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Driver distraction in an unusual environment: Effects of text-messaging in tunnels

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ABSTRACT

Text messaging while driving can be distracting and significantly increases the risk of being involved in a collision. Compared to freeway driving, driving in a tunnel environment introduces factors that may interact with driver attentional resources to exacerbate the effects of distraction on driving safety. With planning and design of the 18 km Stockholm Bypass tunnel ongoing, and because of the potentially devastating consequences of crashes in long tunnels, it is critical to assess the effects of driver distraction in a tunnel environment.

Twenty-four participants (25–50 years) drove in simulated highway and tunnel road environments while reading and writing text messages using their own mobile phones. As expected, compared to driving alone, text messaging was associated with decrements in driving performance and visual scanning behavior, and increases in subjective workload. Speeds were slower compared to baseline (no text-messaging) driving when participants performed the text-messaging tasks in the tunnel environment compared to the freeway, suggesting that drivers may have attempted to compensate more for the increased text-messaging-related workload when they were in the tunnel. On the other hand, increases in lane deviation associated with the most complex text-messaging task were more pronounced in the tunnel compared to on the freeway. Collectively, results imply that driver distraction in tunnels is associated with generally similar driving decrements as freeway driving; however, the potential consequences of these decrements in tunnels remain significantly more serious. Future research should attempt to elucidate the nature of any differential compensatory behavior in tunnel, compared to freeway, driving. In the meantime, drivers should be advised to refrain from text messaging, especially when driving in tunnels.

1. Introduction

A new tunnel project is currently underway in Sweden. The Stockholm Bypass is a new motorway linking southern and northern Stockholm, which when completed in 2020 will be approximately 18 km in length, making it one of the longest road tunnels in the world. The Swedish Transport Administration estimates that, by 2035, the Bypass will be used by approximately 140,000 vehicles per day (STA, 2011).

Although crash risk associated with tunnel environments is lower than that associated with open roads (Carvel and Marlair, 2005), safety measures are a high priority in tunnels because the consequences of traffic collisions can be far more devastating than in open-air surroundings. In particular, fire and asphyxiation are major concerns (Ministry of the Interior, 1999). It is therefore of highest importance to explore mechanisms by which to improve crash avoidance in tunnels. Only a handful of studies to-date has explored driver behavior in simulated tunnel conditions (Kircher and Ahlstrom, 2012; Manser and Hancock, 2007; Vashitz et al., 2008; Törnros, 1998).

The physical characteristics of tunnels differ from those of freeways. Most obviously, the presence of walls and a ceiling in tunnel environments limits visual complexity in terms of variety, color, and texture. Further, because they are enclosed, tunnels tend to be darker than freeways (at least during daylight hours); however, recent improvements in tunnel lighting and design have been used to create tunnels that are more appealing to drivers than previously (Jones, 2007).

Driving performance in tunnels differs from freeway driving in a number of important ways. Because of the enclosed environment, tunnel driving affects driving demand and workload by increasing the effort required to maintain lateral control of the vehicle and by increasing the frequency of driver eye fixations to the center of the road (Beall and Loomis, 1996; Chatziastros et al., 1999; Shimojo et al., 1995). Drivers may adopt lower vehicle speeds and rate

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workload as higher in tunnels compared to on freeways because of the increased rate of optic flow in their peripheral visual field (Gibson, 1979), which leads to the mistaken perception that the road is more narrow (Lotsberg, 2001) and would similarly be expected to result in slower speeds (Godley et al., 1999). Strong evidence exists showing that vehicle velocity decreases with narrowing road width, while the number of erratic lateral maneuvers increases (Godley et al., 1999; OECD, 1990). Interestingly, the change in road width does not need to be perceived by drivers to produce the slower speeds. For example, when road width was manipulated in a driving simulator, the reduced speeds adopted on narrower roads were accompanied by drivers' increased ratings of risk despite their inability to identify any change in road width (Lewis-Evans and Charlton, 2006). In a simulator study of tunnel driving, tunnel wall visual pattern and texture were demonstrated to have clear attenuating effects on drivers' speed choice (Manser and Hancock, 2007). Similarly, findings of a recent simulator study were suggestive of an interaction between tunnel illumination and driver's visual distraction on lateral deviation within the lane (Kircher and Ahlstrom, 2012). There are, up until now, no studies that have compared tunnel and open road environments in a systematic way; however, there are reports of higher average speeds on freeways *vs.* tunnels with similar geometric characteristics and within the same speed zone (Diamantopoulou and Corben, 2001).

