evaluation of aspects such as visual search, attention, and executive functioning that may help researchers understand how drivers identify hazards.

As shown in Figure 2, there are trade-offs in each approach in terms of experimental control and context fidelity. Each tool has advantages and drawbacks, and the method of choice depends on the question being asked. Some tools provide a greater degree of sensitivity and lend themselves better to a fine-grained assessment of cognitive function in at-risk people, whereas other tools more closely approximate how drivers might perform in real-world driving settings. As a result, multifaceted approaches to assessing driver performance—including paper-and-pencil neuropsychological tests, computer-based tests of cognitive function, computer simulation, on-road evaluations, and naturalistic data—are likely to provide the clearest picture of driving fitness in at-risk populations (Bieliauskas, 2005; Uc & Rizzo, 2008). The tools outlined in the figure are derived from various disciplines and fit a translational research model as outlined by the National Institutes of Health (NIH) roadmap. Translational research is often divided into Types 1, 2, 3, and 4, each being a step in the translation of a basic scientific discovery into a tool or practice that improves human health. Type 1 refers to the application of new, laboratory-generated knowledge to an emerging method that can be tested using human participants. Type 2 refines the results of these early human studies in ways that can be used in everyday practice, and Type 3 focuses on the effects of these practices on the community as a whole, helping to shape wider population health studies. Type 4 expresses the broadly circular nature of translational research, evaluating the final health outcomes of a discovery generated in a Type 1 study, providing feedback to the process as a whole.

Though seemingly made up of discrete stages, translational research is ideally bidirectional in practice. For example, naturalistic driving data and crash statistics help identify at-risk populations that might not otherwise be apparent, which can then be investigated with basic cognitive science paradigms in the

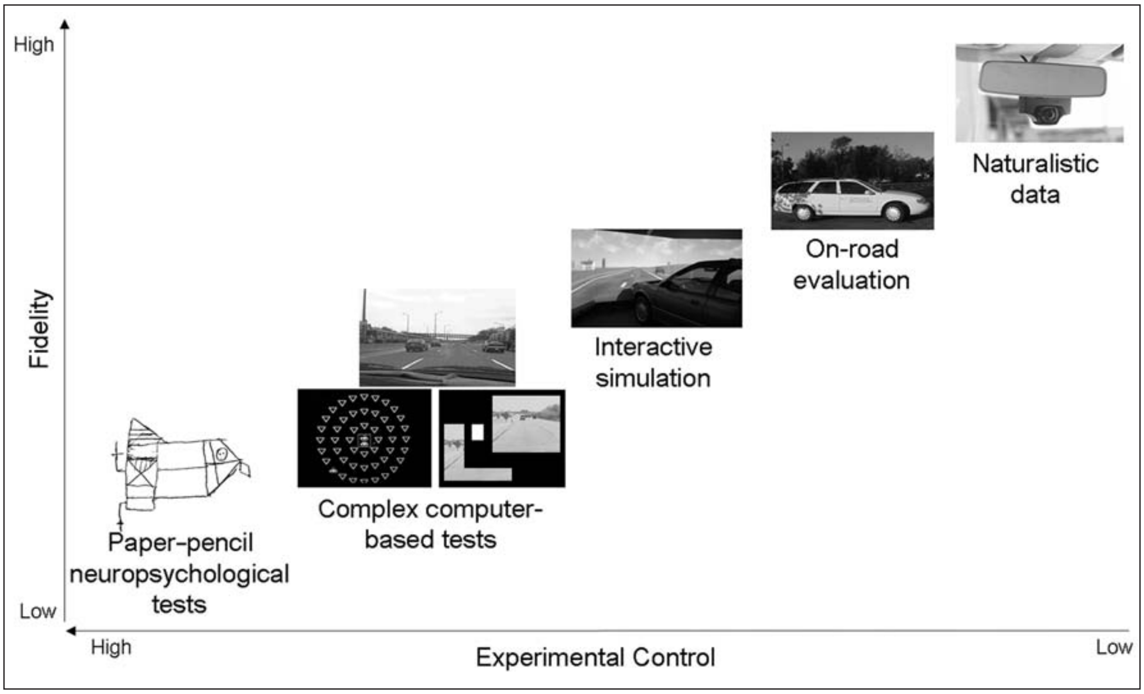

FIGURE 2. Various methods used to evaluate driver performance. Trade-offs exist between experimental control and context or fidelity in studies of driving behavior

laboratory. In addition, paper-and-pencil tests may point to cognitive errors that may undermine driving performance, which can be further examined with increasingly representative levels of driving context (ranging from CB tasks to HP tasks to interactive simulations with feedback to on-road evaluations) to identify and understand at-risk populations. In this way, the researcher in basic science has increased awareness of the issues facing the system designer or, in the case of the transportation researcher in the translational model, a deeper knowledge of the context of the driver. In translational research, feedback is essential, forming an iterative cycle of development that promotes ongoing exploration and advancement until a development goal is achieved, with the continuing possibility of that goal being improved upon. The broadened awareness resulting from multidisciplinary cooperation can reshape the thinking of all involved in the development process, allowing for faster and more effective system creation or, in the case of translational research, safety benefits for human beings. The subsequent sections of this article outline translational approaches for examining older driver performance and identifying potential measures for decreasing the crash risk of at-risk drivers.

Neurological aspects associated with increased crash risk: Understanding the mechanisms of failure

At a basic level, paper-and-pencil neuropsychological tests can provide a window into the specific cognitive deficits present in people with increased crash risk. Such testing is typically sensitive to gross abnormalities and is often treated as the gold standard for assessing cognitive deficits in the clinic. Neuropsychological tests evaluate a range of functions, including visual construction ability (judgment of line orientation, complex figure test copy version, Wechsler Adult Intelligence Scale III block design), memory (complex figure test recall version, Benton Visual Retention Test, Rey Auditory Verbal Learning Test), and executive functioning (trail-making test, controlled oral word association) (see Strauss, Sherman, & Spreen, 2006). A number of studies have shown relationships between performance of at-risk drivers on paper-and-pencil tests of cognitive function and driving behavior in both on-road driving (Dawson, Anderson, Uc, Dastrup, & Rizzo, 2009) and simulated driving (Rizzo, Reinach, McGehee, & Dawson, 1997; Szlyk, Myers, Zhang, Wetzel, & Shapiro, 2002).

Neuroergonomic approaches can help map neurocognitive deficits onto performance and behavior profiles in more complex tasks. For example, work from our laboratory has recently demonstrated that patients with AD (a neurodegenerative disorder caused by the destruction of brain cells and associated with progressive impairments in cognitive functions—notably memory—and related behavioral disturbances) show a wide range of deficits on paper-and-pencil tests of cognitive function, and performance on these tests can provide additional indications of driving performance beyond basic diagnosis alone (Dawson et al., 2009). Furthermore, neuropsychological testing has been shown to correlate with driving performance in healthy aging, with a number of studies showing the predictive value of neuropsychological test scores on driving behavior in advanced age (De Raedt & Ponjaert-Kristoffersen, 2000; Szlyk et al., 2002).

