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Individual differences in cognitive functioning predict effectiveness of a heads-up Lane Departure Warning for younger and older drivers

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Abstract

The effectiveness of an idealized lane departure warning (LDW) was evaluated in an interactive fixed base driving simulator. Thirty-eight older (mean age = 77 years) and 40 younger drivers (mean age = 35 years) took four different drives/routes similar in road culture composition and hazards encountered with and without LDW. The four drives were administered over visits separated approximately by two weeks to examine changes in long-term effectiveness of LDW. Performance metrics were number of LDW activations and average correction time to each LDW. LDW reduced correction time to re-center the vehicle by 1.34 seconds on average (95% CI = 1.12–1.57 seconds) but did not reduce the number of times the drivers drifted enough in their lanes to activate the system (LDW activations). The magnitude of reductions in average correction RT was similar for older and younger drivers and did not change with repeated exposures across visits. The contribution of individual differences in basic visual and motor function, as well as cognitive function to safety gains from LDW was also examined. Cognitive speed of processing predicted lane keeping performance for older and younger drivers. Differences in memory, visuospatial construction, and executive function tended to predict performance differences among older but not younger drivers. Cognitive functioning did not predict changes in the magnitude of safety benefits from LDW over time. Implications are discussed with respect to real-world safety systems.

Keywords

Lane Departure Warning; Older drivers; Cognitive function

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1. Introduction

Extending the mobility of a growing aging population safely has relevance to public health and injury prevention. Cessation of driving restricts mobility and is associated with subsequent depression and decreased well-being[1,2]. At the same time, aging drivers are at increased risk for crashes[3–5]. Research to date shows that age alone is a poor indicator of an older driver's safety[6–8] yet there is little consensus on criteria that distinguish safe from unsafe older drivers[9,10].

Emerging technologies that incorporate Advanced Driver Assist systems (ADAS) hold a particular promise in compensating for declining capacities of older drivers to extend safe mobility in later years[11]. ADAS are becoming more common in all types and price ranges of new vehicles. NHTSA has been considering mandating their inclusion in future vehicles[12,13]. An important scientific question with public health relevance is how much improvement in driving safety is actually realized with ADAS. A recent meta-analytic study showed that automatic emergency braking (AEB) systems has led to 38% reduction in rear-end crashes in the real-world and that these systems seemed to be equally effective in low and high speed zones[14]. Insurance Institute Highway Safety (IIHS) reports also show that property damage and collision claims have declined in models that offer AEB[15]. Accumulating evidence with regard to effectiveness of this feature has paved the way for 20 automakers to recently enter into a historic commitment to make AEB standard on all light vehicles by 2022[15].

In contrast, evidence is mixed on the effectiveness of lane-departure warning (LDW) systems in *production vehicles*. IIHS reports suggest some LDW systems are associated with increased claim rates[16]. Specifically, Buick and Mercedes models equipped with LDWs had increased claim rates while Volvo's equipped with LDW showed decreased claim rates. The reasons for these discrepancies among vehicle makes are not clear. The report suggested that the decreased claim rates in Volvo models may have to do with AEB and/or fatigue warning features rather than LDW. An informative field study evaluated the effectiveness of a prototype integrated vehicle-based safety which included LDW (IVBSS) [17,18]. This study showed that there were fewer lane departures from a 12-day baseline period when LDW was turned off compared to a 28-day period when it was turned on. IVBSS findings also showed both positive and negative behavioral adaptations. For example, turn-signal use increased, a positive behavioral adaptation but headway time was reduced, a negative behavioral adaptation.

An unaddressed question is whether ADAS or other in-vehicle safety technologies compensate for the declining capacities of older drivers. An important limitation of the IVBSS field study was that the older drivers recruited into the study were generally high functioning and thus may not be representative of the population of older drivers on the road. Nevertheless there was no evidence to indicate that effectiveness of LDW varied as a function of driver age[17,18]. Insurance claims data are largely silent on differential effectiveness of these systems for older drivers as market penetration of these vehicles are limited. Most simulator studies to date on LDW also suffer from similar limitations of recruiting middle-aged drivers or generally high functioning older drivers[19–21].

As noted by several groups, individual differences in functional declines associated with aging are large[6,9,22,23] and many of these impairments in basic visual, motor function as well as cognition have been shown to affect driving safety in vehicles that are not equipped with modern safety technologies[6–8,10,24–30]. Bivariate associations of these domains of functioning and driving safety measures range from fair to moderate. Multivariate analyses often show that cognitive function measures improve predictions of older driver safety beyond those based on age and visual function[6,7,10,26]. In other words, effects of age on driving safety often diminish or disappear when individual differences in these functional domains is included in predictive models[7,8]. While high functioning older drivers may adapt to ADAS quickly those with impairments may not derive the full range of benefits or benefits may be slower to emerge. Impairments associated with cognitive functioning may limit older driver's ability to understand the warning system messages[31–32] and impairments in basic visual and motor function may limit their ability to react to warnings in a timely manner[6]. The primary aim of this study was to evaluate the effectiveness of an 'idealized' heads-up LDW for older and younger drivers. The second aim was to examine whether cognitive functioning predicted any safety benefits beyond age in older and younger drivers.

1.2 LDW used in the current study

One of our goals was to test whether older adults who show a range of impairments in functioning typical of aging populations (i.e. poorer motor, visual, and cognitive function) could derive safety benefits from an idealized LDW that do ***not*** replicate the industry practice in important ways[33–34]. The idealized warnings for this study used the following five principles: 1) has both advisory & imminence features; 2) visuals are heads-up displays; 3) visual displays are distinct from real objects in the scene to minimize confusion, 4) displays do NOT adapt to the scenery and thus do not require the driver to interpret the warning (e.g. warning displays do not change orientation to follow lane markers on curved roadways), but they do change 'message' from advisory to imminent (e.g. change color) in simple and consistent ways (Figure 1); 5) the system is active at all speed ranges to increase user's experience of consistency and reliability. A yellow-advisory warning signal (Panel-a of Figure 1) was activated when the driver drifted toward an adjacent lane. A red-imminent warning signal (Panel-b of Figure 1) was triggered when the driver's tires touched the inside edge of lane marker[35]. These signals remained activated as long as either of the above conditions was met. The warning system was turned off when the turn signal was activated and while crossing intersections. There was no auditory component to the warning system. Figure 1 shows these visual alerts are distinct from the background scene to improve perception by drivers of all ages. The signals appeared in the lower half of the visual display to encourage drivers to sustain their attention on the roadway.

1.3 Repeated exposure to LDW and changes in long-term effectiveness

New technologies require a period of adaptation and the intended and/or maximal benefits of relying on that technology may take time to emerge depending on user characteristics and complexity of the technology[31,32,36,37]. Data based on existing field studies such as the IVBSS do not inform the timeline for the emergence of safety benefits to LDW in that prototype system. For example, IVBSS reports have not addressed ***incremental*** improvements in lane keeping or rates of lane departure as a function of time[17–18]. We examined changes in long-term effectiveness of the idealized LDW over four visits. We hypothesized that safety benefits from the idealized LDW would emerge more slowly in older drivers compared to younger drivers. Furthermore, we also hypothesized that individual differences in visual, motor, and cognitive function would predict changes in safety benefits from LDW over time. Older drivers with poorer functioning in these domains may show slower-to-emerge safety benefits over repeated exposures to LDW compared to higher functioning peers.

1.4 Study Goals

We addressed several questions relevant to the idealized LDW in younger and older drivers. Questions of effectiveness and changes in long-term effectiveness over repeated exposures to the system were examined with two measures: number of LDW activations and average correction time for LDW activations (correction RT). We also asked whether (1) effectiveness in general and (2) effects of repeated exposure to LDW (or time) varied as a function of age group. We hypothesized that older drivers would show poorer performance than younger drivers on all lane keeping performance measures (i.e. main effect of age). We also hypothesized that safety gains, especially with respect to correction RT, would increase with repeated exposure to LDW (i.e. interactive effects of time with warning) and in particular for older drivers (three-way interaction of time, warning, age group). In other words, over time older drivers would benefit from the LDW more (e.g. faster correction RTs) as they gained more experience interacting with it. This prediction is consistent with findings that show older individuals can take longer to learn new technologies[31,32,36,37].

We also asked whether (3) individual differences in cognitive functioning predicted LDW effectiveness during repeated exposures over and above age group, basic visual and motor function. Differences in speed of processing and executive function in particular should predict safety gains from LDW. For example, we would expect poor executive functioning to create sluggishness in attention switching between noting the activated warning and interpreting its meaning in the current scenery for corrective action. We would also expect visuospatial construction abilities to delay LDW detection. For example, these individuals may be slow in discriminating the heads-up visuals for the warning from the scenery it is superimposed on even though the LDW heads-up visuals were very distinct from the background scenery. We also expected that memory may be the least predictive of safety gains from LDW. The LDW visuals once activated were left on until corrective action was taken hence did not require cognitive resources associated with memory. With regard to the effects of cognitive function on long-term changes in safety gains of LDW (interactive effects of time with warning), we hypothesized that those who are low in cognitive function, and especially those with poorer memory function, may have particularly slow-to-emerge safety gains compared to those who are higher functioning.

