Auditory forward collision warnings reduce crashes associated with task-induced fatigue in young and older drivers

Carryl L. Baldwin*
Department of Psychology, George Mason University, 4400 University Drive, MS 3F5, Fairfax, VA 22030, USA
Email: cballdwi4@gmu.edu
*Corresponding author

Jennifer F. May
Sentara Norfolk General Sleep Center, 600 Gresham Drive 5B, Norfolk, VA 23507, USA
Email: Jennifer.may@gmail.com

Raja Parasuraman
Department of Psychology, George Mason University, 4400 University Drive, MS 3F5, Fairfax, VA 22030, USA
Email: rparasur@gmu.edu

Abstract: Driver fatigue poses a persistent threat to transportation safety. Auditory warnings provided prior to a potential collision event can reduce crash probability in alert drivers, but it is unclear whether they are effective in fatigued young and older drivers. In the present study fatigue was task-induced in young (18–29 yrs.) and older (65–85 yrs.) licensed drivers via a 1.5 hour simulated car following task. Upon meeting a fatigue criterion – based on individually assessed excessive lane position variability – a single potential collision event was triggered and drivers were either provided an auditory warning or not. The auditory warning significantly reduced overall crash probability and was particularly beneficial in reducing crashes in older drivers. Auditory collisions warnings can reduce fatigue-related rear-end crashes, particularly among older drivers – a population at greater risk of both fatigue and crashes.

Keywords: auditory warnings; collision warnings; crashes; task-induced fatigue; fatigue; young drivers; older drivers; driving; driving simulation; in-vehicle technologies; forward collision warnings; FCWs; automation; transportation safety.
1 Introduction

Fatigue significantly increases crash risk in drivers (Gnardellis et al., 2008; Merat and Jamson, 2013; Williamson et al., 2014). Fatigue is thought to be a major contributing factor in over 1,000 fatalities and potentially as many as 100,000 crashes annually in the USA (FARS, 2009; Tefft, 2010). These statistics likely underestimate the problem since there are currently no standardised procedures for testing for or reporting fatigue, and as such crashes that were caused by fatigue may often be attributed to other factors, such as inattention or distraction (Brown, 1994; Lee, 2008; Regan et al., 2009).

Driver fatigue is associated with increased lane position variability, decreased response time to unexpected events, speed fluctuations, and increased crash rate (Larue et al., 2011; Liu and Wu, 2009). Fatigued drivers are more likely to miss signals of hazardous situations (Tippin et al., 2009). Gnardellis et al. (2008) found that the incidence of fatigue and falling asleep incidents was linearly related to the number of crashes people had – with those reporting higher incidence being more likely to have been involved in multiple crashes.
Auditory FCWs reduce crashes associated with task-induced fatigue

Task-induced fatigue is a major contributor to such driving impairment, and is particularly evident in monotonous conditions such as at night and when driving along freeways or straight roadways (Desmond and Matthews, 1997; Matthews and Desmond, 2002) where it can be considered to equivalent to a vigilance decrement (Milosevic, 1997). For example, Van Der Hulst et al. (2001) showed that task-induced fatigue – 1.25 hours of route memorisation – lead to degradations in fine motor ability, more erratic steering performance, and decreased safety. Fatigue effects have also been observed after only 40 minutes of monotonous simulator driving, as reflected in greater lane position variability with time spent driving (Thiffault and Bergeron, 2003). Thus, it is clear that task-induced fatigue degrades driving performance (May and Baldwin, 2009). But are some populations of drivers more susceptible to the adverse effects of fatigue?

Many different populations of drivers are potentially at risk for fatigue-related crashes. These include: young males who are more likely to be sleep deprived and/or drive at night (Pack et al., 1995); young drivers driving alone while drowsy (Hutchens et al., 2008); commercial vehicle (e.g., truck) operators who typically spend many hours on the road (Wylie et al., 1996); individuals with sleep apnoea (Tippin et al., 2009); and older adults with perceptual (Owsley et al., 1998) or attention deficits (Ball et al., 1988; Parasuraman and Nestor, 1991), or those taking prescription medications that may make them more susceptible to the effects of fatigue (Cooper et al., 2011). Fatigue impairs both driving performance as well as cognitive functioning, and thus impairs the ability of drivers to judge whether it is safe to continue driving (Brown, 1997). Given that young males who are not fatigued have a tendency to over-estimate their own driving abilities and to perceive risky driving behaviours as less serious than their female and older counterparts (DeJoy, 1992), they may be particularly at risk of impaired judgment when fatigued.