Driver distraction has been demonstrated, in on-road naturalistic studies, to be significantly associated with an increase in crash risk (Klauer et al., 2006), and therefore provides an area of crash causation on which to focus. Drivers who use mobile devices to send and receive text messages are at an increased risk of collision (Klauer et al., 2006; Olson et al., 2009), making this behavior of particular concern to road safety authorities worldwide. In Sweden, where there are legal requirements for drivers to maintain due care and attention but no laws specifically limiting the use of mobile phones while driving, 28% of over 3000 drivers surveyed in 2010 reported engaging in text messaging while driving, with 46% of these drivers being aged between 18 and 29 (If, 2010). Similarly, in Victoria, Australia, a large proportion (≅25%) of drivers admit to sending and receiving text messages while driving, despite a long-standing ban on that behavior (Young and Lenné, 2010). These online survey data reveal that 88% of young drivers who use a handheld mobile phone while driving reported *reading* text messages, while 77% admitted to *sending* text messages. Observational survey data support these rates of use. A recent roadside survey found a significant proportion (3.4%) of drivers to be engaged in handheld mobile phone use, including text-messaging (1.5%), at intersections in Melbourne (Young et al., 2010; Rudin-Brown et al., 2009). In line with other reports, younger (<30 years) drivers were over five times more likely than older (50+ years) drivers to be observed text-messaging (Young et al., 2010).

Not surprisingly, while driver distraction is associated with a number of decrements in driving performance, the visual–manual demands associated with mobile phone use, and of text messaging in particular, appear to have particular effects on performance measures involving supervision, or monitoring, of vehicle parameters (Victor et al., 2009). Lateral position metrics are particularly affected, with many studies demonstrating that dialing a mobile phone leads to significant deviation in drivers' lateral position and increased steering wheel movements (Brookhuis et al., 1991; Green et al., 1993; Horrey et al., 2006; Reed and Green, 1999; Törnros and Bolling, 2005). It is not only the biomechanical interference that affects steering behavior; when visual attention is drawn away from the forward scene to a mobile phone, drivers tend to maintain more of a fixed steering position, leading to over-corrections, weaving within the lane, and lane departures (Brookhuis et al., 1991; Törnros and Bolling, 2005). Similarly, texting places demands on visual attention that result in drivers having to switch their attention between activities, rather than sharing attention to two tasks at the same time. Driving simulator evaluations of text messaging have found that both sending and reading text messages negatively affects drivers' ability to control lateral position and their response to traffic signs (Drews et al., 2009; Hosking et al., 2009). Reading text messages *vs.* writing text messages may also have dissimilar effects on driving performance measures. Manual interaction with a mobile phone is associated with increased reaction times to peripheral stimuli and more missed traffic signals (Brookhuis et al., 1991; Törnros and Bolling, 2005), whereas reading text messages impairs drivers' reaction time to a lead vehicle's brake lights more so than composing texts (Drews et al., 2009).