Finally, we recognize that the idealized LDW we implemented may produce performance improvements in driving safety in ways that would not generalize to the real-world. In order to address this important concern, we also had our drivers complete an on-road 45-minute drive test and had their performance evaluated by a certified driving instructor in terms of safety errors. If relative rank-order in driving performance with respect to LDW in the simulated drives and real-world is correlated we would have some re-assurance that the gains associated with LDW may generalize to the real-world.

2. Methods

2.1 Sample

Seventy-eight younger (N = 40) and older drivers (N = 38) participated. The younger drivers were 25 to 50 years old (mean = 35 years), and consisted of 18 males and 22 females. The older drivers were 66 to 87 years old (mean = 77 years), and consisted of 23 males and 15 females. Inclusion criteria included: a) valid driver's license, b) minimum 10 years of driving experience, c) driving at least 1 hour or 50 miles per week, d) negative screen for dementia with Montreal Cognitive Assessment (MoCA > 18)[38], and e) corrected visual acuity better than 20/50. The average score on the MoCA screen was significantly higher for younger than older drivers (p = .021), with 42% of older drivers and 24% of younger drivers scoring in the mild cognitive impairment range. Two participants indicated some impairments in color vision but these did not affect their ability to detect differences in advisory versus imminent LDWs. Eighty-six percent of the sample was white. Educational achievement was distributed as follows: 7% had high school or less, 45% had less than college degree, 45% had a college degree or more, others did not indicate education level.

2.2 Procedure & Design

Following basic visual function and dementia screening (MoCA), participants took a simulator drive (fixed base, full cabin with 180° forward field of view, DriveSafety RS600) to assess motion sickness. Of the 106 drivers recruited, 28 experienced motion sickness and dropped out. These 28 drivers did not differ in terms of age, MoCA, or years of driving experience (minimum p = .077) from the 78 who completed the assessments and whose data are included in the results. The 78 drivers participated in detailed assessments of their cognitive function including processing speed, memory, executive function, and visuospatial construction during a second visit.

In four additional visits scheduled 2–3 weeks apart, participants completed eight simulated drives designed to examine changes in the long-term effectiveness of LDW. In order to minimize the confounding of practice effects (e.g. improved ability to center the vehicle in our simulator environment) with increasing safety benefits from LDW (a learning effect of deriving larger safety benefits from the warning system over time) the participants experienced one of four different drive layouts/routes which were similar in terms of road culture composition (e.g. rural versus urban roadways), total time (15–18 minutes each), and number of hazards encountered in each of the four visits. To be able to repeatedly assess and quantify the safety benefit due to LDW (main effect of warning), the participants experienced both the warnings-on and warnings-off version of these four drives in a given visit (i.e. same layout/route, with same hazards differing only in whether the warnings were invisible to the driver or visible to the driver, hereafter referred to as no-warn vs. warn drives respectively). The order of presentation was randomized and counterbalanced both with respect to: a) whether they experienced the no-warn or the warn version of the drive first in each of four visits b) which of the four distinct drive layouts/routes they first experienced.

In an additional visit, participants drove an instrumented vehicle on the road through an 18-mile route that takes about 45 minutes to complete (see Figure 2). This drive was conducted during non-rush hour traffic on days when weather did not lead to poor visibility or road conditions. The test began after a brief acclimation period to the vehicle, and a trained experimenter sat in the front passenger seat to give instructions and operate the dual controls, if needed. The instructions were typical of on-road tests, e.g. 'turn left at the next lights,' 'take the next exit to interstate 380.' The route included a mixture of residential, suburban, rural, and highway roads, and included navigation tasks discussed in prior publications[7,39–41]. Figure 2 shows the instrumented vehicle, the driver monitoring system that includes a total of 7 cameras in addition to vehicle data from the CANBUS such as tire speeds, and the route the participants drove through. On-road drive data were only available on 63 of the 78 participants due to equipment failure or scheduling difficulty.

2.3 Measures

2.3.1 Driving Safety—Driving performance in the warnings-on versus off version of the simulated drive was quantified with two measures: 1) number of LDW activations (i.e. number of times either the advisory or imminent threshold for LDW was breached) and 2) average correction time to turn the warning-off once the advisory/imminent visuals were activated in seconds. The simulator tracked warning system activation at 60hz in both warning-on and -off versions of the drive so ***lane keeping performance was comparably quantified*** whether the participant potentially could see the warning (in the warning-on version) or not (warning-off version, when warnings are invisible to driver but the simulator was tracking system activation identical to the warnings-on version of the drive). Each instance of LDW activation (imminent or advisory) was counted throughout the drive. If an advisory LDW turned imminent in the next frame before corrective action was taken, this was also considered a single instance of LDW activation. The time (in seconds) it took the participant to correct lane deviations/departures (i.e. correction RTs) for each instance of warning system activation within a drive was computed and averaged within each drive.

The videos of the on-road drive were evaluated by a certified driving instructor, who was blind to performance in the simulator, for safety errors according Iowa-Department of Transportation standards. The coding scheme has been described in greater detail in earlier publications[7,41]. The 76 specific error types (e.g. incomplete stop, straddles lane line, etc) are organized into 15 categories such as stop signs, lane observance, etc. In this study, we used lane observance errors and all other safety errors. The driving instructor's inter-rater reliability compared to another certified instructor on a sample of 30 drives showed a correlation of .73 for overall number of errors while absolute agreement for the 7 common error categories was substantial, Kappa = .79.

2.3.2 Acceptance of LDW—At the end of each drive, the participants were asked to complete a three-item questionnaire regarding their opinion of the LDW, in terms of whether it improved their safety with respect to lane keeping, whether they thought it was annoying, and whether they would consider purchasing a vehicle fitted with this kind of safety technology. The rating scale for each item ranged from strongly agree =1 to strongly disagree = 5.

2.3.3 Visual, Motor, and Cognitive Function—Vision tests included contrast sensitivity with Pelli-Robson Chart[42], near and far acuity with Snellen and Early Treatment Diabetic Retinopathy Study charts[43]. Contrast sensitivity scores range from 0 to 2.25 with high scores indicating better performance, and acuity scores are expressed as logarithm of minimum angle of resolution with high scores indicating poorer performance. The raw test scores were z-transformed and were averaged to form the Visual Sensory Functioning composite (average r = .44) consistent with a recent confirmatory factor analytic study[25]. High scores represented better functioning.

Motor function tests included Get-up-and-Go[44] and Functional Reach[45,46]. Get-up-and-Go is a test of short-range mobility and time to completion in seconds was scored. Functional Reach is a test of balance, positive distance in inches is used to score it. Performance in these two tests are moderately correlated ($r = .51$, $p < .001$). The raw test scores were z-transformed and averaged to form the Motor Functioning composite. High scores represented better functioning.

The battery of standardized cognitive tests was selected on the basis of their conceptual relevance to driving and demonstrated sensitivity to brain dysfunction[47,48]. Brief descriptions and measures from each test are described next. The Judgment of Line Orientation involves matching the orientation and angle of lines in space to 11 lines arranged in a semicircle on a reference card. In WAIS-III Block Design, participants are asked to arrange blocks to match a specific pattern in a limited amount of time. The scoring scheme takes into account both accuracy and speed. During the Complex Figure Test-Copy (CFT-Copy), participants are asked to reproduce a complex figure on a blank sheet of paper, and during the CFT-Recall they are asked to re-draw the same complex figure from memory 30 minutes after they completed CFT-Copy. Scoring in both tests reflects the number and seriousness of errors in reproducing the figure as well as time to completion. For the Controlled Oral Word Association (COWA), the participants are asked to recall as many distinct words as possible in one minute that begin with the letters c, f, and s. Scoring takes into account the number of distinct words recalled. For the Rey Auditory Verbal Learning Test (AVLT), the participants hear a list of 15 words and are asked to recall as many as possible. This procedure is repeated five times on the same list of words. After a 30-minute delay the participant is asked to recall as many of the words on the list as possible. Number correct after the delay is used in scoring. For the Grooved Pegboard (Pegs) the participants are asked to place 25 pegs into randomly positioned slots on a board using only one hand at a time. The time it takes to complete the task is scored and average of left and right hand scores are used. For the Useful Field of View test the participants take four subtests that tap visual discrimination and processing speed[46–48]. Subtest score represents the total duration in milliseconds at which the participant accurately performs on 75% of trials, ranging from 16.67 to 500ms. We used the sum of four subtests in this study. During the Trail Making Test part-A (TMT-A) participants are asked to trace through 25 numbered dots as fast as possible without lifting their hand, and during part-B (TMT-B) they are asked to switch between numbered dots and letters as fast as possible (e.g. 1,a,2,b, etc.). Seconds to complete each part and errors were recorded. During Wisconsin-Card sort the participant is asked to match stimulus cards but not told how to do the matching, however they are given feedback on whether the match is correct or not. Perseverative errors were used. Table 1 provides a summary of the tests administrated.

