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ORIGINAL ARTICLE

Design characteristics of a workload manager to aid drivers in safety–critical situations

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Abstract

The objective of this study was to evaluate a workload manager designed to supervise the presentation of in-vehicle information for two age groups of drivers during safety–critical situations. The benefits of a workload manager were compared in various dual-task conditions involving a preceding or a concurrent in-vehicle alert during critical traffic situations. Objective measures such as drivers' brake response times and secondary task response times as well as subjective measures of driver workload were used. Although older drivers performed worse in the dual-task scenario with longer response times and poorer performance on the secondary task in comparison to the younger drivers, results indicated that both age groups benefited from the implementation of a workload manager. There was a consistent trend of improved driving and secondary task performance when the workload manager delayed non-critical information during safety–critical situations, indicating benefits for some otherwise distracted drivers. Implications for the design of a workload manager are discussed.

Keywords Workload manager · Braking · Secondary task · Ageing · Workload

1 Introduction

Instrument clusters in modern passenger cars increasingly display sophisticated information relating to the engine management and braking systems as well as faults in, for example, airbag systems. Apart from their obvious attention-attracting properties, some messages will also necessitate cognitive engagement as drivers decide whether to take action in the short term and what that action should be. Such messages have the potential to be both visually and cognitively distracting.

Secondary tasks with a visual component can disrupt natural eye movement patterns resulting in errors in heading direction and hence lateral position (Godthelp et al. 1984). Whilst interface guidelines have been developed regarding the visual component of a secondary task (e.g., Rockwell 1988; SAE 2004; JAMA 2004; ESOP 2006), the cognitive component is more difficult to standardise. This difficulty is partly due to there being conflicting results from studies evaluating non-visual tasks, particularly when using vehicle lateral deviations as a performance indicator. On one hand, some studies report increases in lateral deviation (e.g., Salvucci and Beltowska 2008), whilst others report the opposite effect (e.g., Reimer 2009). This conflict may, in part, be due to differences in the behavioural parameters chosen to represent lateral deviations and their computation (e.g., standard deviation of lane position versus time-to-line crossing, Li et al. 2017). With increases in cognitive activity, changes in gaze concentration or "visual tunnelling" have also been observed, whereby drivers appear to focus more on the road ahead, at the expense of periphery events (Victor et al. 2005). Motor actions are also negatively affected: when car-following, drivers performing a cognitively distracting task take longer to release the accelerator pedal (Hurwitz and Wheatley 2001; Lee et al. 2002). Foot movement time and responses to braking events are influenced by the type of distracter task and the order of in-vehicle task presentation, leading to improvements in braking performance when the braking task is presented after the in-vehicle task (Hibberd et al. 2013). Therefore, manipulation of distracter task modality may not be a completely effective method for the removal of an in-vehicle distraction effect (Vollrath and Totzke 2005), but accurate timing of the secondary tasks is

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rather important to prevent the driver from being overloaded or engaging in "mind wandering" at safety–critical time points. Such mind wandering (i.e., a diversion of thought away from the primary task of driving) has been associated with longer response times to sudden events, increased speeds, and shorter headway distances (Yanko and Spalek 2014; Geden and Feng 2015).

Whilst traffic and vehicle safety information can be useful to the driver, there are some possible negative side effects in terms of increased task demand and capacity overload (Pauzié and Alauzet 1991; Verwey 2000; Blanco et al. 2006), especially for some older drivers, who may have decreased perceptual, motor, and cognitive functioning due to normal ageing (Anstey et al. 2005). While driving is generally self-paced and compensating strategies can be executed to limit the interference of secondary tasks (Becic et al. 2010; Tractinsky et al. 2013), the previous research has indicated that drivers still engage in distracting tasks such as calling or texting, even though they report them as being dangerous (McEvoy et al. 2007; Nelson et al. 2009; Atchley et al. 2011). This might be explained by the concept of "comparative optimism" whereby risks associated with one's own behaviour are perceived as lower than those associated with others'. For example, in a re-analysis of White et al. (2004) data, risk perceptions relating to mobile phone use while driving depended on whether they related to perceptions of oneself or others (White et al. 2007). In addition, drivers rate proactive engagement as more risky than reactive engagement (Atchley et al. 2011; Nelson et al. 2009). Therefore, system (vehicle)-initiated messages may be deemed by the driver as being less distracting and the inappropriate timing of their presentation could result in driver overload or inattention. This is particularly important in less predictable safety–critical situations in which attempted self-regulation may not be timely and accurate.

A way of reducing the potential negative impact of system-initiated messages is via a workload manager. Workload management functions are designed to prevent excessive workload and distraction by dynamically supporting the driver to manage both driving and non-driving-related tasks. They can control information initiated by in-vehicle systems and limit the system functionality available to the driver in potentially demanding situations. A number of studies have examined the effectiveness of workload managers in simulator, track, and on-road environments (Piechulla et al. 2003; Uchiyama et al. 2004; Donmez et al. 2006; Wu et al. 2008; Tijerina et al. 2011). Research suggests that workload managers may provide some benefits to the driver via intervention strategies such as "locking" an in-vehicle information system to deny access to initiate a task function (Tijerina et al. 2011). Although this strategy promotes consistently quick response in braking, Tijerina et al. (2011) suggested that implementation of a locking strategy on an in-vehicle task that is already underway should be avoided due to additional cognitive processing in interpreting why the task was interrupted. This is particularly important in driving conditions which suddenly grow more intense, requiring drivers' attention to the driving task to maintain safe driving. An example of such a safety–critical scenario could be a sudden event requiring the driver to perform a braking response; a short response window is available and the failure to detect changes in the environmental complexity due to inattention, distraction, or attentional tunnelling could result in a crash (Baddeley 1972; Endsley 1995, 2006). A workload manager may, therefore, help to manage any potential system-controlled information available to drivers, in the event that a safety–critical driving situation is detected via in-vehicle sensors (e.g., radar).