The focus of the present simulator study was on driver distraction in the context of tunnel driving. More specifically, it sought to investigate the effects of text messaging on driving performance and driver visual behavior in tunnel *vs.* freeway environments. It was hypothesized that:

H1. Compared to on the freeway, driver distraction in the tunnel environment would be associated with differences in driving performance measures, including slower speeds, a more central position in the lane with less lane deviation, more glances of shorter duration to the mobile phone, and increased subjective workload; and

H2. Regardless of road environment, compared to driving alone, driving while text messaging would be associated with significant differences in driving performance measures, including more variable lateral control of the vehicle, slower and more variable vehicle speeds, fewer glances to the roadway, and increased subjective workload. Further, compared to *reading* a text message, the combined task of *reading and writing* a text message while driving would further exacerbate the expected differences in performance.

2. Method

2.1. Experimental design

A two-way (2 × 3) repeated measures design with road environment (tunnel *vs.* freeway) and task (Baseline, Texting—read only, and Texting—read and write) as within-subjects factors was used to test the two study hypotheses. To assess drivers' performance on the text-messaging tasks, speed and accuracy of text-messaging served as dependent variables. For driving performance, dependent variables included vehicle speed and speed variability, and standard deviation of lane position (SDLP). To investigate driver visual behavior during text-messaging, the percent of drivers' total gaze time on road centre *vs.* on the mobile phone (during text-messaging conditions) were used as dependent measures. Finally, to assess drivers' perceived workload between the road environments and across text-messaging tasks, ratings of subjective workload served as the dependent variable. Order of presentation of road environment was counterbalanced across participants, and order of task presentation was counterbalanced within each road environment.

2.2. Participants

Twenty-four licensed drivers aged between 25 and 50 years (mean = 33, SD = 10) who considered themselves to be "regular users of text messaging services" (mean number of minutes per week = 100, SD = 100) participated in the study. The decision to recruit a cross-section of 'middle aged' drivers was made to allow the assessment of a range of driver ages, with the within-subjects study design ensuring that each acted as their own control. Studies on the effects of age on driving behavior have shown that effects are gradual and tend to be limited to very young (*i.e.*, teenagers aged 16–19) or very old (*i.e.*, >75) drivers, whereas the effects of

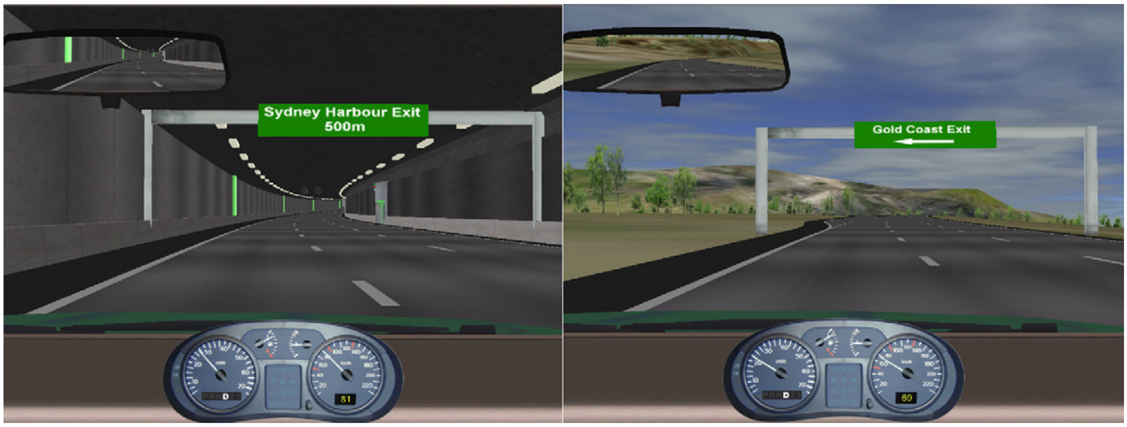

Fig. 1. Simulated road environments: tunnel (left) and freeway (right).

inexperience are much more significant (McCartt et al., 2009; Koppel et al., 2011). With that in mind, an attempt was made to minimize any potential effect of age on driving performance by limiting participant age range to only 'middle aged' drivers (*i.e.*, those between the ages of 25 and 50), who were also full driver's licence holders, thus avoiding young and old extremes. Likewise, while gender was not an independent variable of interest in this study, it was important to recruit an equal number of men and women in order to ensure the sample was representative of the broader driver population. Half of the participants used a keypad mobile phone and half used a touch screen phone to carry out the text messaging tasks. All participants were required to have held a valid driver's license for at least three years, and to have normal or corrected-to-normal vision. Participants were recruited through advertisements at Monash University. Ethics approval for the study was obtained from the Monash University Human Research Ethics Committee. Participants were compensated $30 AUD for their time.