The raw scores on the individual tests were z-transformed. Guided by findings from a recent confirmatory factor analytic study[25], the z-scores were first reversed when appropriate so that high scores represented better functioning, (indicated with (R) below) and then averaged to form the following composite scores: speed of processing (Pegs (R), TMT-A (R), UFOV (R); average-r = .61), visuospatial construction (CFT-C, Judgment of Line Orientation, Blocks; averager = .38), memory (CFT-R; COWA, AVLT, average-r = .38), executive function (TMT-B, WCST, average r=.37).

2.4 Statistical Analysis

Mixed linear models using maximum likelihood estimation were used to address study questions. These models have distinct advantages over the traditional ANOVA framework. First, all available data can be used in simultaneous estimation of effects of interest in the mixed model setting without having to restrict the sample to those who completed the entire protocol as in the ANOVA setting. Second, mixed models easily accommodate subject-specific patterns in the timing of data collection on the repeated ‘time’ factor which typically deviates from an ‘ideal’ timetable set in the original protocol. Third, mixed models easily accommodate continuously distributed individual difference factors (e.g. cognitive function) as predictors both in the sense of their ‘main’ and interactive effects with other factors in the design without having to rely on arbitrary dichotomization of participants along the median typical in the ANOVA setting[52].

We describe basic model parameterization and summarize which terms in the mixed model would support the study hypotheses concerning effectiveness of the idealized LDW over repeated exposures. Warning status and age group each were modeled as binary predictors with two levels; no-warn versions of the drive and younger drivers were scored as zero in the data set. Time was scored as elapsed days from the first (set at time zero) through the fourth drive. When so parameterized, a significant main effect for warning status and age group in the absence of any interactions would indicate an additive model consistent with age differences and LDW effectiveness (or lack thereof) apparent in the first drive on lane keeping performance measures. A main effect of time without any interactions with other factors in the study design would be consistent with practice effects such as improved ability to center the vehicle in the simulator environment. A significant interaction of warning status with time would be consistent with long-term changes in LDW effectiveness (i.e. changes in the difference from the no-warn to the warn drive over repeated visits). Interaction of age with other factors would be consistent with differential effectiveness of LDW (age X warning status) and differential patterns of learning/practice effects (age X time) for older versus younger drivers. A three-way interaction would indicate that the effectiveness of LDW varies for older vs. younger drivers and the pattern in that variation changes across time.

Models were tested in three stages. In the first stage, the main effect of warning status, age group, time, and all two- and three-way interactions among these three factors were entered as described above. In the second and third stages, questions pertaining to whether individual differences in functioning moderated the effects of the three main study factors were examined. In the second stage, only the effects of basic motor and visual function were examined. Any nonsignificant interaction effects above p >.10 involving individual difference variables in visual and motor function with study factors were subsequently removed. In the third stage, any additional effects of cognitive functioning in four domains over and above basic visual and motor function were tested with a series of models where each individual cognitive functioning variable was entered by itself along with its interactions with 3 factors in the study design. Any non-significant interaction effects above p >.10 were removed and models re-estimated. For brevity, model-predicted values from the best fitting models from second and third stages are presented in Figures. These figures were generated with the time factor taking on the values of 0, 14, 28 and 42 days from initial exposure to LDW; and low versus high relative standing in cognitive function composite variables was examined at the 25th and 75th percentiles of their respective distributions. Following mixed linear models, we examined the correlations of LDW effectiveness with total number of lane observance and all other safety errors obtained from the standard on-road drive.

3. Results

3.1 Preliminary analyses

Table 2 shows the descriptive statistics for the two outcome measures used in the study for the no-warn (shaded values) and warn drives. Table 2 entries do not constitute formal statistical tests but these values suggest large improvements in timed performance measures pertinent to lane keeping in all four drives and large age differences in performance. Both older and younger drivers indicated they believed LDW increased their safety (95%CI=[1.94–2.41] for older and [2.09–2.55] for younger), that they would consider purchasing a vehicle equipped with this system (95%CI [2.18–3.0] for older and [2.67–3.33] for younger), and also indicated some annoyance with the system (95%CI [2.9–3.5] for older and [2.4–3.1] for younger).

3.2 Warning effectiveness, age group, and effects of repeated exposure-time

Table 3 shows the p-values for the terms in mixed linear models that examined the main and interaction effects of three study factors: Warning status, age group, and repeated exposure or time (hereafter). Figure 3 panels depict the predicted values for the two LDW lane keeping performance measures from these models. Warnings (red lines) were effective in reducing average correction RT for each instance of LDW activation but not number of times LDW was activated compared to the warnings off version of the drives (blue lines). There was a significant effect of age group on both outcome measures such that older drivers (unbroken lines) had more LDW activations and slower correction RTs than younger drivers (broken lines). Time was associated with fewer LDW activations but not with changes in average correction RT. There were no significant interactions among the three study factors. Hence, contrary to our hypothesis, LDW effectiveness did not vary as a function of age group (i.e. there was no warning status X age group interaction). Both older and younger drivers showed similar magnitude decreases in correction RTs from no-warn (baseline) to warn drives. Also contrary to our hypothesis, there was no evidence of changes in safety benefits of LDW over repeated exposure to the system (i.e. no warning status X time interaction). In other words, the magnitude of the decrease in correction RTs (no-warn versus warn difference) did not grow over time. The main effect of time, which was significant for LDW activations only, is consistent with practice effects associated with improvements in centering the vehicle in the simulator environment. The absence of a time by warning interaction (the target effect that would be consistent with long-term changes in effectiveness or the ability to derive larger safety benefits from LDW) is evident from the parallelism in the slope and curvature of the warnings-on and warnings-off trends.

3.3 Individual differences in functioning

We fit two sets of additional mixed linear models. The first set of these models examined if individual differences in basic visual and motor function moderated the effects of warnings, age group, and time on the two outcome measures. Neither visual function nor motor function moderated the three factors of study design. The second set of these models examined if individual differences in each of the four domains of cognitive function moderated the effects of three study factors over and above the effects of visual and motor function. Panels of Figure 4 through 10 depict model predicted values for each cognitive functioning domain separately for older (panel-a) and younger (panel-b) drivers in no-warn and warn drives for both outcomes.

Figures 4 through 6 show the effect of statistically significant cognitive functioning variables in relation to LDW activations for older drivers (Panel-A) and younger drivers (Panel-B) separately. Figure 4 shows that cognitive speed of processing primarily predicted poorer performance in terms of LDW activations. Both younger and older drivers who had relatively low cognitive speed of processing (broken lines) activated the warning system more often than their peers who had higher speed of processing (unbroken lines). There was no main effect of warning, i.e. both no-warn (blue) and warn drives (red) were associated with similar number of activations, and the main effect of time indicated practice effects of improved centering of the vehicle in the simulator environment over repeated visits.

In contrast, individual differences in visuospatial construction (Figure 5) and executive function (Figure 6) predicted performance differences among older drivers (panels-A) but not younger drivers (panels-B). Poorer executive function and visuospatial construction abilities (broken lines) predicted greater number of activations among older drivers compared to their peers who were higher functioning in these domains (panel-A). In contrast, level of functioning in these cognitive domains did not predict the performance of younger drivers (panel-B).

Figures 7 through 10 show the effect of statistically significant cognitive function variables in relation to correction RTs. Figure 7 shows that cognitive speed of processing predicted poorer performance or larger correction RTs for both older and younger drivers in both the warnings on (red) and off drives (blue). Drivers with higher speed of processing (unbroken lines) in both age groups corrected deviations in their lane faster compared to their peers with lower speed of processing (broken lines). There was no two-way interaction between speed of processing and warning factor (p=.135). Hence those scoring higher in speed of processing did not derive larger benefits from LDW compared to those lower in speed of processing. However, there was a marginally significant three-way interaction among speed of processing, warning, and time factors (p= .069). This effect can be seen in the slope differences of blue lines (no-warn condition). Drivers with lower speed of processing (broken blue lines) in both age groups had flatter curves than their peers with higher speed of processing (unbroken blue lines) in the no-warn condition. There were no comparable slope differences as a function of speed of processing in the warnings-on condition (red broken and unbroken lines). These are consistent with small practice effects of improved centering of the vehicle in the simulator environment when the warnings are turned off.