In this study, a workload manager was designed which delayed system (vehicle)-initiated messages to minimise driver distraction and maintain performance of the safety–critical aspects of the driving task—in this case, a braking response to a critical cut-in performed by neighbouring vehicle. This particular scenario has been found to significantly increase drivers' workload from a baseline level as well as being one which drivers underestimate in terms of workload (Teh et al. 2014, 2018). Drivers were required to respond to the messages (as a secondary task) under various conditions either with the workload manager engaged or not. With the projected increase of older drivers on the roads (Department for Transport 2012), it becomes necessary to ensure that the development of support systems such as a workload manager considers not only the comfort and safety of younger drivers, but also older drivers. Thus two age groups of drivers were considered. We hypothesised that a workload manager would improve driver performance in a safety–critical scenario by reducing their workload. We also expected to observe differences in performance between the age groups, which may be mitigated by the workload manager.

2 Method

2.1 Apparatus

The study was conducted in the motion-base, high fidelity University of Leeds Driving Simulator, Fig. 1. The driving simulator's vehicle cab is a complete 2005 Jaguar S-type model with all driver controls fully operational. Participants had full control of the longitudinal and lateral motion of the vehicle and were encouraged to operate the controls as they would in their own vehicle. The vehicle is right-hand drive and uses an automatic transmission. Data are collected continuously at 60 Hz.

Fig. 1 University of Leeds Driving Simulator

Verbal responses to the secondary task were collected via a Sony ICD-200X Digital Voice Recorder attached to a Griffin Lapel Microphone. The voice files were post-processed using the Praat audio playback program with sound spectral analysis capability. The files were converted from WMA to WAV format, and using the Praat software sound spectral analysis capability, the sound stimulus and speech response could then be identified, and thus, the verbal reaction time measured to ± 1 ms accuracy.

2.2 Participants

Drivers were recruited from an existing database, via responses to a University of Leeds website and a local poster advertisement. To avoid the issue of older drivers driving less distance annually compared to younger drivers (Rimmö and Hakamies-Blomqvist 2002; Hu and Reuscher 2004, 2008) due to the changes in lifestyle after retirement, all recruited participants were drivers who still used their vehicle more than four times a week, with a self-reported minimum annual mileage of 5000 miles.

A total of 50 drivers were recruited, all holders of a valid driving license for over 5 years with normal or corrected-to-normal vision and hearing. Six participants did not complete the experiment—four participants due to simulator sickness and technical complications, and two older participants due to their large amount of errors in the driving task during the practise stage. Twenty-six drivers aged between 25 and 49 years (13 males, Mage = 32; 13 females, Mage = 33) and 18 drivers aged between 60 and 72 years (10 males, Mage = 66; 8 females, Mage = 66) successfully completed the experiment. The mean annual mileage for the younger and older drivers was 9588 miles and 8700 miles, respectively. All drivers were paid for their participation (£15).

2.3 Driving task

A three-lane motorway was simulated and participants were instructed to drive in the middle lane, maintain a speed of 65 mph and not pass the lead vehicle. Adjacent vehicles pulled in front of the participants, either from the slow or the fast lane. Ambient vehicles in the slow lane maintained 60 mph while fast-lane vehicles travelled at 70 mph. The adjacent vehicle was programmed to pull in at a certain distance from the front of the participant's vehicle. A critical lane change distance was defined as approximately 5 m (± 2 m) upon crossing the lane boundary and a non-critical lane was defined as a lane change beyond 20 m from the participant vehicle. These values were obtained from Teh et al. (2018), whereby the highest levels of workload were reported at the 5 m cut-in distance and no change in workload was observed for cut-ins beyond 20 m. Participants completed two drives (35 min each): one drive with the workload manager off and the other drive with the workload manager on. Each drive contained 20 events involving a mix of critical and non-critical lane changes as well as sections where no-lane changes took place to avoid predictability. The order of the two drives was counterbalanced.

2.4 Secondary task and design of the workload manager

The system-initiated messages (18 vehicle-system- and 18 non-vehicle-system-related messages) were obtained from a vehicle manufacturer and presented on the instrument cluster (Fig. 2).

An example of a vehicle-system message is "COOLANT LEVEL LOW", while a non-vehicle-system message could be "HEAVY TRAFFIC AHEAD". Participants were required to provide a verbal answer 'Yes' to indicate if it was a vehicle-system-related message or 'No' to indicate if it was

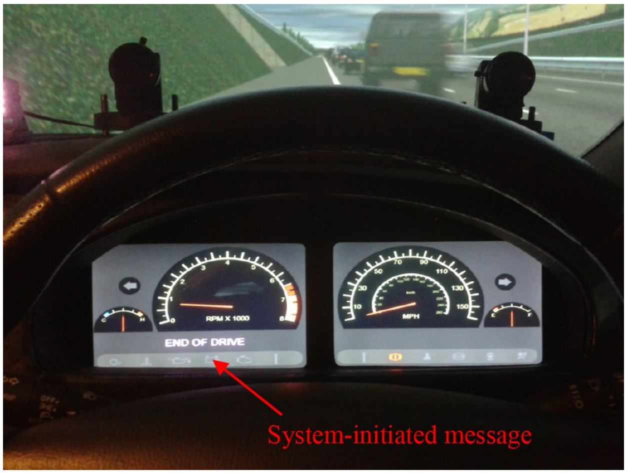


Fig. 2 Location of the system-initiated messages

another type of message. This was defined as the secondary task. The messages were initiated either just before a critical lane change or concurrent with a critical lane change as workload arises not only from each task but also from task switching itself (Pashler 2000). In the concurrent task situation, a driver will have to make an evaluation of the effort required for the secondary task as compared to the effort required for the primary task to decide whether to surrender the secondary task. The principles of resource competition suggest that the concurrent presentation of a secondary task during a critical cut-in requiring accelerator pedal release should produce greater task interference than when presented after the critical cut-in (Wickens 2002). Messages were also presented during no-lane change conditions in each drive to reduce predictability.