2.3. Equipment

Participants used their own mobile phones for the text-messaging task. By ensuring that drivers were familiar with the functionality of the phone, the potentially confounding influence of phone unfamiliarity was minimized. Driving performance was evaluated using the MUARC advanced driving simulator—a high fidelity, motion-based simulator consisting of a 2009 GM Holden VE Commodore sedan mounted on a three degrees-of-freedom motion base platform, and a curved projection screen providing a 180° horizontal, and 40° vertical, field-of-view. Forward vision was produced by three image generators using seamless blended projection onto a cylindrical screen, while rear vision was provided by a separate projection screen at the rear of the vehicle. Simulated, speed-adjusted engine and road/tyre noise was present in all scenarios. An experimenter controlled all driving simulations remotely from a control room.

FaceLab™ (Seeing Machines Ltd., Canberra, ACT) measured drivers' visual scanning behavior. This system comprised two unobtrusive cameras set on the dashboard that were calibrated for angles and depth of the seated driver in order to establish movement parameters of the eyes and head in three dimensions. Camera images and recordings were linked to a user-operated computer interface, allowing for post-drive analysis of glance location and duration.

2.4. Procedure

Upon their arrival at the simulator laboratory, participants signed an informed consent form and filled out demographics and general driving questionnaires. Participants were told that the purpose of the study was "to study the effects of performing distracting tasks on driving behavior". The first exposure to the driving simulator was a 10-min familiarization drive. This drive allowed participants to experience the virtual driving environment and the control dynamics of the simulated vehicle. Participants were instructed to practice accelerating and braking gently, and to practice driving at a consistent speed of 80 km/h.

After the familiarization drive, the simulator was configured for the first of two 7-km test drives comprised of either a tunnel or freeway environment (see Fig. 1). Both environments used exactly the same road geometry, including road curvature, gradient, number of lanes (3), and lane width, and were designed according to the blueprints of a section of the Stockholm Bypass tunnel and adapted for right-hand drive traffic. Pilot testing confirmed that there were no features of either environment that would be interpreted as novel or unusual for Australian drivers. Same direction ambient traffic (approximately 3–4 vehicles per km, on average) was present during each test drive, but not within the participant's lane. Participants were instructed to drive in the left-hand (outside) lane, and to maintain a consistent speed of 80 km/h throughout the drive, with the experimenter providing verbal reminders if participants were observed to deviate more than 5–10 km/h from that speed. They were also directed not to interact with any traffic in adjoining lanes. Each scenario included two sets of overhead traffic signs, one in each road environment: the first sign in each set indicated the approach of an exit in 500 m, and the second was located directly preceding the exit. These signs were included in the scenarios as the 'read only' text-messaging task instructed participants to take a specific exit. Each test drive took approximately 10 min to complete. In between the two test drives, participants were given the opportunity to take a short break.

Each participant received two text messages in each test drive. In the 'read only' condition they received a traffic information message *via* text message instructing them to take the next exit (*e.g.*, "Heavy traffic—Long delays expected. Take Sydney Harbour exit in 1 kilometer"). There were no specific instructions provided to participants before each drive to follow the guidance of the traffic information text message, only that they were to read the message out loud. The 'read and write' condition consisted of a text message asking participants a general-knowledge question (*e.g.*, "What is the capital of Victoria?"), to which they were required to respond by means of composing a text message after having first read the message out loud. Participants could use the predictive text function of the telephone if they reported being regular users of this feature. At the end of each test drive, participants completed a modified version of the NASA Raw Task Load Index (NASA-RTLX) (Hart and Staveland, 1988), which assessed, using a rating scale from 0 to 20, subjective ratings of workload for the task of driving either alone (baseline condition) or combined with performing the text messaging tasks. Upon completion of the second test drive, participants were thanked and paid for their time. Each test session took approximately 1.5 h. All testing was conducted between the hours of 9:00 am and 6:00 pm.