Figure 8 shows memory function predicted performance differences among older but not younger drivers. Older drivers with poorer memory (broken lines) showed larger correction RTs in both the warnings on and off conditions compared to their peers with better memory (unbroken lines) consistent with a significant two-way interaction between age group and memory (p= .0178). In contrast, memory function was not associated with performance differences in correction RT among younger drivers in either the warnings on or off conditions (i.e. minimal separation between broken and unbroken lines in Panel-B). There were no other significant two-way or three-way interactions involving warning, time, or age group.

Figure 9 shows that differences in visuospatial construction entered into a significant two-way interaction with the time factor (p=.016). This interaction was further qualified with a marginally significant three-way interaction also involving age group (p= .085). Improvement in correction RTs over time was steeper for older drivers who were relatively high functioning in visuospatial construction (unbroken lines) compared to their peers who scored low in this cognitive domain (broken lines). The latter effect indicates better functioning older drivers showed larger learning effects over time (between subject effects) but not larger safety benefits from LDW (no-warn to warn difference is similar for high and low cognitive functioning groups) compared to their lower functioning peers. No comparable effects were found for younger drivers.

Figure 10 shows differences in executive function entered into a significant three-way interaction with warning and time factors, p = .045. Furthermore, there was no significant main effect of executive function (p=.249) or two-way interaction of executive function with warning status (p=.329) or two-way interaction of time with warning (p= .95). Collectively, those findings indicate that both older and younger drivers who were generally low in executive function (broken lines) showed less pronounced improvements over time in correction RTs in the warnings-off drives compared to their higher functioning peers in this cognitive domain. Once again, this effect is consistent with improved centering of the vehicle in the simulator environment in the warnings-off drives for higher functioning drivers.

3.4 Associations with real-world safety and simulator performance

Table 4 shows the correlations of the performance metrics from the simulator in relation to LDW, averaged across all available visits in the warnings-on and warnings-off version of the drive with safety errors from the on-road drive. Safety errors from the on-road drive showed significant moderate correlations with the number of LDW activations in both warn and no-warn drives but not average correction RTs from the simulator. There was no evidence of specificity in these correlations, since lane keeping performance in the simulator predicted more than just lane observance errors in the on-road drive.

4. Discussion

The findings showed that the idealized LDW was effective in reducing correction RT but not in reducing LDW activations. These findings indicate that the idealized LDW did not prevent deviations from the center of the lane but only the speed with which drivers corrected such deviations. Older drivers showed poorer performance than younger drivers on both performance measures; they activated LDW more often and had slower average correction RT to LDW activations. These age differences were evident in both the warnings off and on version of the drives. Safety benefits from LDW, reductions in correction RTs, were similar in magnitude for both older and younger drivers. Safety benefits from repeated exposure to LDW emerged at similar rates for older and younger drivers. Observed changes over time were consistent with practice/learning effects associated with improved centering of the vehicle in the simulator environment.

The idealized LDW was designed to address limitations of the older drivers and are not offered in production vehicles. The magnitude of safety benefits from LDW can be gleaned from 95% confidence intervals for correction RT differences between warnings-off and warnings-on drives. Average correction RT to re-center the vehicle was decreased between 1.12 to 1.57 seconds when performance was averaged across all available drives across both groups of drivers. One way to contextualize these safety benefits is in comparison to younger driver correction RT in centering the vehicle without the LDW. In this respect, 95%CI for older driver's correction RT in the warnings-on drives ranged from 3.21 to 3.82 seconds which was better than younger drivers' correction RT without the benefit of LDW which ranged from 4.10 to 4.72 seconds. These effects suggest that the idealized LDW produced large enough benefits to older driver's lane keeping performance that their performance was similar to younger driver's lane keeping without the benefit of LDW[34].

Because the LDW was designed with limitations of aging drivers in mind and the idealized features differed from industry practice, it is difficult to know whether similar magnitude safety benefits can be realized in production vehicles. However, when LDW performance metrics were examined in relation to safety errors in a standard on-road drive, LDW activations predicted safety errors. This finding increases our confidence that the idealized LDW did not alter lane keeping performance in ways that did not correspond to performance in the real-world.

Future studies need to address questions regarding the importance of two particular features of the idealized LDW to the safety gains observed in this study: a) the presence of an advisory component to LDW and b) the choice to have the system active at all speed ranges. Evidence that would support the importance of both features would have implications for the design of production systems with the limitations of older drivers in mind. For example, many of the production LDW systems are often only active above a certain minimum speed and only deliver imminent warnings through a variety of modalities such as steering wheel torque or audio chimes. We believe that in order for a warning system to be effective, especially for older drivers, it must alert the driver early to provide sufficient time to respond. When the system is active in all speed ranges, the user's experience of system consistency and reliability would be naturally higher and consequently increase their ability to utilize and understand warning system messages. However, the findings also indicate that warnings systems that do not take control from the driver like the idealized LDW we tested may not prevent or reduce deviations within a lane. An important implication of these findings is that a system similar to the idealized LDW would issue more frequent alerts which may negate benefits for non-aging drivers and annoy to the point that the system would be disabled. However, future systems that permit tailoring of warning features for the driver rather than adopt the one-size-fits-all approach may overcome this particular limitation.

Individual differences in functional domains predicted lane keeping performance. Both older and younger drivers with higher cognitive speed of processing performed better on both measures; they activated LDW less often and had faster correction RTs. The performance differences for those low versus high in cognitive speed of processing were evident in both the warning-on and warning-off version of the drives. In other words, those with higher speed of processing did not derive larger safety benefits from LDW (i.e. larger reductions in correction RTs) compared to their lower speed of processing peers. Hence this finding is very consistent with those from several other studies indicating that cognitive speed of processing is important in predicting driving performance; it is often associated with better performance in on-road tests, fewer safety errors, and better state-driving records[6,7,24–33,51].

The findings concerning individual differences in memory, visuospatial construction, and executive function to predictions of driving performance with and without LDW contrasted with those for speed of processing. Differences in memory and visuospatial construction tended to predict performance differences in LDW activations and correction RTs among older but not younger drivers. Older drivers who scored higher in these cognitive domains had fewer LDW activations and faster corrections RTs compared to their peers who scored lower in these cognitive domains. These findings indicate that in addition to speed of processing, cognitive functioning in these domains are relevant to older driver's lane keeping performance.

Importantly, differences in visuospatial construction and executive function predicted improvements in correction RTs over time for both older and younger drivers. However, these predictions were further qualified by age group in the case of visuospatial construction and by warning status in the case of executive function. Older drivers who had better visuospatial functioning had steeper improvements over time in correction RTs in both the warnings-on and warnings-off version of the drives compared to poorer functioning peers in this domain. Both older and younger drivers with poor executive function had flatter slopes in correction RTs over time compared to drivers who had better executive function. However, both of these time effects were more consistent with practice/ learning effects of improved centering of the vehicle in the simulator environment when the warnings were turned off. In other words, findings concerning the effects of time did not support our hypothesis that those who are better functioning in cognition would be able to derive increasing safety benefits (e.g. greater reductions in correction RTs) from warnings over time. The findings regarding the importance of cognitive function to LDW effectiveness in particular for older drivers support the message of many earlier studies on driving safety. Namely, several domains of functioning including vision, motor function, and distinct aspects of cognition should be considered in identifying those drivers who could stand to benefit from ADAS[6,24,25,53].

There are three possible explanations for lack of support to our hypothesis on long-term changes in LDW effectiveness. Recall that we hypothesized safety benefits from LDW (i.e. size of the reduction in correction RT across visits) would increase over time and in particular for older drivers. It is possible safety benefits from LDW were already maximized in the first drive. As can be seen in Table 2, there were approximately 40 LDW activations in the first drive. The initial correction RTs and later correction RTs to these 40 activations in the first drive may evince a pattern consistent with our hypothesis. For example, initial correction RTs may be smaller than later correction RTs especially for older drivers. Future studies will evaluate these possibilities. The second possibility is that the idealized LDW was ‘too’ effective and it produced floor effects in the warning condition, i.e. it was not possible to further shorten correction RTs to lane deviations among older drivers. This hypothesis is consistent with small practice effects we observed in the no-warn condition especially for older drivers with high relative standing in several aspects of cognitive function. Finally, it is possible repeated administration of both warnings-on and off drives dampened our ability to detect changes to safety benefits over time. However, repeated administration of the warnings-off condition was critical to our ability to quantify safety benefits from LDW without confounding it with practice effects (i.e. such as improved ability to center the vehicle in the simulator).