Both young and older drivers are over represented in vehicular crashes and fatalities when calculated in terms of the number of crashes per mile driven or the number of at fault fatalities per licensed driver (McGwin and Brown, 1999; Owsley et al., 1991; Williams and Shabanova, 2003). Older drivers are particularly at risk of crashes at complex intersections and crashes involving at least two vehicles (Caird et al., 2007; Clarke et al., 2010). Young males have higher crash rates than young females and are more likely to be at fault in crashes resulting in fatalities (Mayhew et al., 2003; Williams and Shabanova, 2003). Fatigue plays a role in a substantial number of these crashes for both young (Filtness et al., 2012) and older drivers (Clarke et al., 2010).

Collision avoidance systems (CAS) have the potential to mitigate crash risk stemming from active task-induced fatigue in these and other driver populations. CAS represents one of a variety of automation aids that can be implemented to support the human operator, in this case the driver. As such, human factors evaluations of such advanced driver automation tools must be conducted so that their safety benefits can be fully realised (Hancock and Parasuraman, 1992; Young and Stanton, 2002). When driver automation aids are designed with sufficient consideration of such issues as provision of feedback, mental workload, and locus of control (Stanton and Young, 2000), they can provide substantial benefits for driving safety. For example, a combined visual-auditory warning system has been shown to reduce rear-end crashes among alert young drivers in simulation studies (Lee et al., 2002).
Additionally, verbal CAS warnings have been shown to reduce crash rates in a variety of high crash risk simulated driving scenarios. For example, Baldwin and May (2011) examined the effectiveness of verbal collision warnings as a function of signal word and presentation levels in reducing collisions among young drivers in simulated high-risk urban driving scenarios. They observed an acoustic-semantic trade-off that significantly impacted crash rates. Specifically, the word ‘caution’ at a high presentation level and ‘danger’ at a low presentation level were effective in reducing crashes. In general, well designed auditory warnings appear beneficial in reducing crash probability in alert young drivers (Baldwin, 2012). The question remains, however, do auditory warnings benefit fatigued drivers?

Auditory warnings have been suggested as a fatigue countermeasure both to signal to the driver that his or her behaviour is indicative of fatigue or sleepiness, as well as a means of collision avoidance. Auditory warnings have shown some success in combating fatigue related crashes in driving simulations with young drivers (Navarro et al., 2007), though a paucity of research exists in this area. Since young males are more likely to overestimate their driving abilities and be more risk taking than their female counterparts (DeJoy, 1992), they may be less responsive to auditory warnings when their judgment is impaired by fatigue. Conversely, though less risk taking, older drivers tend to take longer to make perceptual decisions and respond to hazardous situations (Baldwin, 2002; Caird et al., 2005) and fatigue could be expected to prolong response times even further. At the same time, non-fatigued older drivers seem to benefit at least as much as their younger counterparts and sometimes even more (Kramer et al., 2007; Porter et al., 2008) from auditory warnings. Therefore, older fatigued drivers could be expected to benefit at least as much as younger drivers from auditory collision warnings.