Despite the ability of certain neuropsychological tests to accurately predict driving performance, many of these tests correlate only weakly, if at all, with driving performance, especially in drivers with subtle cognitive deficits (Bieliauskas, 2005; Bieliauskas, Roper, Trobe, Green, & Lacy, 1998). One reason for this is that paper-and-pencil tests represent simple tasks in which the observer is under little performance pressure; they are often self-paced and low in overall processing demands. Given the heavy processing demands inherent in complex tasks such as driving, it is not surprising that many standard neuropsychological tests in domains known to influence driving performance (e.g., attention, working memory) nonetheless do not correlate with driving behavior. This issue has been addressed in recent years by the introduction of complex computer-based tests designed to more accurately represent the heavy cognitive demands present during driving (Ball & Owsley, 1993a, 1993b; Edwards et al., 2005).

One of these computer-based tests, the UFOV, focuses on measures of attention and processing speed and has been successful in identifying at-risk drivers based on crash records. The standard UFOV test (see Edwards et al., 2005) has several subtests, which increase in difficulty and attentional processing demands. Through greater task demands than paper-and-pencil testing, this computer-based test begins to replicate the intense cognitive processing demands of driving in a laboratory setting: Observers must quickly deploy attention to multiple regions of interest in the environment and select specific relevant items (i.e., targets) in the environment while suppressing other, irrelevant items (noise). As a result, the predictive validity of one version of the UFOV task is high, and it has demonstrated a sensitivity of 89% and specificity of 81% for predicting crash involvement (Ball & Owsley, 1993a; Edwards et al., 2005), especially crashes caused by failure to yield at intersections (Owsley et al., 1991).

Studies using the UFOV task have demonstrated deficits in attention function in at-risk drivers: When faced with a task that strongly engages attention, at-risk drivers are less able to extract visual information from the environment efficiently. In the context of driving, where people must rapidly shift attention to multiple locations to monitor hazards or information of interest (e.g., a pedestrian entering the intersection to their left, the flow of traffic to their right, and navigational landmarks), such a deficit in attention can undermine driving performance and safety. Although this task provides a useful measure for identifying at-risk drivers, mechanistically speaking it does little to pinpoint which aspects of attention function are central to driving. Attention is not a unitary construct but a collection of processes that allow an observer to shift the focus of processing in time and space, control the breadth of information processing, select relevant information, and suppress irrelevant information (see Knudsen, 2007; Posner & Cohen, 1984). Because each of these processes has been associated with different underlying neural systems (see Fan, McCandliss, Sommer, Raz, & Posner, 2002), it is possible that there are selective deficits in some but not other subcomponents of attention in at-risk drivers, and these deficits may play out in different ways on the road.

Using attention deficits in otherwise healthy older adults as a starting point, we have recently attempted to assess what specific mechanisms are linked with attention functions responsible for impaired performance on the UFOV task (Cosman, Lees, Vecera, Lee, & Rizzo, submitted). To this end, we used well-established computer-based cognitive science paradigms known to tap major subcomponents of attention. We classified 54 drivers aged 65–87 years as either impaired or unimpaired based on their UFOV performance. After classification, drivers performed a visual search task in which they had to find a target item embedded in an array of distractors. The task measures the ability to voluntarily shift attention in space in the presence of distracting information. The drivers also performed an attentional cuing task that measures the efficiency of stimulus-driven attentional orienting and shifting in the absence of distracting information (Posner, Snyder, & Davidson, 1980). Because the UFOV task is multifaceted and requires the participants to rapidly shift attention between aspects of the stimulus array in both the presence and the absence of visual noise, these tasks are well suited for elucidating the underlying impairments in basic attention function present in attention-impaired people.

Figure 3 summarizes our results. In the visual search task, attention-impaired and unimpaired drivers performed equally on an easy feature search task, in which the target differed from the distractor items with respect to a specific, salient feature causing the target to stand out from the distractor items. This indicates that both groups of drivers were able to orient attention reflexively to salient features of the environment when those features capture attention. However, UFOV-impaired drivers performed significantly slower than unimpaired drivers in a more difficult conjunction search task in which the target was very similar to distractor items. In this case, drivers must voluntarily shift attention from item to item in a serial fashion. This result indicates a possible deficit in the ability of attention-impaired drivers to voluntarily shift attention in space. Data from the cuing task supported such an interpretation; both attention-impaired and unimpaired drivers showed normal, reflexive orienting to the exogenous cue, as evidenced by the facilitatory effect of the valid cue on reaction times. However, as can be seen in Figure 3b, attention-impaired drivers were slower to disengage attention from an invalidly cued location when the target was presented at the opposite location. In the context of the results from the difficult conjunction search task, this slower disengagement of attention may have been responsible for their slower search: When forced to search serially in the difficult conjunction search task, shifting attention between each item in the array took longer and slowed their search for the target.

Taken together, our results demonstrate that UFOV impairment, and probably associated driving impairments, arise in part from deficits in the ability of these drivers to shift attention. More specifically, these drivers show decrements in the ability to disengage attention from currently attended objects or locations. In the context of driving, such impairment could lead to a number of problems associated with unsafe driving; because a UFOV-impaired driver is less efficient at shifting attention within the driving environment, the driver is likely to attend to fewer objects, fails to shift attention to highly critical objects, and may miss major events that demand action. Normal drivers may attempt to search the environment more exhaustively to avoid missing critical objects and events that require action, but these impaired drivers do not. Their behavior fits well with descriptions of cases in which impaired drivers "look at but do not see" critical roadway events such as an oncoming vehicle at an intersection.

This study shows that an at-risk population of drivers defined in terms of clinical (UFOV) impairment and epidemiological risk has a fundamental neurocognitive impairment of attentional disengagement that has the potential to disrupt human performance in context-rich tasks such as automobile driving. The role of these and related mechanisms can then be addressed in drivers by adding layers of the driving context using CB, HP paradigms, interactive simulation in virtual environments, and naturalistic settings under varying degrees of experimental control.