Each message appeared for 2.5 s before being overwritten by the next. The message initiation was contingent on the development of the lane change scenario to ensure that the task was performed at the critical moment—that is when the adjacent vehicle initiated the lane change. With each incoming message, an audible 'beep' was presented to alert the driver. Verbal response time was calculated as the time delay between the audible beep and onset of the verbal response. Response errors on the secondary task (number of missed and wrong responses) were also measured.

Table 1 provides an overview of how the secondary task was presented to the participants when the workload manager was either on or off and depending on whether the task was presented before or concurrently with the critical cut-in. Also shown is how the secondary task response times were calculated (SecRT).

In the drive with the workload manager off, no delays to the messages were implemented during the critical cut-in.

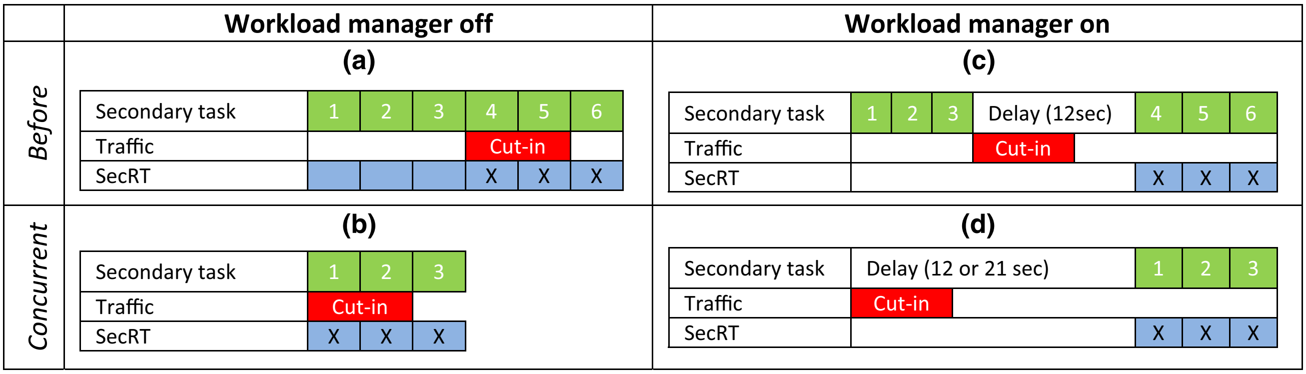
(a) When message onset commenced before the cut-in, in total, six messages were played and the lane change was initiated at the end of the third message. Thus, the driver had to respond to the cut-in during the fourth message. Average response time to the fourth, fifth, and sixth messages was calculated.

(b) For the concurrent cut-in condition, three in-vehicle messages were initiated when the adjacent vehicle started a lane change. Average response time to the first, second, and third messages was calculated.

In the drive with the workload manager on, the messages were managed by delaying them for either 12 or 21 s duration following a lane change. These two values were derived from a previous study (Teh et al. 2018) which ascertained the mean workload recovery period (i.e., defined as the time taken to achieve steady-state workload or baseline workload) following a non-critical and critical lane-change. The minimum workload recovery period was found to be 12 s and the mean was 21 s; these two values were thus implemented as the "workload manager delay".

(a) When message onset commenced before the cut-in, again, six messages were presented, but after the third a delay of 12 s was introduced before the final three messages. Since this constitutes a task interruption, a delay

Table 1 Workload manager design and calculation of secondary task response times



Workload manager off — *Before* — **(a)**

Secondary task	1	2	3	4	5	6
Traffic				Cut-in		
SecRT				X	X	X

Workload manager on — *Before* — **(c)**

Secondary task	1	2	3	Delay (12sec)	4	5	6
Traffic				Cut-in			
SecRT					X	X	X

Workload manager off — *Concurrent* — **(b)**

Secondary task	1	2	3
Traffic	Cut-in		
SecRT	X	X	X

Workload manager on — *Concurrent* — **(d)**

Secondary task	Delay (12 or 21 sec)	1	2	3
Traffic	Cut-in			
SecRT		X	X	X

of 21 s was not used due to the assumption that a task which has been started should be allowed to resume as soon as possible. Average response time to the fourth, fifth, and sixth messages was calculated.

(b) Where the message onset was concurrent with a cut-in, the two delay timings were manipulated, whereby incoming messages were delayed either for 12 or 21 s. Average response time to the first, second, and third messages was calculated.

2.5 Driving performance measures

To evaluate the safety benefits of the workload manager, brake response time (BRT)—defined as the time between the activation of the cutting-in vehicle indicator light to the moment of initial brake pedal depression—was calculated. In addition, the number of trials involving a collision with the cutting-in vehicle was also recorded.