2.5. Statistical analyses

Two-way (2 × 3) repeated measures analyses of variance (ANOVAs) with road environment (tunnel *vs.* freeway) and task (baseline, 'read only', and 'read/write'), as factors were carried out on driving performance, visual behavior, and subjective workload, data. Effect size is listed as partial Eta squared (partial η^2), demonstrating the proportion of the total variance explained by a variable that is not explained by other variables. A partial η^2 of .01 would be considered to be a small effect size, .06 a medium effect size, and .14 a large effect size (Richardson, 2011). Prior to all analyses, data were checked for violations of statistical assumptions, outliers and missing data points, and were removed from the analysis. In all cases, a two-tailed α-level of .05 was used to determine statistical significance. In those cases where an observed α-level approached statistical significance (*i.e.*, those with values between .05 and .10), observed power is also reported. Observed power can be used to assist in interpreting a result; in particular, whether or not a larger sample size would have been likely to improve the significance level (Rosnow and Rosenthal, 1989). The reader is nevertheless cautioned to interpret these effects with caution. Driving and visual scanning data was missing for one participant in the tunnel condition due to the participant crashing at the beginning of the scenario (it was not possible to subsequently re-start the scenario). In this instance, the participant vehicle struck the tunnel wall while the participant was reading the first text message.

3. Results

3.1. Performance on secondary (text messaging) tasks

There was no effect of road environment on the time it took participants to perform the 'read only', $F(1,16) = .68$, $p > .05$, or the 'read/write', $F(1,16) = 1.7$, $p > .05$, text messaging tasks. A similar proportion of participants in the tunnel *vs.* freeway environments answered correctly in their written text messages, $\chi(1) = .312$, $p > .05$.

3.2. Driving performance.

To compare the secondary (text messaging) task conditions, driving performance data collected throughout the baseline condition were compared to data collected during segments where drivers were performing the two text messaging tasks.

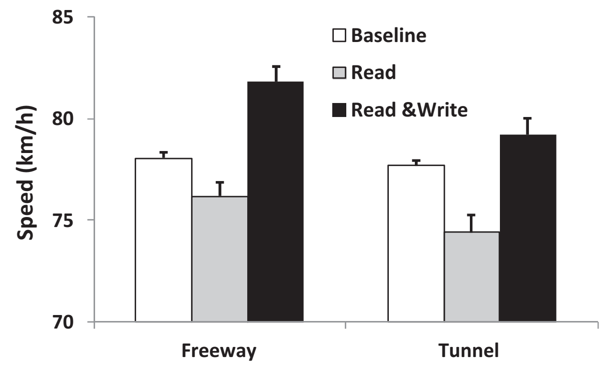

Fig. 2. Interaction between road environment and task type on vehicle speed (all conditions significantly different at $p < .05$; error bars represent standard error of the mean [sem]).

3.2.1. Speed and speed variability

The interaction between road environment and task type was significant for vehicle speed, $F(2,44) = 3.66$, $p < .05$, $\eta^2 = .14$, with participants driving faster in the freeway environment compared to the tunnel when performing both text messaging tasks (Fig. 2). This interaction underlay main effects of road environment $F(1,22) = 11.57$, $p < .01$, $\eta^2 = .35$, and task type, $F(2,44) = 29.0$, $p < .001$, $\eta^2 = .57$. Participants drove faster overall in the freeway environment compared to the tunnel (Fig. 3, left panel), and when performing the 'read/write' task compared to both baseline and 'read only' tasks, and in the baseline condition compared to the 'read only' task (Fig. 3, right panel).