Using a driving context to understand the errors drivers make in the real world

As mentioned previously, older drivers are overrepresented in intersection crashes (McGwin & Brown, 1999; NHTSA, 2009; Preusser et al., 1998; Zhang et al., 1998). These drivers are often involved in crashes that include a failure to yield the right of way, unseen objects, or a failure to heed stop signs—errors that might indicate perceptual problems, attentional failures, or recognition problems (McGwin & Brown, 1999). The CB phenomenon seems particularly relevant to such crashes. CB is an inability to detect large changes in a visual scene, often associated with a visual disruption such as an eye movement, blink, or film cut (Pringle, Irwin, Kramer, & Atchley, 2001; Rizzo et al., 2009). An example CB image is presented in Figure 4a, in which the driver is required to notice the vehicle on the far left disappearing over time. Although different methods are used to simulate visual disruption, often changes are made to a static image. Noticing scene changes requires attention and visual working memory so that visual information

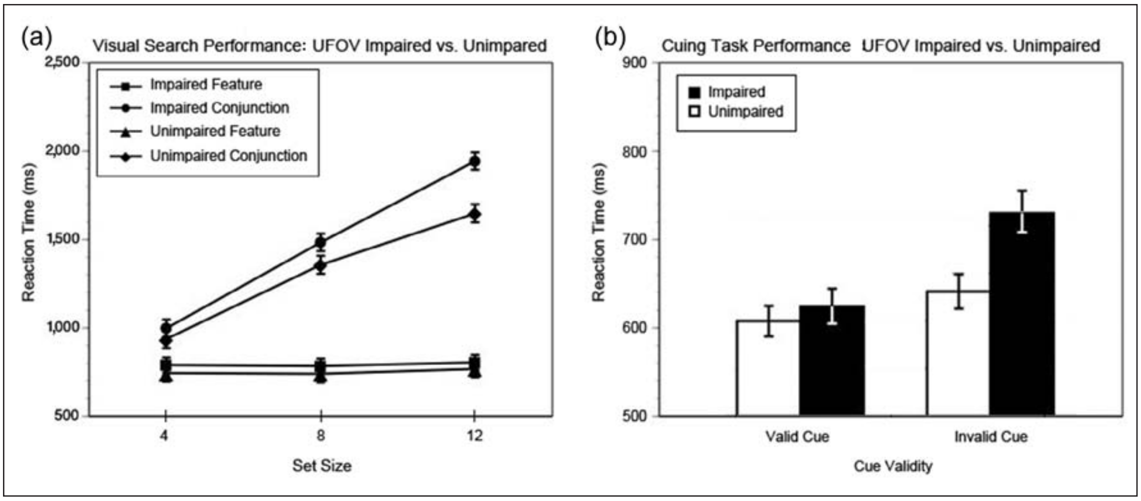

FIGURE 3. (a) Data from the visual search task for both useful field of view (UFOV)-impaired and unimpaired drivers. UFOV-impaired drivers searched more slowly for a target item in the difficult conjunction search task. (b) Data from the Posner cuing task. Of note are the disproportionately long reaction times on invalid trials for UFOV-impaired drivers, reflecting a decrease in their ability to disengage attention from the invalidly cued location

before and after the change occurs can be stored and compared (Pringle et al., 2001; Simons & Ambinder, 2005). The difficulty of such tasks often depends on the eccentricity, meaningfulness, and salience of the changing object (Pringle et al., 2001). Research suggests that older adults, especially those with neurological disorders, are slower and less accurate when performing CB tasks compared with younger adults (Caird, Edwards, Creaser, & Horrey, 2005; Pringle et al., 2001; Rizzo et al., 2009).

The benefit of such tasks is that they can incorporate high levels of scene complexity, representative of the scenes that confront drivers, and can contribute to a deeper understanding of crash involvement by older drivers. For example, Caird et al. (2005) examined decision-making accuracy at intersections in young, middle-aged, young-old, and old-old drivers using a modified CB task. During the task, drivers viewed 36 intersection scenes and were asked whether it was safe to travel in a particular direction (straight, turn left, or turn right), what had motivated their decision, what changes had occurred in the scene, and their level of confidence in the decision they made. After a direction arrow was shown, intersection scenes were previewed for either 5 or 8 s alternating between the original image, a mask, and an altered image. For catch trials no change was made to the original scene. Older drivers (young-old drivers, aged 65–73 years, and old-old drivers, aged 74 years and over) were less accurate—incorrectly indicated it was safe to go—than middle-aged and younger drivers. Visual acuity and contrast sensitivity, object size, and contrast did not account for differences in performance. The authors further examined differences using logistic regression and by examining differences in performance qualitatively. Age was a significant predictor of decision accuracy in 10 of the 36 intersections. Overall, older drivers had more difficulty making turn decisions when required to detect pedestrian events and traffic sign changes, and the authors noted that older drivers may have been overly reliant on traffic control devices when making decisions about whether they could proceed.

Rizzo et al. (2009) examined CB performance as a function of age and found that as age increased the hit rate decreased, reaction times increased, and sensitivity (d') decreased. Examining CB across the various age groups, the study found that CB performance decrements accelerated at certain ages: 54 years for hit rate and 68 years for both response time and d'. In addition, comparisons between older adults with and without AD suggested that declines in overall cognitive function (attention, short-term visual memory, and executive function tasks) correlated with worse

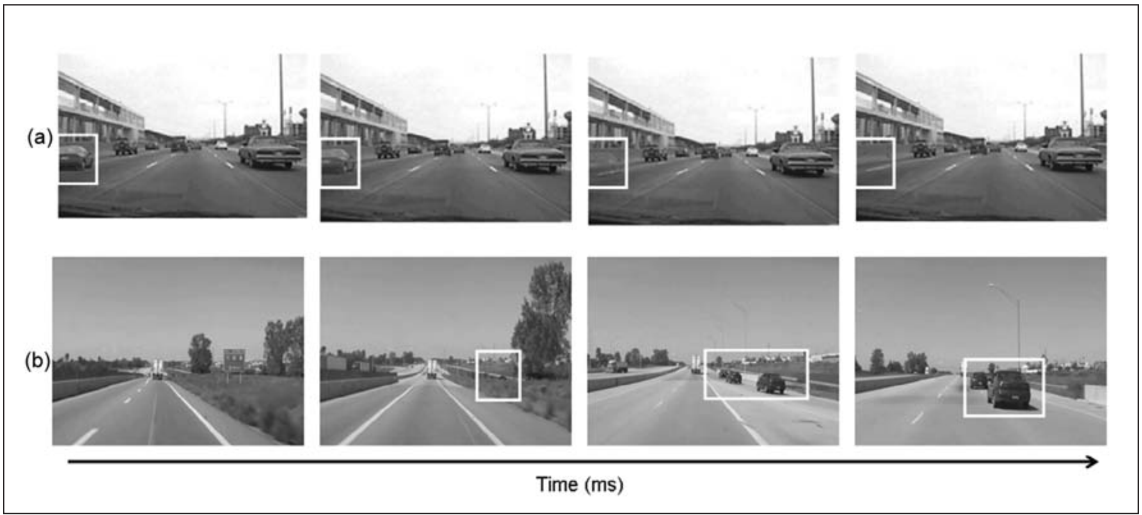

FIGURE 4. (a) Change blindness task used by Rizzo et al. (2009) and Lees et al. (2007). The changes occurred over time, with the change element being modified to either appear, disappear, or change color or change location. However, changes were made to a static image. (b) Hazard perception task in which the driver is asked to view filmed traffic situations and indicate when a hazard appears. Both tasks represent closed feedback in that the driver cannot influence the environment, but the hazard perception task has a broader focus and considers the temporal aspect of driving

CB performance. The results of these studies suggest that older drivers with and without neurocognitive disease may be less able to perceive visual changes. Such degradations in performance probably transfer to driving situations in which drivers need to identify and respond to changes in their environment in order to avoid being involved in an accident.