Yet, relatively little research has been conducted on the impact of fatigue on the performance of older drivers. Furthermore, there is a paucity of studies on fatigue that have used either a medium or high fidelity simulator that can better capture the ecology of naturalistic driving. In one exception, a high fidelity driving simulation investigation of the impact of sleep loss, task-induced fatigue and age on driving performance (Roge et al., 2003) demonstrated that both fatigue and age reduced the useful field of view (UFOV) during the simulated driving task. Several researchers have examined the potential for non-fatigued older drivers to benefit from collision warnings using either medium or high fidelity driving simulators (e.g., Caird et al., 2007, 2008; Kramer et al., 2007; Lees et al., 2012). Kramer et al. (2007) found that both younger and older drivers benefited from collision avoidance warnings and older drivers benefited in particular when the driving task was more difficult. Kramer et al. (2007) examined warnings of different modalities and found warnings with an auditory component to be particularly beneficial (relative to visual only or visual in combination with vibrotactile.) Further, Donmez et al. (2006) observed that both middle-aged and older drivers benefited from an auditory cues for distraction mitigation when asked to perform a distraction task during risky driving manoeuvres. Therefore, it seems clear that auditory warnings have the potential to benefit older drivers. But it remains unclear whether auditory warnings will benefit older drivers experiencing fatigue and if so, to the same or perhaps a greater degree than young drivers. Furthermore, regardless of their impact on older drivers, will auditory warnings differentially impact young females relative to young males – who like older adults are at higher risk of fatigue-related crashes, but unlike older adults are likely
to underestimate their degree of impairment and overestimate their driving ability (DeJoy, 1992; Rhodes and Pivik, 2011)? The current study was designed to address these questions.

2 The current study

The study was designed to examine the effectiveness of auditory CAS warnings in reducing crashes in fatigued older and younger drivers. Both verbal and non-verbal warnings were used, for the following reasons. Older adults have greater difficulty than young adults in understanding messages presented as visual symbols (Scialfa et al., 2008). Like visual symbols, non-verbal auditory warnings are abstract sounds that may not be readily understood. Without training older adults have greater difficulty comprehending the meaning of product labels and warnings (Hancock et al., 2005), particularly if they are symbolic, complex or involve only symbols or icons without accompanying text (Lesch et al., 2011; Scialfa et al., 2008). In addition, auditory warnings can possibly startle fatigued drivers, leading to a potentially dangerous over-steer reaction (Hancock and Verwey, 1997). Providing a prepulse can reduce startle responses (Blumenthal et al., 2006) but fatigue reduces its effectiveness while leaving the startle affects intact (Van Der Linden et al., 2006). Older drivers may be particularly vulnerable to startle effects, particularly when auditory warnings are comprised of abstract sounds and when they are fatigued. Therefore, verbal warnings may reduce confusion and lead to greater crash mitigation, particularly in older adults. For these reasons, both verbal and non-verbal warnings were used in this study.

Fatigue was induced by having participants perform a simulated driving task in combination with a secondary task for approximately 1.5 hours. When drivers demonstrated fatigue (as assessed by excessive lane position variability) a critical rear-end potential collision event was triggered. A single such event was used, rather than multiple potential collision events as in many studies, to better capture the natural ecology of driving, where rear-end collisions are typically a rare occurrence. Drivers received either no warning or a verbal or non-verbal CAS warning. We hypothesised that CAS condition, age and gender would significantly predict CAS response (crash or stopped). Specifically, we predicted that older drivers would benefit more from the collision avoidance warnings than younger drivers because older drivers as a group tend to drive more cautiously (e.g., do not follow as close, drive slower) (Lam, 2003; McGwin and Brown, 1999) and would potentially benefit more from the sensory aid provided by the auditory warning (Baldwin, 2002, 2012). Similarly, based on crash rates observed in epidemiological studies (Evans, 2000; Obeng, 2011) and national databases (NHTSA, 2007) we predicted that males would have higher crash rates relative to females, regardless of whether or not a CAS warning was provided.

We also hypothesised that participants who stopped in time to avoid the collision would have a greater stopping distance if they received a CAS warning. Finally, of the participants who crashed, we hypothesised that participants who received a CAS warning would have a lower speed at the time of impact (presumably as a result of attempting to stop). Speed at time of impact could be taken as an index of crash severity in this simulation scenario.
3 Method