Although not statistically significant, there was a trend for drivers to demonstrate more speed variability when driving in the tunnel, compared to the freeway, environment, $F(1,22) = 3.36$, $p = .08$, $\eta^2 = .13$, observed power = .42 (Fig. 4, left panel). There was also a significant main effect of task type on the standard deviation of speed, $F(2,44) = 17.2$, $p < .001$, $\eta^2 = .44$, with variability being greatest in the 'read only' condition compared to both baseline and 'read/write' tasks, and in the 'read/write' task compared to baseline (Fig. 4, right panel).

3.2.2. Lateral deviation

The interaction between road environment and task type for standard deviation of lane position was statistically significant, $F(2,46) = 3.2$, $p < .05$, $\eta^2 = .12$, with drivers deviating more within the lane during the 'read/write' condition when in the tunnel compared to when on the freeway (Fig. 5, left). The interaction underlay a main effect of task type, $F(2,46) = 9.9$, $p < .001$, $\eta^2 = .30$, with participants deviating significantly more within the lane when performing the 'read/write' task than when performing the 'read only' task and

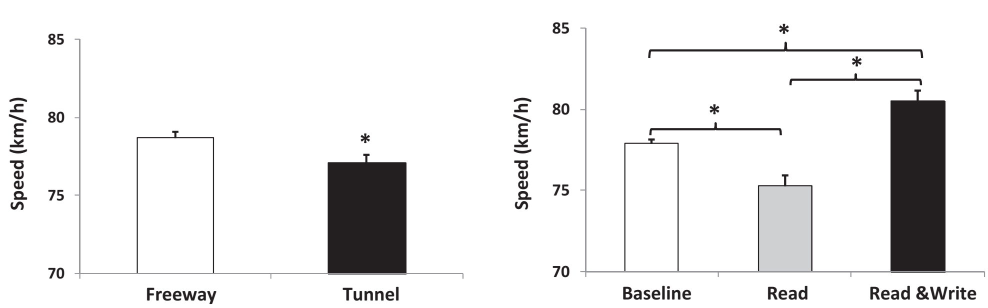

Fig. 3. Effect of road environment (left) and task type (right) on vehicle speed (*$p < .01$; error bars represent sem).

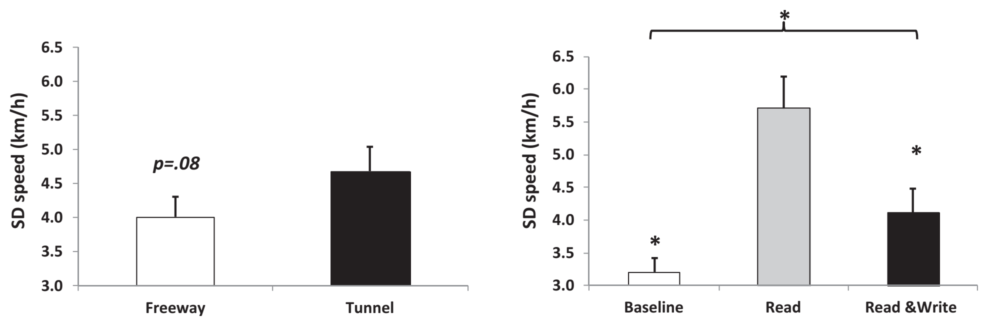

Fig. 4. Effect of road environment (left) and task type (right) on speed variability (standard deviation of speed) (*$p < .01$; error bars represent sem).