In a follow-up study the authors examined the underlying features of two attention-related tasks, CB and UFOV, in relation to commonly used vision and cognitive test batteries, and they assessed driving performance measures using a simulator and an instrumented vehicle that measured real-world driver behavior (Lees, Sparks, Lee, & Rizzo, 2007). Driving performance was evaluated using simulated driving events (a police car located on the side of the road and a vehicle that ran a stop sign) and during an on-road drive where drivers were asked to perform a route-following task and a landmark and traffic sign identification task (see Uc, Rizzo, & Anderson, 2005; Uc, Rizzo, Anderson, Shi, & Dawson, 2004). Seventeen older adults participated in the study, eight with early AD (74–81 years, $M = 77.5$) and nine without (64–73 years, $M = 68.3$). As shown in Table 1, three factors (attention and decision making, hazard detection and evaluation, and identification and intervention) were identified using a factor analysis that accounted for 57% of the variation across measures. Although UFOV correlated with CB hit rate, $R^2 = -.668$, $p < .01$, and CB detection time, $R^2 = .578$, $p = .015$, the two tasks loaded on different factors.

The findings suggest that UFOV relates to attention and decision making, and CB relates to hazard detection and evaluation. These different underlying dimensions may account for the differing correlations of UFOV and CB with driving performance in the simulator and on the road. Specifically, UFOV demonstrated a general relationship to driving and correlated with a number of on-road performance measures. In contrast, the association between CB and driving seems to depend largely on the specific images incorporated by the task and types of changes being detected. For example, the ability to correctly detect the appearance of a stop sign correlated with multiple on-road performance measures. The results suggest that CB and UFOV tasks may relate to different cognitive processes and different aspects of driving. Refined CB tasks may be particularly beneficial in understanding older driver failures and may complement information gained through other tasks.

HP tasks are another useful tool that might help identify at-risk drivers and elucidate what broad mechanisms relate to driver safety. HP, the ability to recognize and anticipate hazardous roadway situations, is a critical driving-related skill and correlates with accident involvement and driver experience (Horswill & McKenna, 2004; McKenna & Crick, 1994; Quimby & Watts, 1981). During HP tasks, drivers are asked to watch filmed traffic clips and identify as quickly and accurately as possible when they observe a potential hazard. Thus, these types of tasks have not only high levels of visual realism but also a temporal component (see Figure 4b). In addition, these tasks offer increased experimental control because all drivers receive the same set of stimuli. Pelz and Krupat (1974) found that drivers without crashes or convictions responded 0.5 s faster than drivers with a crash history and 1.2 s faster than drivers with violations. Horswill and McKenna (2004) found that drivers with more crashes had worse HP scores. Other researchers have found that novice drivers are less accurate and slower in perceiving hazards in filmed traffic situations than experienced drivers (Horswill & McKenna, 2004; McKenna & Crick, 1994). Although the majority of studies examining HP ability have focused on inexperienced and young drivers, there is evidence that HP declines with age in drivers aged 65 and older (Horswill et al., 2008). For example, in line with the age-related trajectory of decline in CB associated with age (Rizzo et al., 2009), one cross-age study found that the ability to perceive hazards peaked at age 55 and then declined (Quimby & Watts, 1981). A recent study found that older drivers with diminished contrast sensitivity, larger reductions in the UFOV, and longer simple reaction times performed worse when identifying and responding to filmed roadway hazards (Horswill et al., 2008). In line with these findings, another study found that older drivers aged 75–84 were significantly slower in identifying hazards than both middle-aged drivers and older drivers aged 65–74 (Horswill et al., 2009). Contrast sensitivity, simple reaction time measures, and UFOV were found to account for the difference between the different age groups.

The benefit of such tasks is that they offer the ability to incorporate the visual complexity representative

TABLE 1. Factor analysis of cognitive and visual tests and driving performance measures

	Factor 1: Attention and decision making (33%)	Factor 2: Hazard detection and evaluation (13%)	Factor 3: Identification and intervention (12%)
Attention	UFOV[a] (.657)	CB[a]: Response time (.756), *z*-score (–.649)	
Decision making	Controlled oral word association[b] (–.449)		
	Trail-making test[b] (.804)		
	RFT[c]: times lost (.716), wrong turns (.704)		
Memory	Benton Visual Retention Test[b] (.624)		
	Auditory Verbal Learning Test[b] (–.543)		
Visuoconstruction ability	Judgment of line orientation (–.713)		
	Complex figure test–Recall[b] (–.566)		
	Complex figure test–Copy[b] (–.372)		
	Wechsler Adult Intelligence Scale III block design[b] (–.870)		
Vision		Visual acuity[b] (.520)	
		Contrast sensitivity[b] (–.529)	
Response selection		RFT[c]: at-fault errors (.826)	Crash at intersection[c] (.604)
		LIT[c]: at-fault errors (.667)	Police car reaction time[c] (–.626)
		Police car[c]: responded (.522)	
Identification			LIT task performance[a]: critical signs (.818), restaurants (.710)

[a]*CB/UFOV.*
[b]*Visual/cognitive task.*
[c]*Driving task.*
Note. CB = change blindness; LIT = route following task; RFT = landmark identification task; UFOV = useful field of view.

of everyday driving not used in neuropsychological or computerized tasks and still allow high levels of experimental control that are not possible with on-road driving tasks or naturalistic data collection. Such tasks may be particularly useful in identifying at-risk older drivers. In addition, several studies have shown that exposing drivers to hazards or providing training can improve HP ability in novice drivers (Fisher, Pollatsek, & Pradhan, 2006; Grayson & Sexton, 2002; McKenna & Crick, 1994; McKenna, Horswill, & Alexander, 2006). Such training might also benefit older drivers when refined appropriately.

Using a car as a diagnostic device to understand driver errors and track behavior

CB, HP, and interactive simulation can be used to make detailed measurements of performance and behavior in healthy and impaired drivers and to design and evaluate technology and displays to improve driver performance and safety. However, drivers may behave differently in the real world than might be expected based on their self-report of driving behavior, paper-and-pencil tests, or computerized tasks administered in the clinical laboratory (Reger et al., 2004; Rizzo, Robinson, & Neale, 2007). Therefore, studies performed in operational settings can be of great value, and quantitative recordings of drivers operating their own instrumented vehicles (IVs) over time in the real world can provide the gold standard of driver performance (Dingus et al., 2006; Neale, Dingus, Klauer, Sudweeks, & Goodman, 2005).