4.1 Conclusions

Our findings indicated large safety benefits from LDW for both older and younger drivers in terms of correction RTs to LDW but not total number of LDW activations. Cognitive functioning predicted performance differences. Speed of processing appeared important for both age groups while memory, visuospatial construction, and executive function appeared more important in predicting older driver performance. Those findings encourage the inclusion of cognitive speed of processing in future studies that seek to inform optimal timing for warning system activation for individual drivers to maximize safety benefits. For example, individuals who are higher functioning in these cognitive domains may prefer to receive warnings relatively late to reduce annoyance and unnecessary warnings while those who are lower in speed of processing may prefer and benefit from receiving warnings earlier.

The study had several limitations. First, while our sample sizes were reasonable for dense assessments of driving safety in multiple platforms, larger sample sizes would have increased our confidence in the findings due to greater statistical power to detect smaller but meaningful differences. Second, due to the idealized nature of the LDW we designed, it is difficult to know which specific components of the warning system design contributed the most to observed safety benefits. However, we believe the safety benefits, in particular for older drivers, were due to three factors: a) presence of advisory LDW, b) LDW was active in all speed ranges, and c) warnings did not require the driver to look away from the forward roadway. The best way to study the effectiveness of ADAS both in the short and long-term in the real-world is to instrument production vehicles equipped with advanced safety technologies in controlled studies. Our findings support the notion that it is possible to produce performance improvements among older drivers so that their performance is comparable to that of younger drivers without the benefit of LDW. Third, our findings are not applicable to lane keeping systems that take control from the driver as the idealized LDW we tested never took control from the driver. Lane keeping systems may present challenges to older drivers with cognitive decline in that these safety features are typically not available in all speed zones and certain roadway features/weather conditions reduce system performance. In order to derive maximal benefit from such systems drivers of all ages would need to understand system limitations well enough to anticipate and take corrective action to preserve driving safety. Educational campaigns may prove useful in general to alert the driving public to system limitations. However, if an ADAS requires driver vigilance in understanding those limitations to anticipate and take corrective action, the usefulness of the system for older drivers in particular may be limited.

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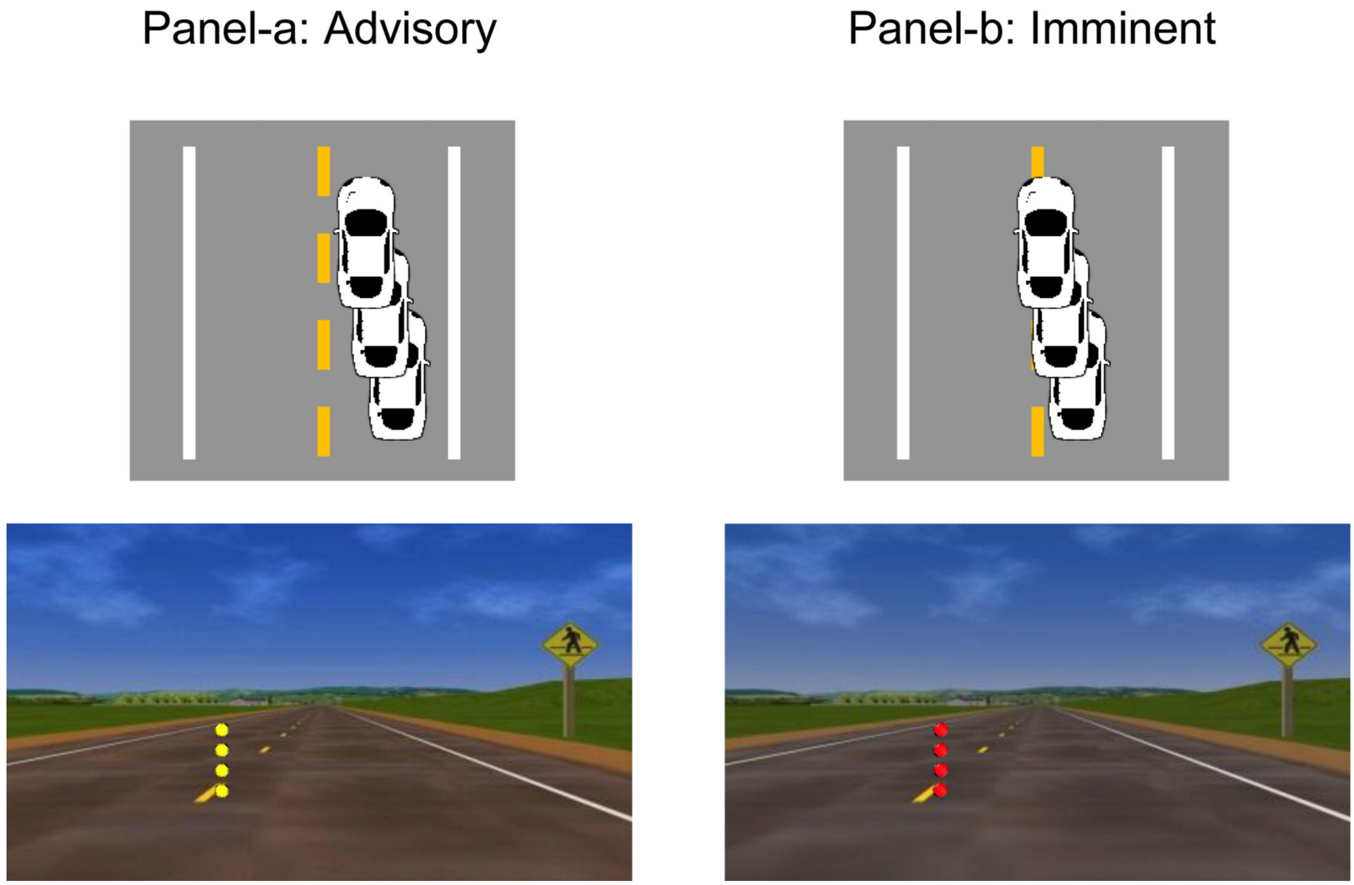
Highlights

- Heads-up lane-departure warning produces large safety benefits for older drivers
- Cognitive speed of processing predicts lane-keeping performance for both older & younger drivers
- Memory, visuospatial construction, and executive function predict lane-keeping performance for older but not younger drivers
- Cognitive functioning does not predict changes in the long-term effectiveness of LDW



Panel-a: Advisory

Panel-b: Imminent

Figure 1.
Illustration of LDW visuals (bottom) and the subject’s corresponding lane position (top)

Figure 2.
Views of the instrumented vehicle for standard on-road drives.

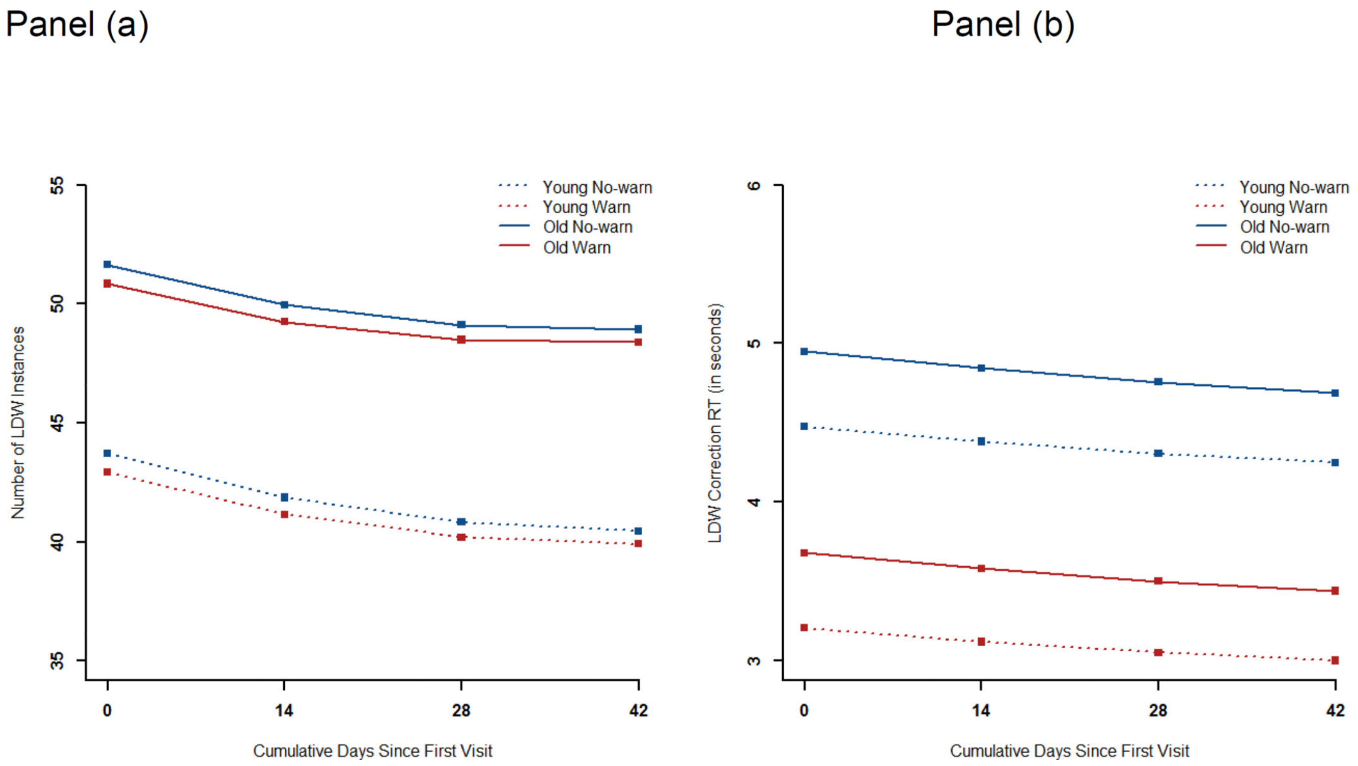


Figure 3.