2.6 Subjective workload measures

Two measures of subjective workload were elicited: overall workload (via the NASA-RTLX and RSME) and continuous subjective rating (CSR). Subjective measures are not only to be sensitive to the overall changes in traffic complexity but also more superior than other types of measures in capturing fluctuations in workload (Carsten 2014). The NASA Task Load Index (Byers et al. 1989) is an example of a commonly used subjective mental workload scale which reflects the multidimensional property of mental workload. The NASA-RTLX, a reduced version of the NASA-TLX originally proposed by Hart and Staveland (1988), was developed, because the collection and analysis of the original TLX scale was cumbersome and labour-intensive. It contains six sub-scales and on each a single point is marked to reflect workload. The RSME scale Zijlstra (1993) is a uni-dimensional scale, whereby mental effort is rated on a 150 mm-long vertical line marked with nine anchors points, ranging from 'absolutely no effort' (close to the 0 point), to 'rather much effort' (approximately 57 on the scale) to 'extreme effort' (approximately 112 on the scale). Both the RSME and NASA-RTLX were administered at the end of each drive. Fluctuations in driver workload were measured at various points during the drives via a verbal 10-point rating scale (CSR) as described previously in Teh et al. (2014).

2.7 Procedure

Upon arrival at the simulator, participants were given the briefing sheet and a consent form to complete. They then conducted a practise drive (approximately 15 min) to ensure familiarity with the vehicle controls and the tasks to be conducted. In the practise drive, a series of critical and non-critical lane changes as well as blocks of in-vehicle messages were presented. The participant then performed the two experimental drives. After the completion of the second drive, they were debriefed and paid for their time.

3 Results

Data from 44 participants were compiled to form a database of 1232 lane change events. Each variable was checked for normal distribution and homogeneity of variance using the Kolmogorov–Smirnov test and Levene's tests, respectively. Greenhouse–Geisser correction was applied where necessary. All data were analysed using two-way repeated-measures ANOVA with the lane origin (slow and fast) and workload manager (on and off) as within-subject factors and age as the between factor (younger and older). These tests were applied to all analyses undertaken and, thus, will not be described in detail for each. The BRTs were analysed separately depending on whether message onset was before or concurrent with a lane change.

3.1 Brake response time

3.1.1 Secondary task onset before a critical cut-in

There were significant main effects of Workload Manager [$F(1, 42) = 17.406$, $p < 0.001$] and lane origin [$F(1, 42) = 34.05$, $p < 0.001$) on BRT. With the workload manager on ($M = 1.714$ s), participants responded 263 ms more quickly as compared to when off ($M = 1.917$ s), see Fig. 3. BRTs were quicker when the cutting-in car was joining from the slow lane ($M = 1.53$ s) compared to the fast lane ($M = 2.15$ s). There was no main effect of age.

A significant three-way interaction of lane origin × workload manager × age [$F(1, 42) = 5.494$, $p = 0.024$] on BRT was found and paired-sample *t* tests indicated that when the workload manager was on, both age groups exhibited faster braking performance when the lane change originated from the slow lane (Mdiff older 0.203 s, Mdiff younger 0.380 s). However, for fast-lane cut-ins, improvement in braking performance was only found for older drivers (Mdiff older 0.467 s). This improvement with the workload manager on, brought them in line with the BRT of the younger drivers, in the same scenario.

3.1.2 Secondary task onset concurrent with a critical cut-in

Again, significant main effects of workload manager [$F(1, 42) = 19.61$, $p < 0.001$] and lane origin [$F(1, 42) = 99.83$, $p < 0.001$] on BRT were found. When the workload manager was on and when vehicles pulled in from the slow