IVs permit quantitative assessments of driver performance in the field (i.e., in a real car) under actual road conditions and are not subject to the same type of human observer biases as standard road tests. Such tools allow researchers to examine objective indices of driving performance in normal and potentially unfit drivers (Uc et al., 2004) and to assess the safety and usability of prototype automotive technologies evaluated in earlier stages using virtual environments and off-road tasks. One ethical issue for use of IVs in research is protecting the privacy of drivers who agree to be studied, especially those who may be considered at greater risk and who therefore face greater scrutiny by licensing authorities. Another issue concerns how illegal driving behaviors or other activities are reported. Research involving IVs normally has a protocol for dealing with such events that is specified before enrollment in the study through an informed consent document.

Vehicle kinematic profiles in common roadway scenarios may provide specific evidence of driving safety problems in older drivers with age- and disease-related declines in visual, cognitive, and attentional impairments that relate to overall driving safety and cognitive abilities. Several studies have documented a higher crash risk of older drivers at intersections, particularly those with a stop sign (McGwin & Brown, 1999; NHTSA, 2009; Preusser et al., 1998; Zhang et al., 1998). This is a substantial concern because 700,000 police-reported crashes occur at stop signs every year (Retting, Weinstein, & Solomon, 2003), which is particularly problematic given the severity of such crashes. In one study, 70% of the crashes investigated that occurred at intersections with a two-way stop sign were attributed to stop sign violations (Retting et al., 2003). In cases where the driver reported coming to a stop before entering the intersection, 44% of drivers indicated that they had failed to notice the other vehicle.

Bao and Boyle (2008, 2009) evaluated driver performance in young, middle-aged, and older drivers at two rural expressway intersections. Drivers were asked to maneuver straight across the intersection, make a left turn, and make a right turn at high- and low-crash intersections. Older and younger drivers demonstrated different braking profiles than middle-aged drivers (Bao & Boyle, 2008). Compared with middle-aged drivers, younger and older drivers were less likely to come to a complete stop before entering an intersection, took more time to initiate a braking response, and took less time to reach maximum braking. Interestingly, drivers were less likely to come to a complete stop when turning left or right than when traveling across the intersection. In a follow-up, the authors examined visual scanning behavior of these drivers while performing different driving maneuvers at the two intersections (Bao & Boyle, 2009). Overall, the results of the study suggest that compared with middle-aged and younger drivers, older drivers spent a smaller proportion of time scanning to the left and right when approaching an intersection, when approaching a median, and when exiting an intersection. Older drivers also spent less time checking their rear-view mirrors, suggesting that they limit their visual sampling to certain areas.

These problems are magnified in older drivers with neurodegenerative impairments such as AD. Drivers with AD may have difficulty identifying traffic signs and landmarks and commit more at-fault safety errors than older drivers without AD (Dawson et al., 2009; Rizzo et al., 2004; Uc et al., 2004, 2005). Recently we tested whether drivers with and without AD demonstrate different driving behavior when approaching stop signs during an on-road drive in an instrumented vehicle. Performance was evaluated at a four-way stop sign that required drivers to go straight and at a T-intersection where drivers made a right turn. Thirty-four drivers with probable AD (ages

51–89, M = 74.3) and 158 neurologically normal drivers without AD (ages 52–74, M = 64.6) participated. Performance measures included (a) speed when stop sign first visible, (b) time when accelerator released, (c) time when brake applied, (d) total brake duration (total time the brake was applied when approaching the stop sign), (e) transition time from brake to accelerator after full stop (Figure 5), (f) number of brake pumps (times the brake was applied then released), (g) maximum brake position, and (h) number of head turns after stop.

The results suggest that the four-way stop and the T-intersection imposed different demands on drivers. Older drivers with and without AD had somewhat different braking profiles that varied according to the intersection. At the four-way stop drivers with AD had a tendency towards faster approach speeds (p = .071). Such differences might be due to the inability of drivers with AD to recognize the need to slow down. For example, one study found that compared with older drivers without AD, older drivers with AD had more difficulty recognizing traffic signs (Brashear et al., 1998). While performance depended on the sign, the study found that, although 98% of normal drivers correctly identified a stop sign, only 76% of drivers with AD were able to do so. At the T-intersection, drivers with AD also applied more brake pumps (p = .082), which may suggest an inability to identify how to modulate braking in relation to the upcoming stop sign. Drivers with AD made more head turns when deciding to enter the intersection at the four-way stop (p = .072) and took longer to reaccelerate after stopping at the T-intersection (p = .093). Such differences in performance may reflect increased search time and go/no-go decision making in these at-risk drivers with cognitive impairment. Overall, these field studies suggest behaviors that might contribute to intersection crashes involving older drivers with and without neurological impairment (Bao & Boyle, 2008, 2009) and provide a rationale for developing and designing particular countermeasures.

Along these lines, research suggests that older drivers with attention impairments may be more willing to attempt crossing a road under unsafe conditions than older drivers without impairments (Pietras, Shi, Lee, & Rizzo, 2006). Pietras et al. examined traffic entry behavior in older drivers with and without UFOV impairments. Drivers were asked to make judgments from a stationary vehicle about the last possible moment they could safely cross a road in the presence of an oncoming vehicle. In addition, they were asked to cross the roadway when no traffic was present. Speed and distance of oncoming vehicles were obtained using light detection and ranging. The study found that older drivers with attention impairments accepted shorter time-to-contact values, took longer to cross the road, and had shorter safety margins than older drivers without impairments. UFOV scores negatively correlated with the three safety measures, suggesting that larger UFOV impairments are associated with more risky intersection-crossing behavior. Using a Monte Carlo simulation, the study found that such differences in traffic entry decisions increased the risk of a crash for impaired drivers by 6.9 times compared

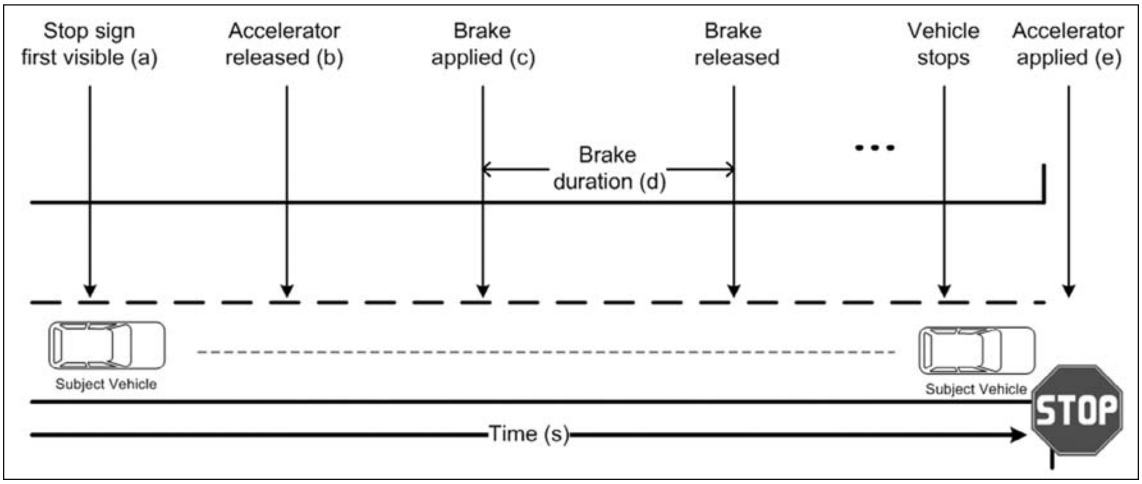

FIGURE 5. Demonstration of measures derived to determine driver response to stop sign over time

with unimpaired drivers when the approaching vehicle failed to brake and 17.0 times compared with unimpaired drivers when the approaching vehicle compensated for the situation.