3.1 Participants

Forty-eight participants between 18 to 82 (M = 46.56, SD = 22.52) voluntarily participated in this study after providing written informed consent for a University approved IRB protocol. Note that the age restrictions for older and younger groups resulted in the exclusion of three participants between the ages of 35 and 60, one of whom crashed in the no-warning condition. Three participants were excluded as outliers (defined as 3 SD above the mean) due to either their excessive following distance or speed deviation. Of the remaining participants included in the subsequent analyses, 19 were between the age of 18–29 (5 males and 14 females) with an average age of 22.3 years (standard deviation of 3.4 years) and 23 were between the ages of 60 and 82 (11 males and 12 females) with an average age of 67.6 years (standard deviation of 5.4 years). All participants were licensed drivers and 95.6% of participants reported driving at least three to five times per week. A majority (93.3%) of participants reported using a computer. All participants received scores of over 26 on the mini-mental state exam (Folstein et al., 1975), had normal hearing as assessed by a pure-tone audiometric exam, and self-reported normal or corrected to normal vision. All participants reported that English was their native language and that they drove at least once per month. The average reported driving frequency for both the young and older group was three to five times per week and did not differ significantly between the groups.

3.2 Procedure

Participants were first familiarised with various CAS warnings and rated each for its perceived urgency, alerting effectiveness and annoyance level [procedure modelled after Baldwin and May (2011)]. After a brief orientation to the driving simulator, participants completed a practice drive. A general electric capital I-SIM driving simulator (see Figure 1) was used to present the simulated driving task. The simulator consists of a built up cab unit with wrap around 40 inch screens ran by independent computers presenting an approximately 180 degree field of view. Inset views on each of the screens serve to present a rear-view and side mirrors. The built up cab unit simulates the handling characteristics of a Crown Victoria. Participants used normal vehicle controls (i.e., steering wheel, accelerator, brake) to maintain their position and apparent speed on the simulated roadway.

The practice drive consisted of a car-following task, with traffic included in the second half of the drive. The lead car maintained a constant speed of 55 mph. This served to regulate the speed at which the participant could drive. Driving much faster than 55 mph would result in overtaking the lead car and driving much slower would result in losing the lead car. In this way, individual differences in driving speed were minimal. The practice drive also included a CAS warning (notice) related to a car stranded on the side of the road which the participant had to manoeuvre around, so the participants would have experience with a CAS event.
Auditory FCWs reduce crashes associated with task-induced fatigue

- **Fatigue inducement:** Participants then completed approximately 1.5 hours of simulated driving consisting of a car following task and secondary speech processing task in both high density and no traffic freeway scenarios. Included in this part of the experiment was a baseline car-following drive where average lane position variability (average standard deviation of their lane position, or amount of weaving) was calculated. We used this average lane position variability and calculated one standard deviation above this average as an index of task-induced fatigue (fatigue threshold).

- **Collision scenario:** The potential collision scenario consisted of a car following task with no other traffic. Lane position variability was monitored in real-time to determine fatigue level. Once the participant reached his or her fatigue index the researcher triggered the lead car to suddenly decelerate and come to a rapid complete stop. When the lead car slowed to 50 mph (from 55 mph), three possible CAS conditions occurred. Sixteen participants had no warning (control condition), 15 participants heard the 1,000 Hz tone, and 14 participants received the verbal ‘danger’ CAS warning. Participants received no prior information regarding this potential crash situation but had been exposed to the CAS warnings during an earlier portion of the investigation.

The main variable of interest was the response to the potential collision situation (crashed or stopped). Speed variability (standard deviation) and average following distance were also calculated. Stopping distance from lead car was recorded if the participant did not crash, and speed at moment of impact was recorded if the participant crashed.

Figure 1  GE I-SIM driving simulator (see online version for colours)
4 Results

Twenty-nine percent (13 of 45) of drivers crashed. Of these, 61.5% (8 of 13) of crashes occurred in the no warning group, 23% (3 of 13) occurred in the non-verbal warning group, and 15% (2 of 13) occurred in the verbal warning group (see Figure 2). The distribution of crashes as a function of warning condition and age is graphically represented in Figure 3. For all participants, the mean average following distance was 49.54 metres (SD = 19.67) and the mean speed deviation was calculated as 3.37 (SD = 1.32) mph.