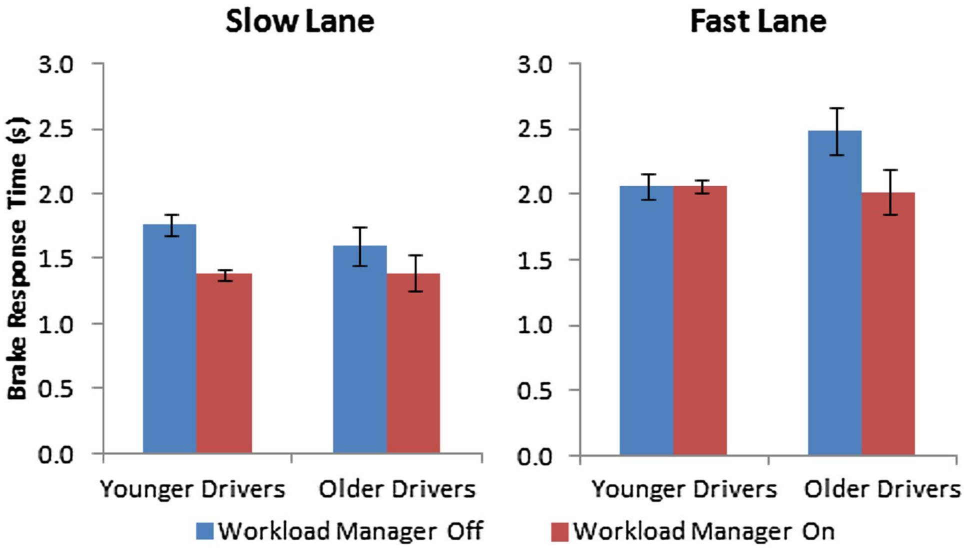


Fig. 3 Brake response time for secondary task onset before a critical cut-in

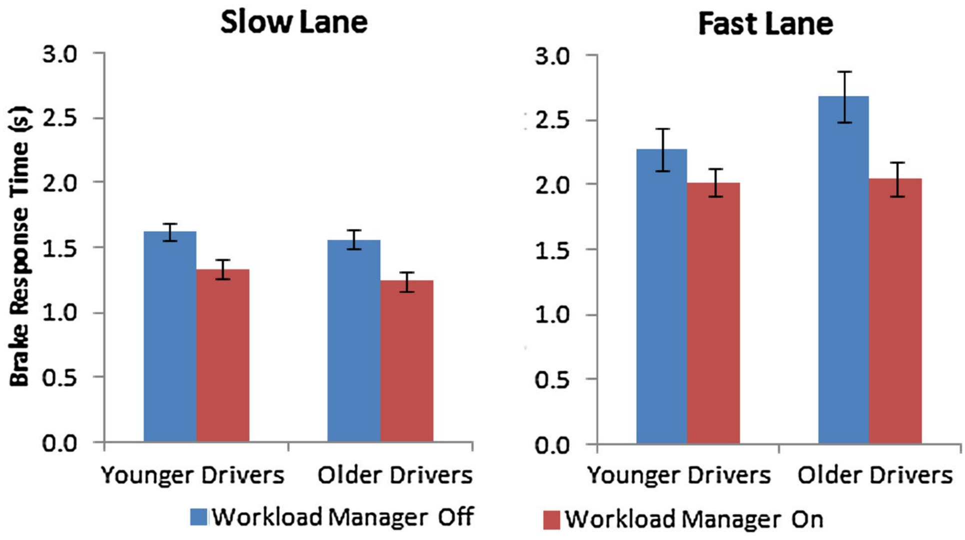


Fig. 4 Brake response time for secondary task onset concurrent with a critical cut-in

lane, BRTs were quicker (see Fig. 4). No main effects of age were found, nor were there any interaction effects.

3.2 Collisions

Only descriptive data are presented, since the number of collisions across the entire experiment is not sufficient to perform statistical analysis. Nevertheless, as demonstrated in Table 2, there was an indication that more collisions occurred when the workload manager was off compared to when the workload manager was on. Further analysis of the number of collisions in the workload manager off condition showed that these could be attributed mainly (85%) to younger drivers.

Table 2 Number of collisions per scenario

Workload manager	Secondary task onset before a critical cut-in		Secondary task onset concurrent with a critical cut-in	
	Number of collisions	% events with collision	Number of collisions	% events with collision
Workload manager off	26	14.77	15	8.52
Workload manager on	2	0.01	0	0.00

3.3 Driver workload

3.3.1 Overall workload

For overall workload, measured via RSME and NASA-RTLX, paired-sample *t* tests were carried out to compare the differences in workload between the two drives (workload manager on or off). Results showed a substantial reduction in average workload ($p < 0.05$) with the use of a workload manager (Fig. 5).

With respect to age, both age groups of drivers reported overall lower workload (as measured by NASA-RTLX and RSME) when the workload manager was on ($p < 0.05$). Although older drivers, in general, provided lower ratings of workload and effort in comparison to the younger drivers in all conditions, the average reduction in workload and effort with the workload manager on was similar between the age groups.

3.3.2 Continuous workload

Momentary workload was elicited via the CSR (collected using the 1–10 point rating scale) at the end of each cut-in event within a drive. These data allowed the examination of differences between slow- and fast-lane cut-ins as well as differences between secondary task onset (before or concurrent with the lane change).

When the secondary task onset came before a critical cut-in, there was a significant main effect of workload manager [$F(1, 42) = 38.22$, $p < 0.001$] with workload being lower when it was active. Lane origin [$F(1, 42) = 47.72$, $p < 0.001$] was also significant, whereby drivers' momentary workload in slow-lane cut-in situations ($M = 5.949$) was higher than for fast-lane cut-ins ($M = 4.778$) (see Fig. 6). Similar to the findings on NASA-RTLX and RSME, a significant main effect of age on workload ratings was also found [$F(1, 42) = 7.107$, $p = 0.011$]. Younger