Model predicted values from basic study design on two outcome measures. Panel (a): number of LDW activations, panel (b) correction RT.

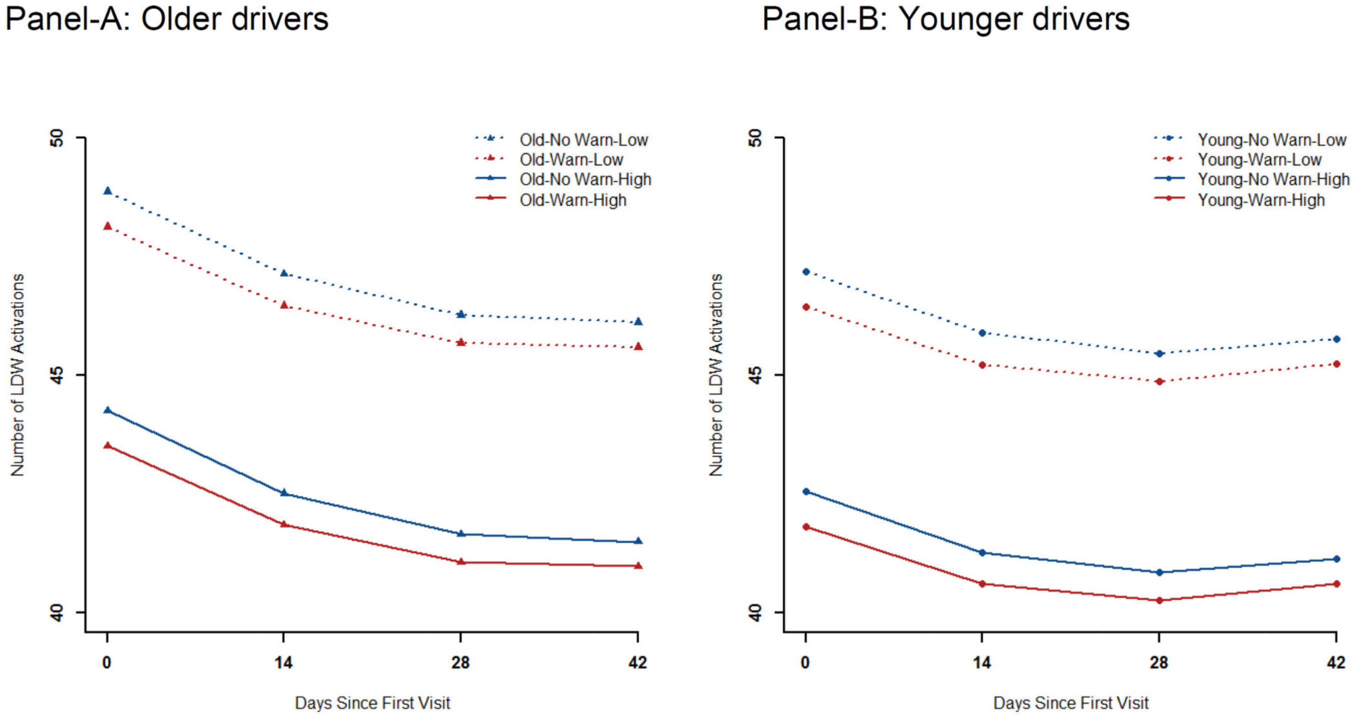


Figure 4.

Model predicted values for LDW activations as a function of speed of processing and age group.

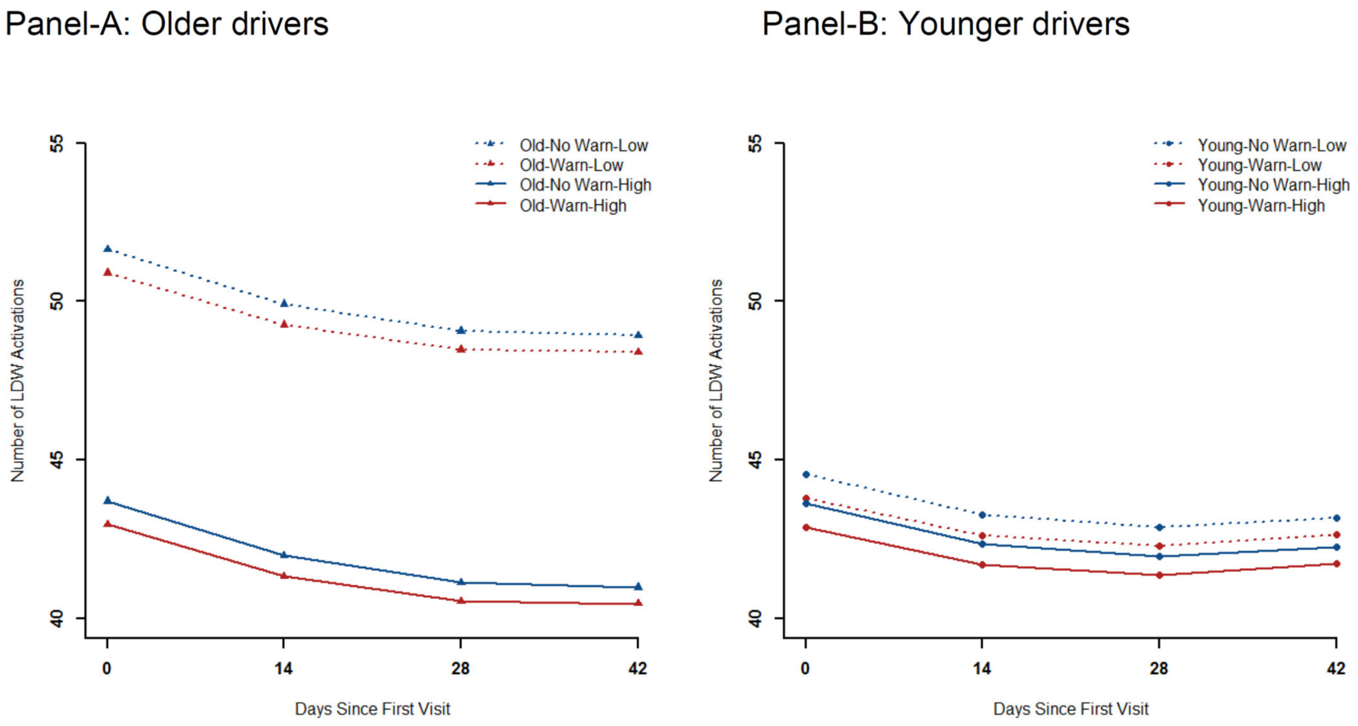


Figure 5.

Model predicted values for LDW activations as a function of visuospatial construction and age group.