Figure 2  Number of responses (crashed or stopped) by CAS type

![Figure 2](image1)

Figure 3  Number of crashes by age group and CAS type

![Figure 3](image2)

A binary logistic step forward regression was performed to identify significant predictors of CAS response (stopped vs. crashed). Variables included in the analysis were CAS type (no warning, 1,000 Hz tone, ‘danger’), age, gender, average following distance, speed
deviation and fatigue threshold. CAS type was the only significant predictor of CAS response ($\beta = -0.975$, $p = 0.037$, Nagelkerke $R^2 = 0.151$).

Separate regression analyses were ran to examine the impact of CAS type in the young and older drivers. CAS type was a strong predictor of crash probability in the older group ($\beta = -2.207$, $p = 0.05$, Nagelkerke $R^2 = 0.392$), but was not a significant predictor for the younger group. No other variables were significant predictors of crash probability in either subgroup.

A 2 (age: young and older) by 3 (CAS type: non-verbal, verbal, control) MANOVA was performed to examine differences in CAS type and age on speed deviation, average following difference and fatigue threshold. The Wilk’s Lambda criterion was used for this analysis. A significant main effect of age was revealed, $F(3, 34) = 4.81$, $p = 0.007$, $\eta^2 = 0.30$. Univariate analyses showed average following distance accounted for this age effect, $F(1, 36) = 13.57$, $p = 0.001$, $\eta^2 = 0.25$. Older drivers (M = 58.9, SD = 18.12) had a larger average following distance than the younger drivers (M = 39.3, SD = 17.67). No other significant main effects or interactions were found.

A separate MANOVA was performed to examine the effect of response type (stopped and crashed) on speed deviation, average following distance and fatigue threshold. No significant effects were found.

Separate ANOVAs were performed to examine the effect of CAS type on stopping distance (for participants who stopped, N = 31) and speed at time of collision (for those who crashed, N = 13). There was no significant difference in the stopping distance between the three CAS types for participants who stopped, nor was there any significant difference for speed at time of collision for participants who crashed. Again, these analyses were repeated to include age group. Results showed a significant age effect for stopping distance, $F(1, 23) = 6.6$, $p = 0.017$, $\eta^2 = 0.22$. Older drivers had a larger stopping distance (M = 17.2, SD = 9.59) than the younger drivers (M = 9.81, SD = 4.22). Speed at time of collision did not significantly differ between the two groups.

5 Discussion

The results of this study show that auditory CAS warnings can be helpful in reducing crashes in high risk rear end collision situations when drivers are fatigued. Nearly 18% of drivers crashed when provided no prior warning. This observation confirms the success of our method of operationally defining a high collision risk situation in the simulation scenario used in the current investigation. When provided with an auditory warning, only roughly 11% of drivers crashed. This represents a significant reduction in crash rate relative to the no warning control condition. Auditory warnings were particularly effective in reducing collision potential among older drivers. In fact, when given an auditory warning only one driver over the age of 60 was unable to avoid collision. Disappointingly, providing an auditory warning had little impact on crash rates in drivers under the age of 35.

Average following distance, speed deviation and fatigue threshold did not differ as a function of CAS warning or between those who crashed and stopped. This finding is quite positive in that we know that following too close was not a cause for the crashes, and that fatigue levels appear equal across the groups. This was also evident in that these variables were not predictors of CAS response in the regression model.
Average following distance was larger for the drivers over the age of 60, indicating that these drivers may be more cautious when following a lead car, or that they increase their following distance more when fatigued, as compared to younger drivers. Previous literature has documented that fatigue was associated with increased headway during a monotonous driving task (Van Der Hulst et al., 2001). The increase in following distance coupled with an auditory collision warning may help older drivers avoid crashes. It is important to point out that despite the greater following distance maintained by older adults, when provided no prior auditory warning a substantial number (just over 17%) of these drivers crashed. Therefore the current results suggest that an auditory CAS warning may be particularly effective in reducing crash rates among older drivers experiencing task-induced fatigue.

For drivers who crashed, speed at time of impact did not vary across the CAS conditions. The potential for CAS warnings to reduce crash severity may have been obscured by low statistical power in the current investigation. Despite the relatively high rate of crashes (29%) across drivers a total of only 13 crashes were observed. Further examination of the potential for CAS warnings to reduce crash severity in a larger sample size is warranted. The significant reduction in crash rates among drivers provided with a warning indicate that auditory CASs have the potential to reduce both occurrence and severity of fatigue-related rear-end crashes, especially among older drivers.