Multiple studies have used IVs in traffic safety research (e.g., Bao & Boyle, 2008, 2009; Dingus et al., 1997; Rizzo et al., 2004; Uc et al., 2004, 2005). In most cases an experimenter is present, and drivers who are aware of being observed are likely to drive in an overly cautious and unnatural manner. Because total data collection times often are less than an hour and crashes and serious safety errors are uncommon, no study until recently has captured precrash or crash data for a police-reported crash. Internal networks of modern vehicles allow continuous detailed information from the driver's own car over extended time frames (Rizzo, Jermeland, & Severson, 2002). Modern vehicles report variables relevant to speed, emission controls, and vehicle performance, and some vehicles allow more detailed reporting options via the vehicle's onboard diagnostics port. Lane-tracking video can be processed to assess lane-keeping behavior. Radar systems in the vehicle can gather information on the proximity, following distance, and lane-merging behavior of the driver and other vehicles on the road (Pietras et al., 2006). Global positioning systems can show where and when a driver drives, takes risks, and commits errors. Cell phone use can be tracked without recording conversations to assess potential driver distraction and risk acceptance (i.e., choosing to be distracted). Wireless systems can check the instrumentation and send performance data to remote locations.

These developments can provide direct, real-time information on driver strategy, vehicle use, upkeep, drive lengths, route choices, and decisions to drive during inclement weather and high traffic. A person driving his or her own instrumented vehicle is exposed to the usual risk of the road environment without the psychological pressure that may be present when a driving evaluator is in the car. Road test conditions can vary depending on the weather, daylight, traffic, and driving course. This is an important advantage for naturalistic testing: Repeated observations in varying real-life settings provide rich information about driver risk acceptance, safety countermeasures, and adaptive behaviors.

Such information provides unique insights on the ranging relationships between low-frequency, high-severity driving errors and high-frequency, low-severity driver errors. Such "brain-in-the-wild" relationships (Rizzo et al., 2007) were explored in detail in a study of naturalistic driving performance and safety errors in 100 normal individuals, driving 100 total driver years (Dingus et al., 2006; Neale et al., 2005). All enrolled drivers allowed installation of an instrumentation package into their own vehicle (78 cars) or drove a new model-year IV provided for their use. Data collection provided almost 43,000 hours of actual driving data, more than 2,000,000 vehicle miles. There were 69 crashes, 761 near crashes, and 8,295 other incidents (including 5,568 driver errors) for which data could be completely reduced (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). Crash severity varied, with 75% being mild impacts, such as when tires strike curbs or other obstacles.

Using such data collection procedures with at-risk drivers is likely to provide an abundance of knowledge and to provide the context for errors or lapses that result in crashes. Such data can also verify the assumptions of theoretical models and the results of laboratory studies regarding the role of variables such as how much time it takes drivers to react (Gabler & Hinch, 2009). As shown in Figure 6, event recorders allow vehicle data to be collected when severe steering or braking triggers such systems. The driver in this example had cognitive deficits that were documented in detail with neurocognitive testing and in a virtual environment. By analyzing the quantitative data in context, researchers can better understand the factors surrounding a crash. For example, if a driver crashes with a vehicle while making a left turn, such data would allow researchers to see whether the driver came to a stop, whether he or she looked to determine whether it was safe to proceed, and so on.

Naturalistic data also provide a small window into the social and cultural influences that guide drivers. Although such factors are rarely the proximal causes of crashes, they may well represent a critical contribution to driving safety. Driving culture has an enormous influence on the driving safety of the population through its influence on norms and acceptable bounds for behavior and expected responses in a broad range of situations. Culture influences safety-critical behavior such as wearing a seatbelt,

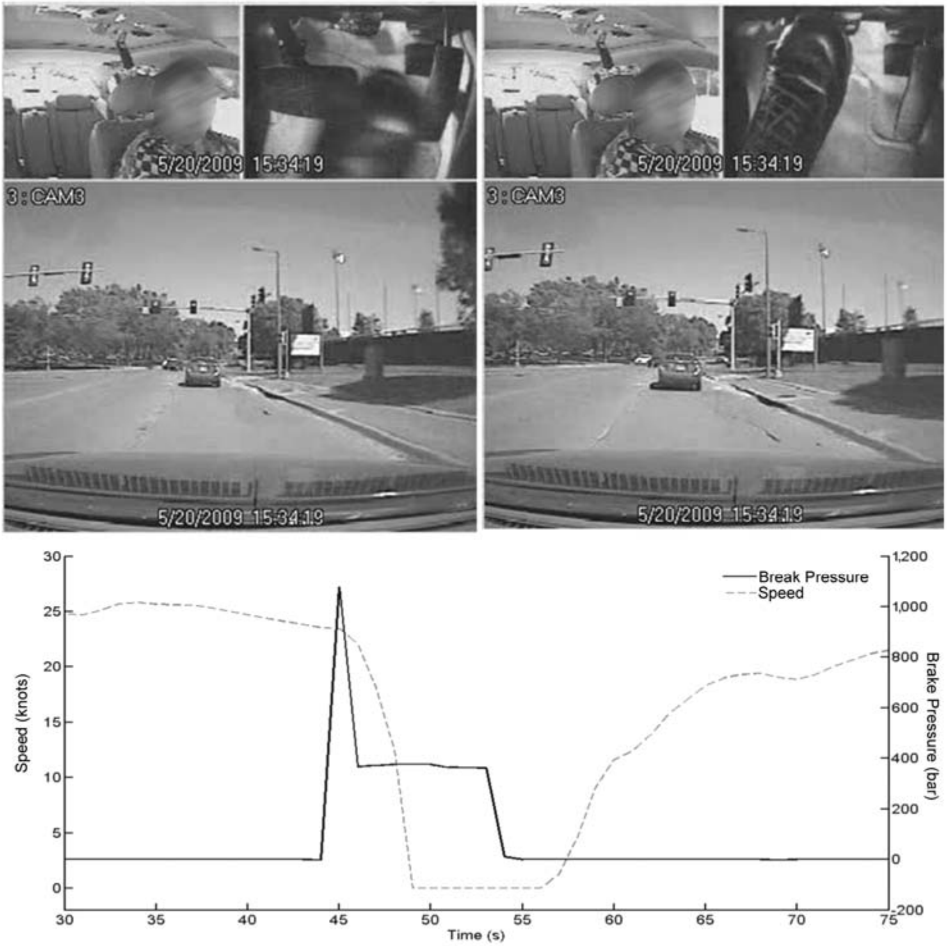

FIGURE 6. An inattentive older driver in an instrumented vehicle approaches a lead vehicle (top) at more than 30 mph (25 knots) and brakes hard to avoid a rear-end collision. There is a corresponding dip in speed, as shown by the electronic data from the vehicle. The severity of the braking triggered a DriveCam system to record the video of the event