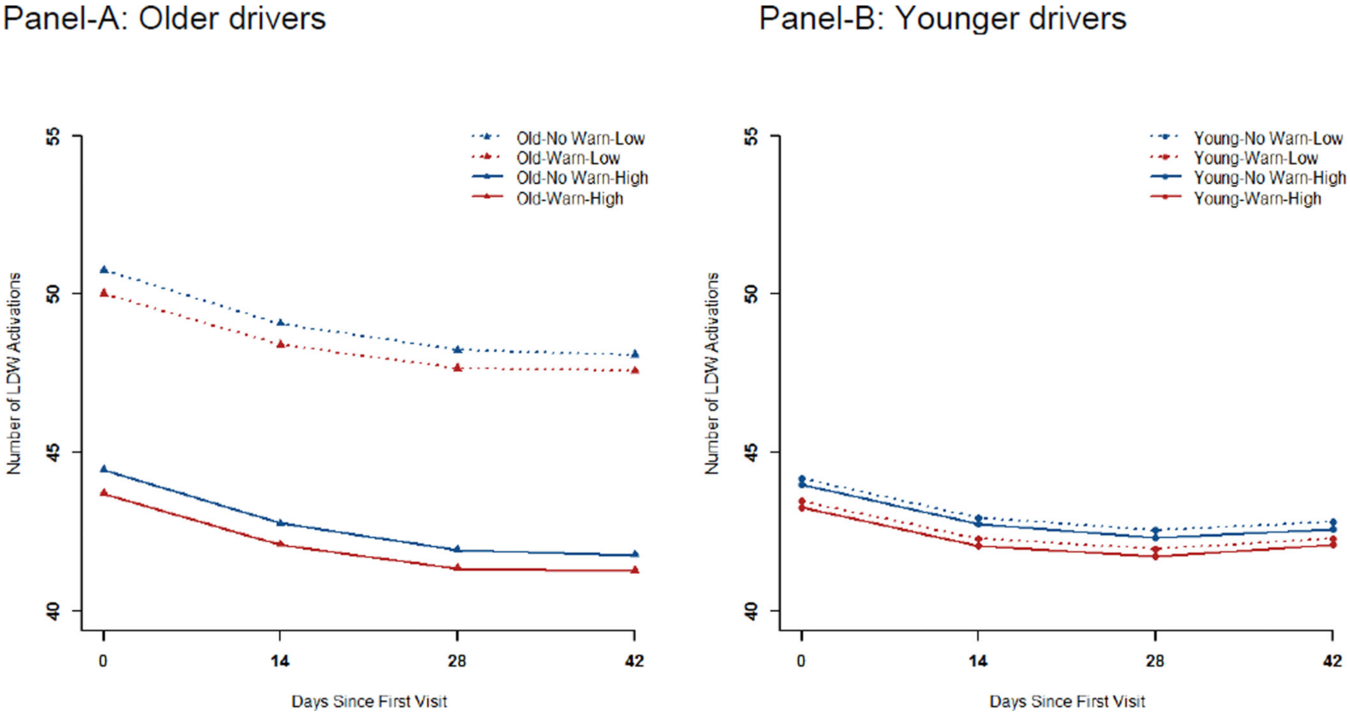


Figure 6.

Model predicted values for LDW activations as a function of executive function and age group.

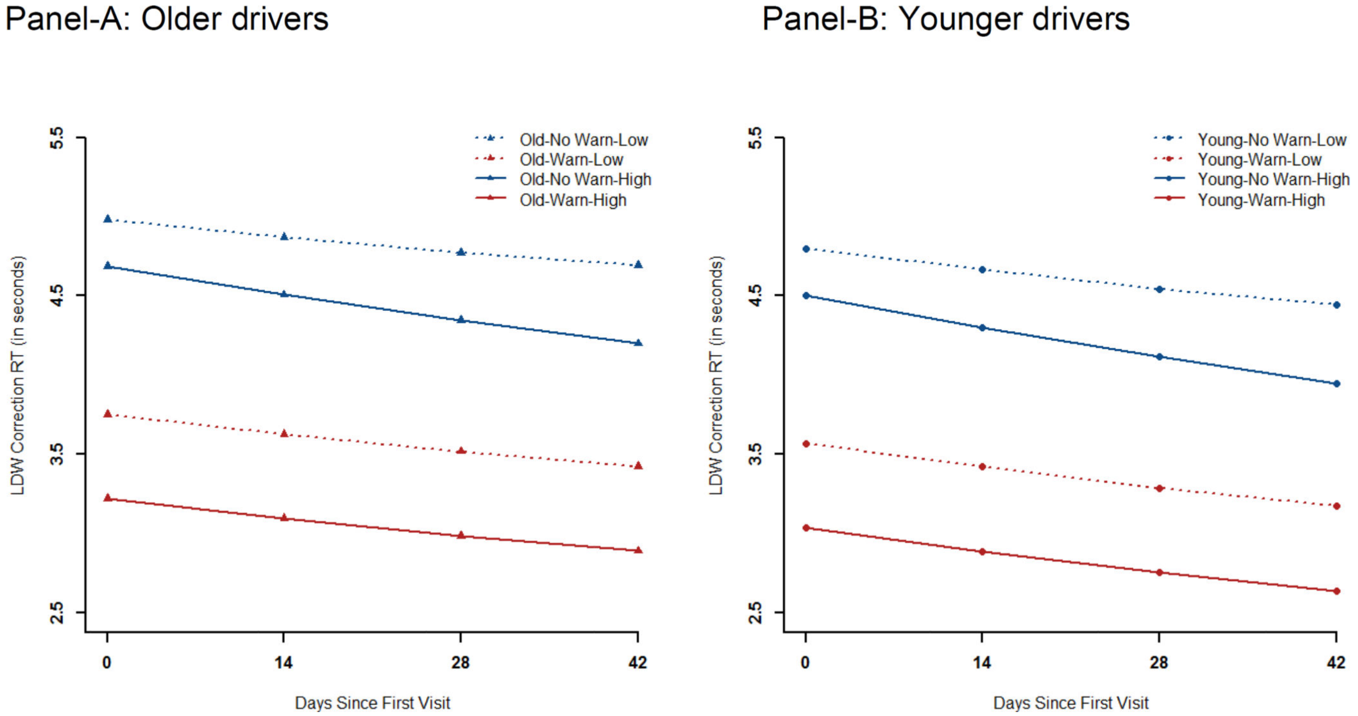


Figure 7.

Model predicted values for correction RT as a function of speed of processing and age group.

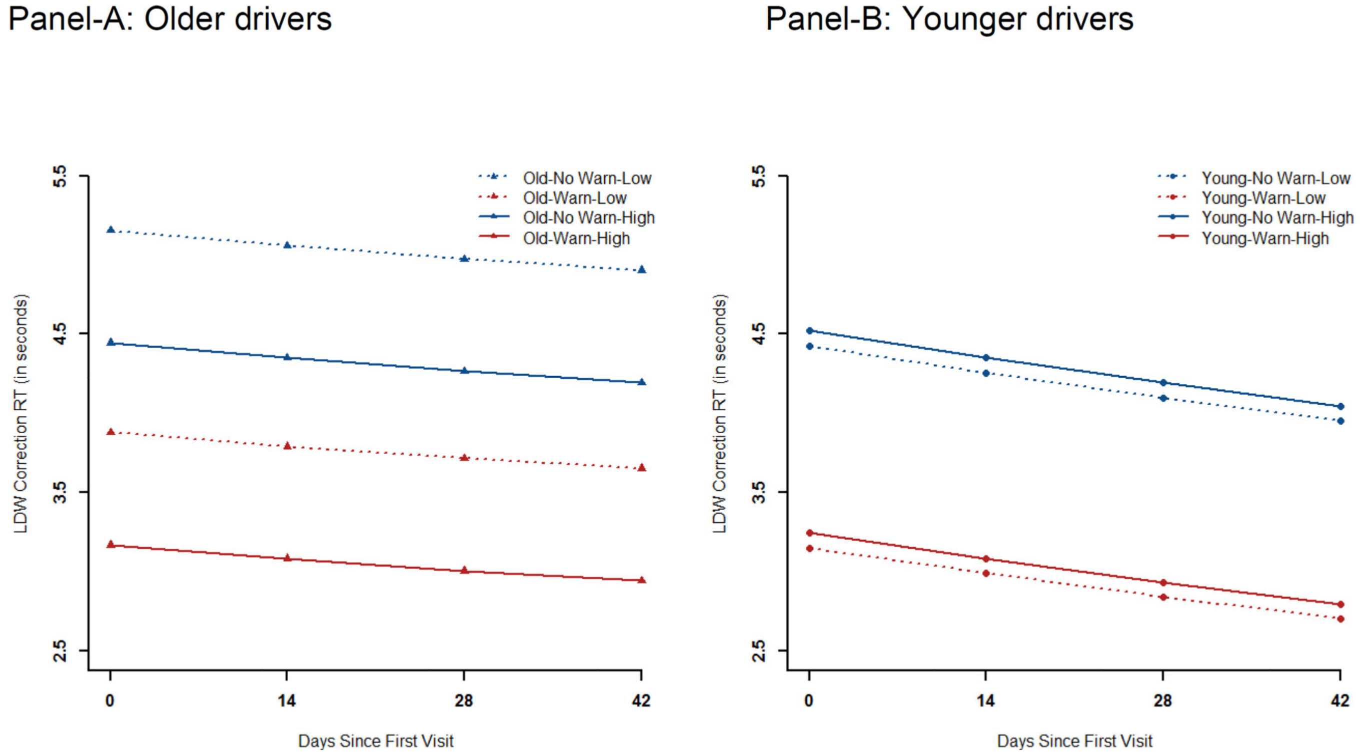


Figure 8.

Model predicted values for correction RT as a function of memory and age group.