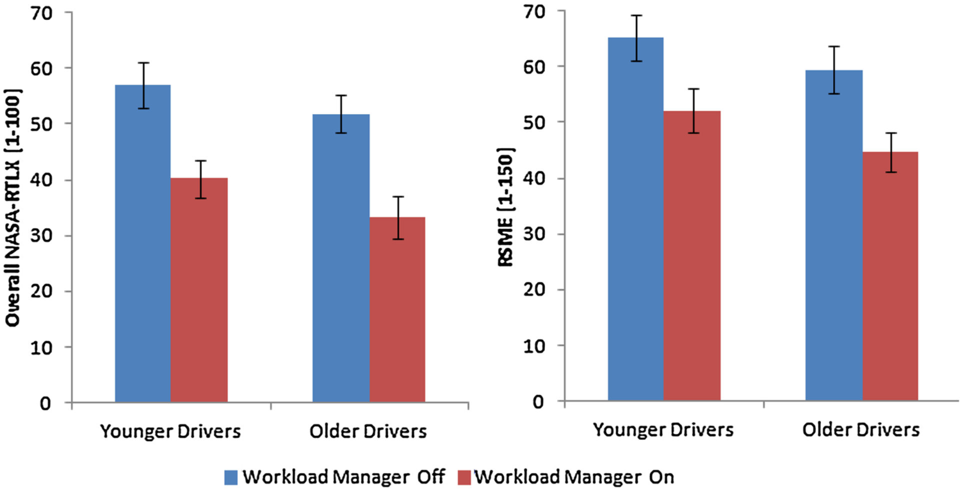


Fig. 5 Workload manager effect on overall NASA-RTLX and RSME

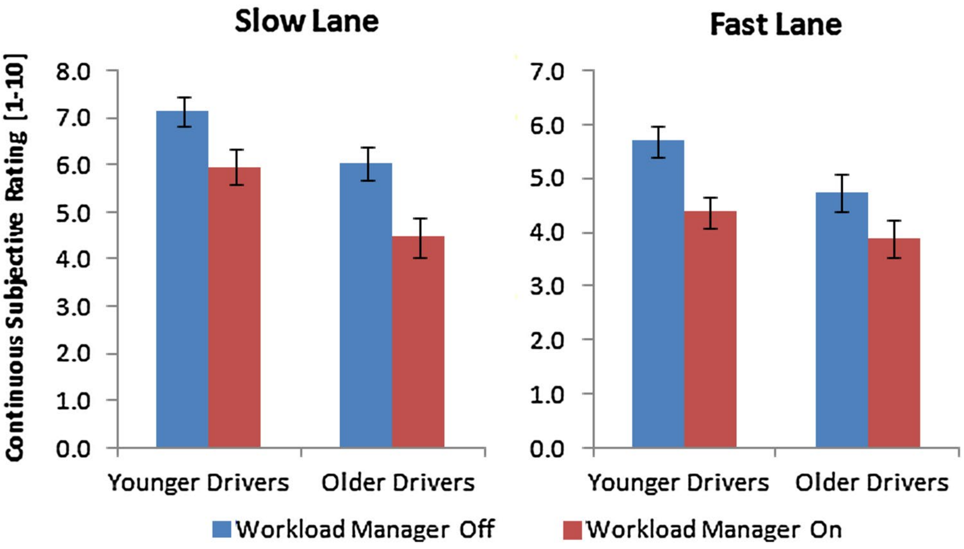


Fig. 6 Continuous workload for secondary task onset before a critical cut-in

drivers in general rated workload higher than the older drivers.

When the secondary task was concurrent with a critical cut-in, a main effect of workload manager was found [$F(2, 84)=36.927$, $p<0.001$]. Reported workload reduced with the increasing delay duration (0 s = 5.726, 12 s = 4.403, 21 s = 3.911); however, pairwise comparisons showed that there was no difference between the two delays (12 and 21 s). Lane origin was also significant [$F(1, 42)=33.915$, $p<0.001$]; workload ratings were higher in a slow-lane critical cut-in ($M=5.442$) as compared to fast-lane critical cut-in ($M=3.918$). Again, older drivers ($M=4.316$) provided a lower rating than younger drivers ($M=5.045$, mean difference 0.729, SE 0.140, $p<0.001$) for all critical cut-in situations (Fig. 7).

3.4 Secondary task performance

A summary of secondary task response times and error rates for younger and older drivers in all dual-task conditions is shown in Fig. 8.

3.4.1 Secondary task onset before a critical cut-in

The secondary task response times prior to a critical cut-in were defined as the baseline, which was then compared with the secondary task response times following a critical cut-in with the workload manager off or on (i.e., 12 s delay). A three-way repeated-measures ANOVA with Workload Manager (baseline, off, and on) and Lane Origin (slow and fast) as within-subject factors and age as the between factor was carried out on the participants' verbal response times. A main effect of Workload Manager was found [$F(2, 84)=123.66$, $p<0.001$], and post hoc testing revealed that response times were slowest when the workload manager was off in the critical cut-in. Lane origin was also significant with response times being slower in a slow-lane cut-in [$F(1, 42)=122.16$, $p<0.001$]. With regards to age, compared to younger drivers, older drivers were found to response more slowly to the secondary task [$F(1, 42)=27.43$, $p<0.001$]. A significant interaction between age and workload manager revealed that the effect of a critical cut-in on response times was particularly strong in older drivers [$F(2, 84)=10.75$, $p<0.001$] as shown by the large increase in response times with the workload manager off.

Analyses of the percentage of errors made on the secondary task revealed a main effect of workload manager [$F(1, 42)=146.89$, $p<0.001$], whereby participants made more errors when the workload manager was off ($M=16.40\%$) than when on ($M=1.57\%$). For Lane origin [$F(1, 42)=73.84$, $p<0.001$], participants performed worse during slow-lane critical cut-ins ($M=13.00\%$) as compared to fast-lane cut-ins ($M=4.97\%$). There was also an age effect [$F(1, 42)=7.14$, $p=0.011$] with older drivers ($M=11.00\%$) making more errors than younger drivers. Age interacted significantly with workload manager [$F(1, 42)=9.21$, $p=0.004$]: both age groups performed poorly with the workload manager off, but a larger percentage of these errors was attributed to older drivers ($M=20.62\%$).

3.4.2 Secondary task onset concurrent with a critical cut-in

A three-way repeated-measures ANOVA with workload manager having three levels (off with 0 s delay, on with 12 s delay, and on with 21 s delay) and lane origin (slow and fast) as within-subject factors and age as the between factor was carried out on the participants verbal response times. There was a significant main effect of workload manager [$F(2, 84)=19.01$, $p<0.001$], whereby participants' response times were the longest when there was no delay provided. On average, response times were 0.2 s faster when a delay was introduced (regardless of length). There was a main effect of lane origin [$F(1, 42)=112.85$, $p<0.001$], such that responses were slower for a slow-lane cut-in and a main effect of age, whereby older participants responded 397 ms slower than younger participants [$F(1, 42)=27.25$,