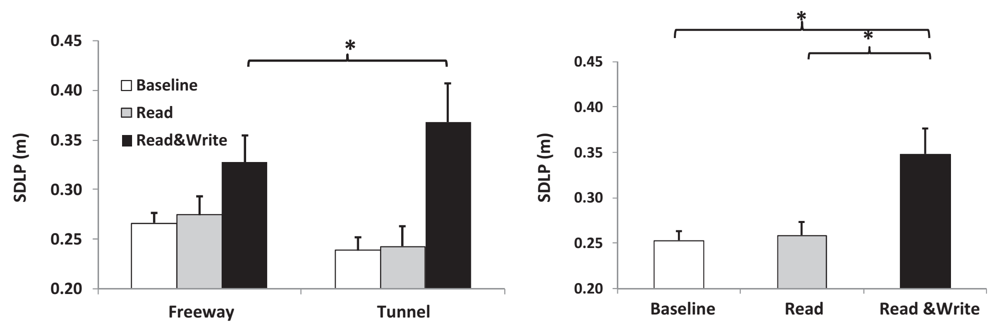

Fig. 5. Interaction between road environment and task type (left) and main effect of task (right) on standard deviation of lane position (SDLP) (*$p < .05$; error bars represent sem).

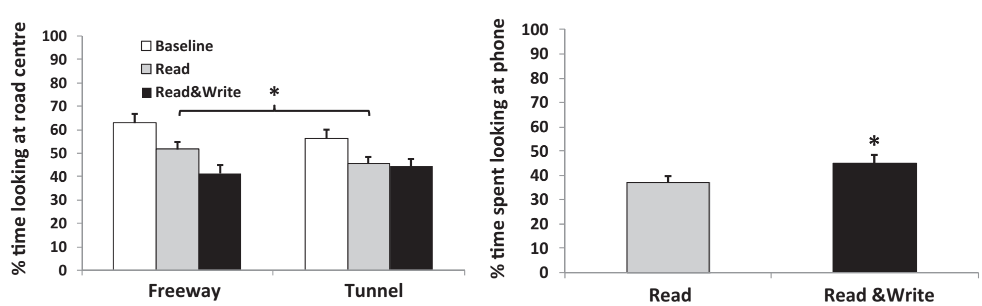

Fig. 6. Percent of time spent looking at road centre (left) and at mobile phone (right) during performance of text messaging tasks (*$p < .05$; error bars represent sem).

when performing no task (Fig. 5, right). There were no effects of road environment on SDLP.

3.3. Visual scanning behavior

Two indices of visual scanning behavior were generated from the FaceLab™ data: percent of total time that a participant's gaze was directed toward the center of the roadway[1] (when performing the text messaging tasks compared to baseline driving), and percent of total text messaging task completion time that a participant's gaze was directed toward the mobile phone (when performing the text messaging tasks only). The interaction between road environment and task type for Percent Road Center approached statistical significance, $F(2,44) = 3.08$, $p = .056$, $\eta^2 = .12$, observed power = .57, with both road environments associated with less time with eyes on road center during the 'read only' condition than during baseline driving, and less time again during the 'read/write' task compared to 'read only'. However, participants made fewer glances toward the center of the roadway when they performed the 'read only' task in the tunnel environment compared with when they performed this task on the freeway ($p < .05$) (Fig. 6, left). There was a significant main effect of task type on percent of glance time made to road center, $F(2,44) = 12.7$, $p < .001$, $\eta^2 = .37$, with drivers looking at road center for a larger proportion of time during the baseline condition than when performing the 'read only' and the 'read/write' tasks, and more again during the 'read only' task compared to the 'read/write' task. The opposite pattern was observed for the percent of time spent with the gaze directed toward the mobile phone, $F(1,22) = 6.1$, $p < .05$, $\eta^2 = .22$, with a significantly greater proportion of time spent looking at the phone during the 'read/write' task compared to the 'read only' task (Fig. 6, right). There were no main effects of road environment on either measure of visual scanning behavior.

3.4. Subjective workload

At the end of each test drive, participants completed a modified version of the NASA-RTLX (Hart and Staveland, 1988), which assessed subjective ratings of workload for the task of driving either alone (baseline condition) or combined with performing the text messaging tasks. The NASA-RTLX was completed separately for the

[1] Percent Road Center was calculated as the sum of all gazes above dashboard and within ±8° of horizontal field of view divided by the sum of all gazes during that segment.