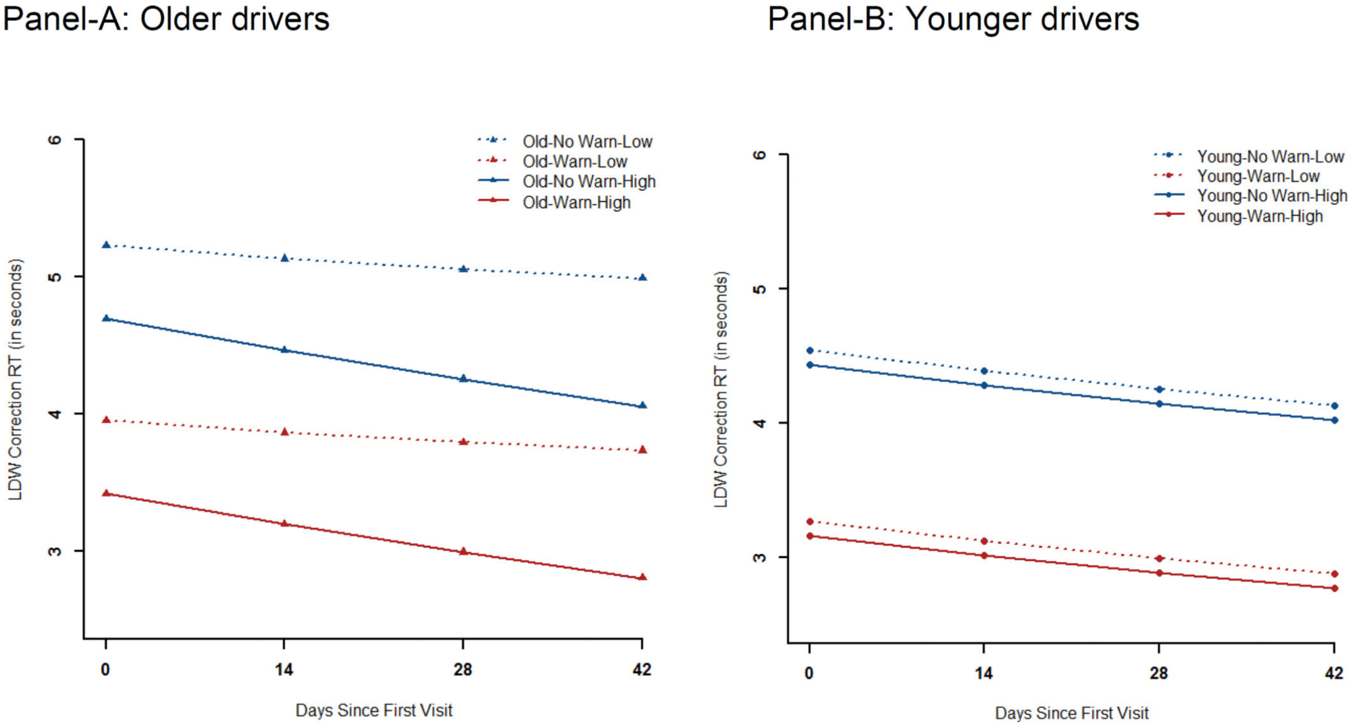


Figure 9.

Model predicted values for correction RT as a function of visuospatial construction and age group.

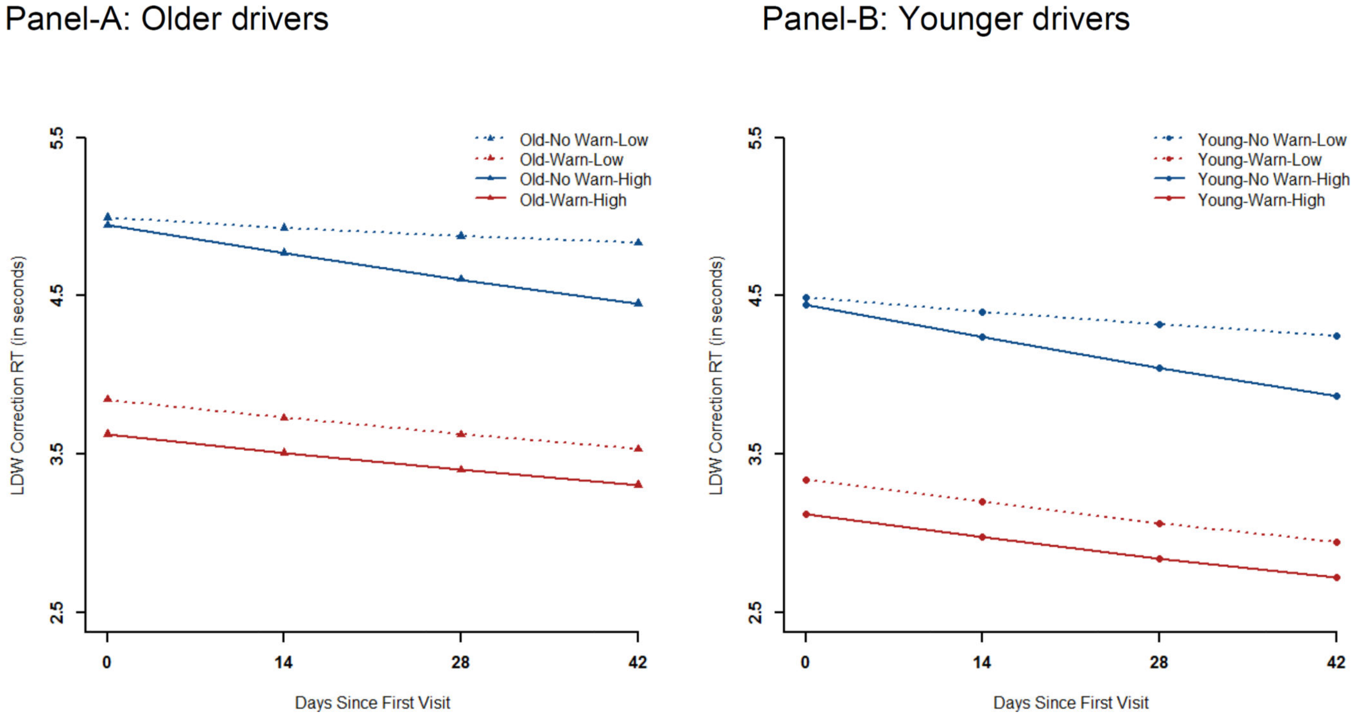


Figure 10.

Model predicted values for correction RT as a function of executive function and age group.

Table 1

Summary of tests administered from each functional domain

Domain	Sub-domain	Tests
Basic Vision		Near & Far acuity, Contrast sensitivity
Motor Function		Get-up & Go, Functional Reach
Cognition:	Speed of Processing	Pegs, TMT-A, UFOV
	Visuospatial Construction	CFT-Copy, Blocks, Judgment of Line Orientation
	Memory	CFT-R, COWA, AVLT
	Executive Function	TMT-B, WCST

Table 2

Mean (M), standard deviation (SD), N for older (O) and younger drivers (Y) on LDW effectiveness measures.

		# of LDW activations				**Correction RT**			
		No-Warn		**Warn**		**No-Warn**		**Warn**	
		Y	**O**	**Y**	**O**	**Y**	**O**	**Y**	**O**
Drive 1	M	43.3	52.64	42.33	52.13	4.55	5.12	3.13	3.70
	SD	12.6	13.2	12.4	12.68	1.18	1.62	0.80	1.13
	N	40	36	39	38	40	36	39	38
Drive 2	M	44.94	50.26	44.65	49.29	4.49	4.94	3.12	3.64
	SD	10.72	10.32	9.59	10.72	1.20	1.64	0.85	0.95
	N	34	34	34	34	34	34	34	34
Drive 3	M	40.85	47.33	40.7	46.58	4.20	4.75	3.15	3.55
	SD	10.32	11.82	9.27	11.23	1.14	1.48	0.86	1.37
	N	33	33	33	33	33	33	33	33
Drive 4	M	41.16	47.55	40.26	47.03	4.30	4.37	3.09	3.26
	SD	14.22	10.11	11.4	12.09	1.35	1.23	0.78	0.97
	N	31	33	31	32	31	33	31	32

Table 3

P-values associated with the terms from mixed linear models from first stage.

Predictors:		**LDW activations**	**Correction RT**
Time	-linear	**.0080**	.2120
	-quadratic	**.0100**	.6990
	-cubic	**.0069**	---
Warning status		.4927	<**.0001**
Age group		**.0088**	**.0286**
Age group X Warning status		.9885	.9369
Warning status X Time-linear		.7652	.8273
Age group X Time-linear		.6178	.7638
Age group X Time-linear X Warning status		.9502	.3966

Table 4

Pearson correlations between simulator performance and standard on-road drive measures.

	LDW activations		Correction RT	
	No-Warn	**Warn**	**No-Warn**	**Warn**
Lane observance errors	.40**	.54**	.22^{+}	.20
All other errors	.46**	.53**	.04	.12

N = 63.

$^{+}$p < .10,

**p <.01.