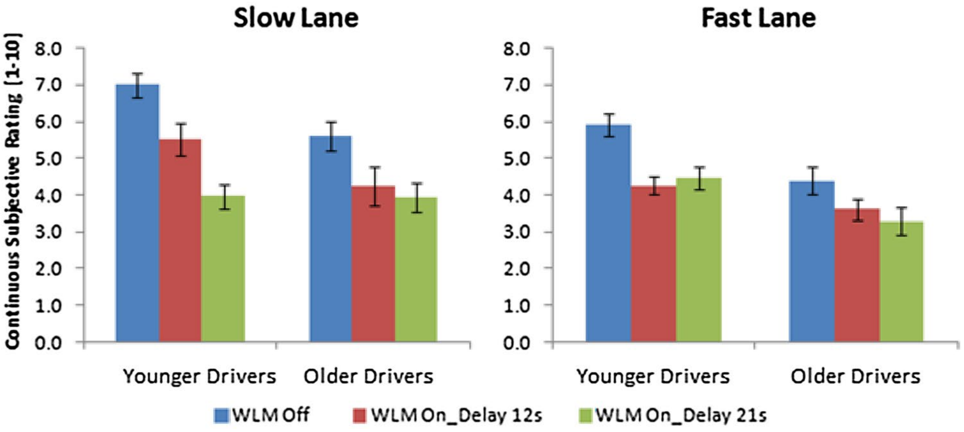
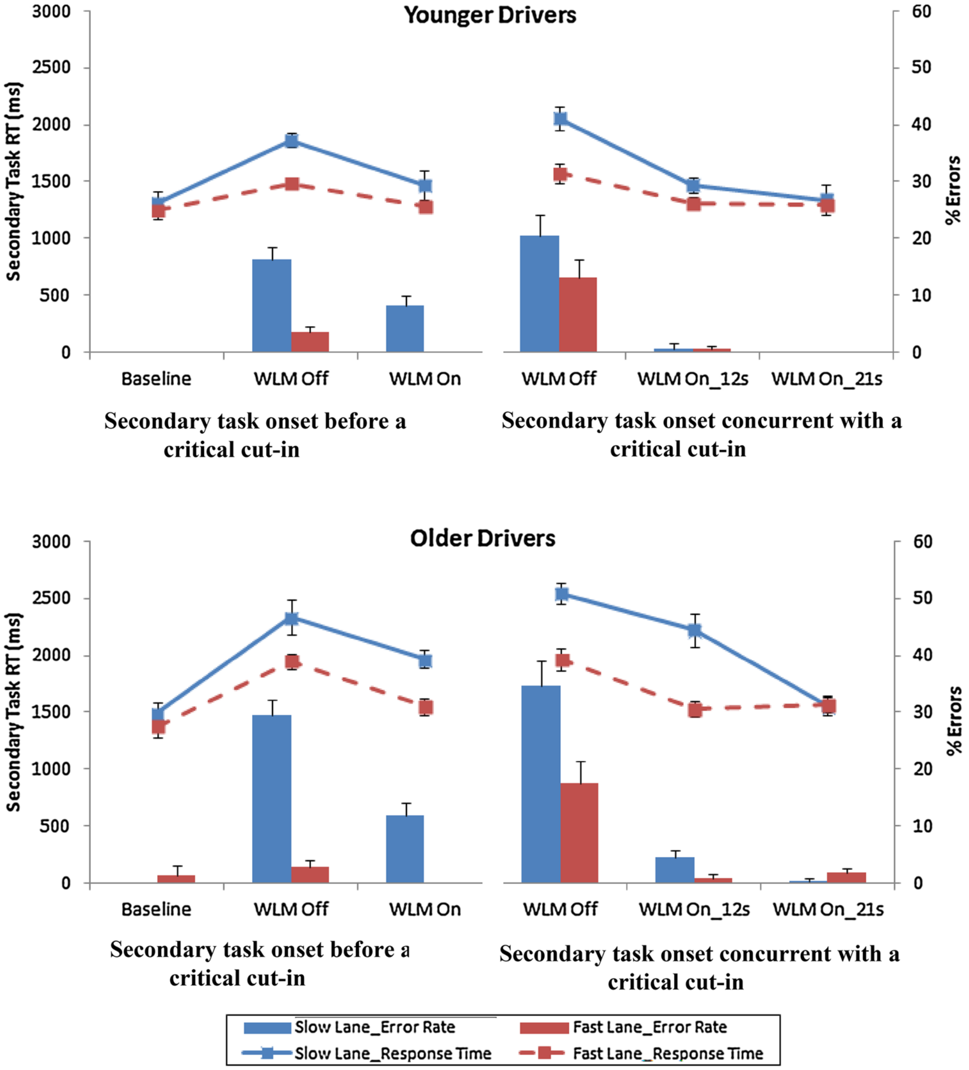


Fig. 7 Continuous workload for secondary task onset concurrent with a critical cut-in

Fig. 8 Mean secondary task response times (with standard errors) with mean percentage error (with standard errors)



$p < 0.001$]. A significant interaction was found between lane origin and workload manager [$F(2, 84) = 23.53$, $p < 0.001$], and to examine the simple effects of the interaction, a one-way ANOVA was conducted on each lane origin. Results showed that while response times reduced with increasing delay, the benefit of longer delay onset (21 s delay) was found only in slow-lane critical cut-ins. Pairwise comparisons showed that the response times for 12 and 21 s delay were not significantly different in fast-lane critical cut-ins.

In terms of percentage error, participants made significantly fewer errors with the workload manager on [$F(2, 84) = 85.57$, $p < 0.001$]. In addition, drivers were also found to make more errors in slow-lane than in fast-lane cut-ins [$F(1, 42) = 21.77$, $p < 0.001$]. Similar to other dual-task conditions, there was also an age effect [$F(1, 42) = 6.50$, $p = 0.017$], whereby older drivers on average had 4.21% more errors than younger drivers. Inspection of the contribution of missed responses in percentage errors by age group indicates that the overall increase of errors in dual-tasking for older drivers is due to their having more misses than younger drivers when simultaneously performing the driving task and the secondary task.

Overall, both age groups of drivers benefited from the workload manager that implemented a delay of 12 s during critical cut-in conditions. Longer delays of up to 21 s had a significant impact on improving drivers' secondary task performance, particularly in slow-lane critical cut-in conditions. Considering that older drivers performed more poorly than younger drivers in the secondary tasks, older drivers may actually benefit more than younger drivers with the implementation of longer delays.