In the current investigation, only one potential collision event was experienced by each participant. Though including only a single event per participant dramatically reduced the number of data points collected, it greatly increased the ecological validity of the study. It is highly irregular to experience more than one crash event per day and conventional wisdom in the driving research community indicates (Aust et al., 2013) that by including more events there is a trade-off in realism of the simulation.

In terms of the direct implications for task-induced fatigue-related crashes, a limitation of the current investigation is the exclusion of a control group exposed to the collision scenario and CAS conditions in the absence of fatigue inducement. In this way the effectiveness of the CAS warning could be compared in fatigued and non-fatigued drivers. In addition, subjective measures of fatigue could have supplemented the lane deviation measure to ensure the drivers were in fact fatigued.

The results point to the utility of auditory CAS warnings adaptively linked to measures of driver performance decrement. In the present study fatigue-related driving impairment was indexed by excessive lane position variability. After this fatigue inducement, warnings were presented in response to a high-risk collision situation. In the present study, all warnings were for potential rear-end collisions and therefore the CAS functioned as a forward collision warning (FCW). The auditory FCW-CASs used in this investigation were highly effective in mitigating these rear-end collision situations. Single vehicle road departures are a common form of sleep loss related fatigue. Future research could examine warnings for lane departure events and a more prospective approach by investigating the potential benefit of providing drivers with low hazard level visual or auditory warnings when driving performance degraded irrespective of a potential collision situation.

A limitation of the current study is arguably that auditory alerts that are not ideal were utilised. Speech warnings and pure-tones can be easily masked in the cars, particularly when drivers are listening to music or driving with the windows down. It is interesting to note that although the auditory warnings used in the current study are not ideal, the fact that they still demonstrated benefits for reducing crashes among older adults is
promising. More effectively designed warnings are likely to demonstrate greater benefits and future research in this area is well warranted.

Another limitation of this study is that the simulator used in this experiment was incapable of providing brake response times and therefore we do not have that data. However, despite the fact that crashes are a rather crude measure, they are arguably ecologically valid measures, particularly when measured in driving simulations involving only one potential crash event participant.

The auditory CAS warnings examined in this study could also be presented adaptively, based on individual driver performance characteristics (e.g., excessive fatigue-related lane deviation) or aspects of the driving environment, given that adaptive automation has been shown to regulate operator workload and performance (Parasuraman, 2000). Adaptive systems based on real-time measurement of operator states such as high mental workload using neuroergonomic measures (Baldwin and Penaranda, 2012) have shown promise in reducing performance decrements in supervisory control tasks (Wilson and Russell, 2007). Similar systems can be developed for mitigating performance decrements due to excessive mental workload or fatigue in drivers (Hancock and Verwey, 1997; May and Baldwin, 2009). Fatigued drivers continue to drive for a number of reasons and often choose ineffective countermeasures (Armstrong et al., 2010). Future research on adaptive automation to mitigate fatigue in drivers might also consider other performance and physiological measures, including EEG (Lal et al., 2003), blink rate (Lal and Craig, 2002), or eye movements (Ji et al., 2004). Hybrid adaptive systems that use multiple physiological, performance, and system measures (e.g., Ting et al., 2010) might allow for the optimisation of safety benefits. However, any potential benefits would need to be carefully examined for potential trade-offs stemming from nuisance alarms and signals not effectively matched to the hazard level of the situation. Ensuring that signals are appropriately mapped for the urgency of the signal without being excessively annoying is critical for effective warning design regardless of the modality used (Baldwin and Lewis, 2014). Finally, as with all automated systems, driver aiding systems will need to be evaluated carefully for issues related to appropriate use and reliance of such systems (Balkin et al., 2011; Parasuraman and Riley, 1997).

References


Auditory FCWs reduce crashes associated with task-induced fatigue


Auditory FCWs reduce crashes associated with task-induced fatigue