driving under the influence of alcohol, and speeding. In the case of seatbelt use and drinking and driving, changes in social norms have saved thousands of lives (Moeckli & Lee, 2006). Although it is part of the broader culture, it can be useful to consider older drivers as having a distinct culture, and how this culture is shaped could have critical consequences. If age-related cognitive decline becomes a stigma in the culture of older drivers, then people may be inclined to persist in driving even when they recognize it is not safe. Naturalistic data that can be placed in the social context of driving might be particularly valuable in identifying the factors that influence drivers to drive in situations where crashes are likely. Understanding how such distal causes contribute to driving safety may identify novel interventions that might otherwise be overlooked.

Developing crash countermeasures with particular driver populations in mind

Knowing which specific cognitive functions are impaired in specific populations of at-risk drivers becomes important when we consider the development of countermeasures to remediate attention deficits in at-risk populations; to the extent that the basic, underlying cognitive and neurological mechanisms of the cognitive dysfunction are known, specific countermeasures may be used ethically to mitigate these deficits (Larriviere, Williams, Rizzo, & Bonnie, 2009). For example, if we know exactly which brain networks are involved in a deficit, along with the pharmacologic properties underlying that network's physiology, it may be possible to suggest specific pharmacologic interventions to counter the deficit. By the same token, peripersonal environmental countermeasures such as in-vehicle warning systems can be designed to more effectively exploit knowledge of specific cognitive deficits in order to increase alert efficacy. Alongside neuropsychological tests and complex computer-based tests of cognitive function, more specific computer-based tests based on cognitive psychology paradigms can provide a greater degree of assessment specificity and sensitivity, resulting in the ability to tailor countermeasures to specific populations with specific deficits. Finally, crash statistics, on-road assessments, and naturalistic data can provide information about what crashes certain drivers are overrepresented in and what breakdowns occur and possibly lead to crash involvement.

Such information can dictate what types of countermeasures would be most beneficial to certain populations. For example, given the review provided here, the data strongly suggest that older drivers with and without impairments would benefit from a variety of countermeasures aimed at helping with intersection approach and negotiation. Such countermeasures might warn them of upcoming traffic signals or help drivers identify hazards that might otherwise be missed (e.g., speech warning that the driver is approaching a stop sign, visual warning highlighting the upcoming sign or crossing traffic), prompt drivers to engage in certain behavior (e.g., LEDs placed on the side mirrors, rear-view mirror, and window pane to increase the driver's scanning of an intersection), or increase safety margins and gap acceptance (i.e., using sonification to indicate gap size).

Recent work in our laboratory has focused on the development and implementation of such countermeasures in at-risk drivers, and we have begun to assess the basic cognitive operations that are impaired in different driver populations. By using computer-based psychological tasks that are sensitive to the specific components of high-level cognitive functions such as attention, we can adapt our countermeasures to better fit the needs of different populations of at-risk drivers. Because the neurological origins of impaired driving performance probably differ widely between different groups of at-risk drivers, and there are different cognitive manifestations of these deficits, such specificity will allow more effective remediation of driving difficulties across a range of driving-impaired people. For example, information about basic attention function in a population of at-risk drivers can provide a starting point for the design of a system capable of remediating specific attention deficits in UFOV-impaired older drivers.

Alerting drivers to specific driving situations is a promising approach in increasing their situation awareness and increasing driving safety. Our findings suggest that older drivers with attention impairments might benefit from salient, directional alerts that reflexively draw attention to critical locations in the driving environment to overcome these drivers' subtle deficits in voluntary attentional shifting (Cosman et al., submitted). In another study, we examined the effectiveness of cross-modal alerting for orienting attention to external targets using a variation of Posner's orienting of attention paradigm (Lees et al., 2009). The findings suggest that older drivers with and without UFOV impairments benefited most when provided with auditory and auditory–haptic cues. These results correspond with other research that has examined the benefit of using multimodal cues in more complex settings (e.g., using a simulator) (Ho, Reed, & Spence, 2006, 2007; Kramer, Cassavaugh, Horrey, Becic, & Mayhugh, 2007; Spence & Ho, 2008).

Auditory warnings that convey a specific meaning in addition to reflexive directional orienting of attention might further increase driving safety. In general, a sound is processed through the sensory transduction of sound waves that enter the ear, and additional transmission leads to signals that are passed on to the brain (Lehto & Buck, 2008). Three primary mechanisms work together to perceive and recognize sounds. First, the peripheral auditory system detects sound waves that are further processed by the receptors and transmitted to the central auditory unit via action potentials. Then they are decoded into audible sounds. Cognitive processes at the third level allow the sound to be modified into meaning (Chisolm, Willott, & Lister, 2003). These three stages involve different anatomic areas: the perceptual stage involves the outer, middle, and inner ear, the intermediate or central auditory unit includes neural nuclei in the brainstem, midbrain, and thalamus, and the final stage is located in the auditory cortex and other processing areas in the brain (Munkong & Juang, 2008).

Sounds might be particularly effective as warning signals because of advantages on several of these auditory processing stages. On the perceptual level, sounds are likely to attract attention regardless of a person's workload (Edworthy, 1994). Moreover, many sounds are omnidirectional, which increases their likelihood of being detected (Haas & Edworthy, 2006) when compared with visual warnings. On the cognitive level, auditory icons (caricatures of natural sounds based on everyday experiences) have proven to be intuitive and quickly understood (Barrass & Kramer, 1999; Lucas, 1994; Petocz, Keller, & Stevens, 2008). These types of warnings have the potential to reduce cognitive processing effort, which can thereby speed responses (Belz, Robinson, & Casali, 1999). Several laboratory and simulator studies have found that such warnings can reduce response times to visual stimuli (McKeown & Isherwood, 2007). However, this general benefit of auditory icons as warning signals might not apply to certain populations, such as young soldiers who have sensorineural hearing loss caused by exposure to repetitive blast percussions, or older drivers, who might have more difficulties in identifying such sounds and mapping them appropriately to relevant hazards in the visually complex roadway panorama, especially when time is a factor. In addition, the ability of the human ear to detect frequencies between 500 and 3,000 Hz (Deatherage, 1972) might decrease because age-related sensory degradation is associated with a decline in the ability to hear high-pitched sounds (Chisolm et al., 2003). This might be a problem for warning sounds with a high fundamental frequency, which is generally supposed to lead to high ratings of urgency (Haas & Edworthy, 2006). For these reasons, the applicability of auditory icons as warning signals for older drivers warrants further investigation.