4 Discussion

Various automobile companies are focusing on developing more advanced workload managers which monitor driving performance in real time and help drivers to stay focused on the road during high-demand situations. Although workload managers have been partially developed, to date, they have not taken into account the moment-to-moment demands arising from the external traffic environment. This study investigated how a workload manager might benefit drivers by applying delays to incoming messages, when the demand placed on the driver by other traffic was high. Results showed that drivers' brake response times were impaired by the secondary task, of having to respond to a system-initiated message, suggesting that they were allocating less attention to the surroundings and were thus less aware of the unfolding driving situation. Across all measures of performance and subjective workload, the workload manager was beneficial, although there were varying effects depending on the movement of the surrounding traffic and the age of the participants. The main effects are shown in summary in Table 3, applying equally to both secondary task timings (concurrent and before vehicle cut-in) and the significant interactions are discussed in the following.

The secondary task alert was given either before a lane change or concurrently with it, and under both conditions without a workload manager, brake response times were around 2.04 s and decreased to 1.66 s when the workload manager was active. With the use of a workload manager, the requirement to respond to both tasks simultaneously can be avoided; with this assistance, there was also a reduction in driver workload. In addition, there was a trend towards drivers being involved in a fewer collisions when the workload manager was on, as they could now allocate more attention to the primary task of driving. A delay of 12 s in the secondary task was found to be useful in reducing driver workload and improving driver performance, and findings from this study suggest that implementation of such a delay was appropriate for all critical cut-in situations (i.e., regardless of whether the adjacent vehicle originated from the slow lane or the fast lane).

There was also evidence of how different age groups behaved in dual-task conditions. For example, when comparing the BRTs for the two different age groups, older drivers performed more slowly in both driving and secondary tasks, as compared to the younger drivers. Older participants were more affected by dual-task performance, showing longer secondary response times and poorer performance (i.e., a higher error rate) in the secondary task in comparison to the younger drivers. They appeared to surrender performance on the secondary task at a high workload level as indicated by a high percentage of missed signals on the secondary task compared to younger drivers. Although this suggests that these older drivers might not have the resources for task switching, they did manage the dual-tasking to some extent. Gwyther and Holland (2012) had shown that, with controlled driving experience, older drivers do perform greater self-regulation than younger drivers. Older drivers needed more time to inspect the visual messages on the dashboard and, therefore, have partly given up the secondary task and focused on the driving task. However, this also indicates that they were more cautious in driving as older drivers were also involved in fewer collisions as compared to the younger participants despite slower reaction times. This is possibly due to the higher number of years of driving among older drivers despite the fact that both age groups had similar annual mileage. With greater driving experience and perhaps due to older drivers choosing to surrender the secondary task, they had also experienced lower levels of effort in completing the driving task (i.e., lower rating in RSME, NASA-RTLX, and CSR) in comparison to younger drivers who chose not to surrender the secondary task.

Participants of both age groups benefitted from the use of a workload manager (i.e., delay of the in-vehicle messages) in all critical cut-in situations via an improvements in workload and driving performance. In addition, the percentage of collisions among the younger drivers was also reduced. This suggests that the use of a workload manager in these dual-task situations may have merit not only for older drivers but also for the younger drivers, who may, otherwise, be overwhelmed by the workload arising from the two tasks.

5 Conclusion and recommendations

This work has demonstrated that alerting drivers to potential safety–critical scenarios (in a manner that does not unwittingly increase workload) warrants further investigation. This is particularly relevant given the current technological limitations of radar used in forward collision warning systems. These are currently limited to operational

Table 3 Summary of main effects

	Workload manager On	Lane origin Slow	Age Older
Brake response time	Quicker	Quicker	No effect
NASA/RSME workload	Lower	N/A	Lower
Continuous workload	Lower	Higher	Lower
Secondary task response time	Quicker	Slower	Slower
% Error on secondary task	Less	More	More

millimeter wave (short range) radar and laser radar systems with a horizontal field of view of up to ± 15°, while horizontal field of view for a vision-based system might be ± 30° to ± 40°. When an obstacle appears suddenly in a driver's path, such as in critical scenarios involving lane changes performed by a neighbouring vehicle, a forward collision warning system would, perhaps, need to present drivers with an additional alert to refocus their attention more quickly.

The previous research by Donmez et al. (2006) demonstrated that drivers trust visual feedback the most due to their reliance on sight throughout their daily lives. Visual feedback requires a high level of driver attention and is most effective in vehicles when combined with another form of feedback (Dingus et al. 1997). Auditory feedback can also produce excellent results when used as a driver warning feedback method (Jensen et al. 2007) and was found to reduce crash rate especially for older drivers (warning tone of 1000 Hz; May et al. 2006). Some studies, however, have shown auditory warnings to lengthen reaction times and to be the cause of confusion when combined with auditory disturbances such as road noise (Wiese and Lee 2004). To direct a person's attention to a particular location (such as the forward view), studies have indicated a cross-modal connection in spatial attention between vision and touch (Butter et al. 1989; Spence and Driver 2004). Tactile warning signals not only can direct driver's attention to the spatial direction, but also can trigger a driver to respond appropriately (such as a braking response). Ho, Reed, and Spence (2006) demonstrated that incorporating vibrotactile feedback (with vibrotactile frequency of 290 Hz) through tractors fastened to the driver's stomach and back, decreased braking response times, and directed visual attention to the appropriate location, thus helping to prevent front and rear-end collision. Such haptic alerts via the steering wheel have proven effective in reducing reaction times for lane departure (Suzuki and Jansson 2003) and improvement in avoiding hitting obstacles when introduced a supplemental feedback to the driver. Therefore, in the presence of a critical lane change performed by a neighbouring vehicle, there may be benefits in providing a vibrotactile cue to alert the driver of the potential danger and to provide time-critical information. With the use of such alerts, drivers' reaction times to braking may, perhaps, improve further, particularly to those who were busy dual-tasking in the event of a critical cut-in.

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