In one study, we evaluated how 10 older drivers between the ages of 66 and 77 paired a set of auditory warnings with 12 roadway scenes (Figure 7). During the study each warning sound was played while the driver viewed each of the 12 scenes. This procedure was repeated for nine auditory icons and five distractor sounds that were not directly related to any of the driving situations (e.g., sneeze sound), and presentation was randomized across drivers. A variety of sounds were evaluated, some more specific to items in certain scenes (e.g., bike bell, footsteps, jackhammer) than others (e.g., siren, crash). For each driving scene, drivers had to decide whether and how

FIGURE 7. Static traffic scenes presented, from left to right and top to bottom: (a) curve, (b) traffic light, (c) bus, (d) speed limit sign, (e) oncoming car, (f) stop sign, (g) lead vehicle braking, highway, (h) bike, (i) construction, (j) merge, (k) crosswalk, (l) lead vehicle braking, city

the sound related to the situation. When the driver indicated that the sound was related he or she was also asked to specify the item associated with the sound or what he or she might expect to happen based on the sound.

A number of patterns emerge from the data in Table 2. First, specific warnings (e.g., "bike bell 1," "footsteps 1," and jackhammer) were highly effective for conveying information about certain situations. For example, when "bike bell 1" was used, 8 of 10 people correctly indicated that the warning corresponded to the bike in the scene, and from these answers the median rating of the match was 4 (1 = *weak match,* 5 = *strong match*). In addition, people rarely associated this warning with other types of situations, such as a vehicle or sign. This suggests that these warning sounds have a high degree of specificity. Second, not all auditory warnings are the same, even when they are intended to convey the same message. The experiment used two different versions of a bike bell warning and of a footsteps warning. In both cases, one version dominated the other. For example, 9 of 10 people associated "footsteps 1" with the pedestrians in the crosswalk, compared with 4 of 10 people making the association when "footsteps 2" was played. A similar trend occurred for the image with pedestrians by the bus stop, suggesting that "footsteps 1" better conveys the presence of pedestrians because more people associated this sound with the picture, even though the match was rated to be only slightly higher for this sound (median = 3). Third, people generalized ambiguous warnings to a variety of situations (e.g., siren, car horn, and screeching tires). Some of the general warnings used also had a high association with specific situations. For example, 7 of 10 people associated the car horn sound with the oncoming car, and the rating for the match was fairly high (median = 4). Fourth, some situations were not matched with any of the warning sounds by some drivers. This finding could have two implications: No appropriate warning sound was used in this study, or some people do not think that these situations warrant a warning.

Overall, empirical findings from this and other studies suggest that the screeching tires sound may be most suitable for an imminent collision (Fricke & Thuering, 2009; Graham, 1999; Ho et al., 2007; Keller & Stevens, 2004) and for situations involving stop signs, traffic lights, and construction. Drivers appear to associate this sound with the need to slow down. This warning seems to be applicable for a wide variety of warnings and even valuable for special populations such as older adults. Such interventions must be evaluated with the full range of techniques

TABLE 2. Absolute frequency with which a particular auditory icon was associated with a given situation and median value of the match (1 = weak, 5 = strong)

	Situation (Y)											
Warning (X)	**Bike**	**Crosswalk**	**Bus**	**Construction**	**Lead vehicle braking, highway**	**Lead vehicle braking, city**	**Merge**	**Curve**	**Traffic light**	**Stop sign**	**Speed limit sign**	**Oncoming car**	**Row sum (X)**
Bike bell 1	8 (4)		1 (5)					1 (5)	1 (3)		1 (5)	4 (5)	16
Bike bell 2	3 (2)	0.5 (2.5)									1 (2)	1 (1)	6
Footsteps 1	4 (3.5)	9 (3)	7 (3)			3 (3)					1 (4)	2 (2.5)	26
Footsteps 2	3 (3)	4 (3)	2 (2)			1 (5)					1 (4)		11
Jackhammer	1 (2)		2 (3)	9 (3)	1 (1)			2 (2)	1 (4)	1 (1)	1 (2)		18
Screeching tires	1 (1)	5 (2)	4 (3.5)	4 (3.5)	2 (2.5)	2 (3.5)		2 (3.5)	6 (3)	5 (3)	2 (3)	3 (4)	36
Crash	2 (2)	2 (3)		2 (2.5)	1 (3)	1 (3)			2 (3)	2 (2.5)			12
Siren	3 (4)	2 (5)	4 (4.5)	3 (4)	3 (4)	4 (3)	2 (4.5)	4 (3)	6 (4)	4 (4.5)	3 (4)	3 (4)	41
Car horn	6 (3)	4 (3)	3 (4)	2 (3)	3 (3)	4 (2)	1 (1)	1 (1)	2 (4.5)	1 (2)		7 (4)	34
Column sum (Y)	31	27	23	20	10	15	3	10	18	13	10	20	

Note. *Empty cells represent cases in which no response occurred, light gray cells correspond to specific warnings, and dark gray cells correspond to more general warnings. Distractor sounds are excluded.*

described in this article, spanning physiologic recordings, controlled laboratory tasks, driving simulators, and ultimately an assessment of how such devices affect people during their everyday driving.

Conclusions

Neuroergonomics is a multidisciplinary translational approach that merges elements of neuroscience, cognitive psychology, human factors, and ergonomics to study brain structure and function in everyday environments. Applied to the salient example of automobile driving, such an approach aims to elucidate performance and safety using multiple sources of evidence and is likely to yield a deeper understanding of cognition in the natural settings. Driving makes demands on multiple cognitive processes that are often studied in isolation and so presents a useful challenge in generalizing findings from controlled laboratory tasks to predict safety outcomes. Neurology, neuroscience, and cognitive psychology can be used to explain the mechanisms of cognitive breakdown that might be associated with a specific subset of drivers. However, a more complete picture of the actual impairments that such a driver would experience in the real world might come from examining this person in controlled laboratory studies to determine the level of cognitive impairment or to determine that certain functioning has been affected. Expanding the scope of investigation even further to interactive simulation or naturalistic data collection, the researcher might further document the errors that the driver makes and determine how well the driver can compensate given his or her impairment. Moving from the controlled laboratory tasks to simulators and ultimately to naturalistic driving situations engages an increasingly broad range of influences. In driving, cultural and social influences might play as large a role as neurological influences. Although this article used a neuroergonomic approach to examine older drivers, such an approach is useful for investigating a variety of populations in a various environmental settings.

NOTES

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