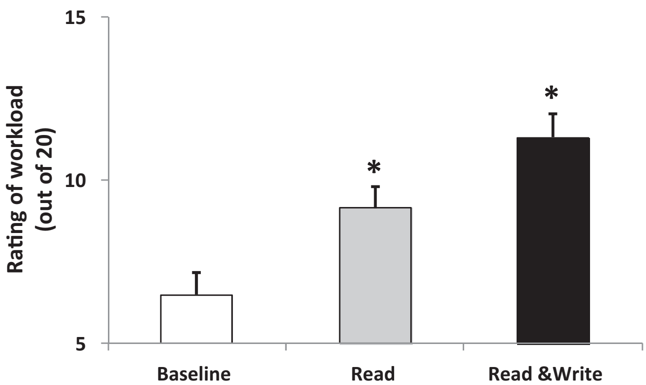

Fig. 7. Effect of task type on subjective workload (*$p < .001$; error bars represent sem).

freeway and tunnel segments of the drive. There was a significant main effect of task type on overall workload rating, $F(2,46) = 34.3$, $p < .001$, $\eta^2 = .60$, with participants rating their workload as greater when performing the 'read only' task compared to baseline, and as significantly greater when performing the 'read/write' task compared to the 'read only' task (Fig. 7). There were no effects of road environment on subjective workload ratings.

4. Discussion

Collectively, results demonstrate that reading and writing text messages while driving in both tunnel and freeway environments distracts drivers. When performing the text messaging tasks, drivers showed poorer lateral vehicle control, exhibited changes in vehicle speed and speed variability, spent a reduced proportion of time looking at the roadway ahead, and rated their subjective workload as higher. The effects of text messaging on distraction generally do not appear to be selective to one environment over the other. However, there was a tendency for drivers to drive slower when they were performing the text-messaging tasks in the tunnel, and to deviate more within the lane when most distracted (performing the 'read/write' task) in the tunnel compared to the freeway.

With respect to the first study hypothesis—that distraction in tunnels would be associated with differences in driving performance measures compared to freeway driving—two driving performance measures showed selective effects of the tunnel. Drivers drove slower compared to baseline driving when they were distracted (performing the text-messaging tasks) in the tunnel compared to when performing the same tasks on the freeway. The relatively greater reduction in speed in these task conditions in the tunnel may reflect drivers' attempts to compensate more for the distracting effects of text-messaging in the tunnel (Fuller, 2005), which would be expected based on previous research showing higher demand and estimations of risk in tunnels than on freeways (Beall and Loomis, 1996; Chatziastros et al., 1999; Shimojo et al., 1995). However, subjective workload ratings of the two road environments across the text-messaging tasks did not differ, suggesting that participants were either not aware of any difference in perceived risk, or that the workload instrument was not able to accurately measure it.

Increases in lane deviation associated with the most complex text-messaging task were more pronounced in the tunnel compared to on the freeway. This finding suggests that drivers were less able to effectively monitor the vehicle's position in this task condition, which has also been observed when drivers manually dial a mobile phone (Brookhuis et al., 1991; Törnros and Bolling, 2005) and in simulated tunnel driving when using a visual in-vehicle information system (Vashitz et al., 2008). An increase in lateral deviation in the tunnel environment compared to the freeway would not be expected if drivers were attempting to compensate more for the added workload in this environment (Fuller, 2005). It is possible that drivers used vehicle speed, and not lateral positioning, as the primary mechanism through which they maintained an acceptable level of task difficulty, or risk—a possibility that would be predicted by the task-capability interface (TCI) model of driver behavior (Fuller, 2005), which views speed as the "primary solution to the problem of keeping task difficulty within selected boundaries" (p. 461). The increased lateral deviation in the tunnel under the most demanding 'read/write' task may instead reflect drivers' attempts to overcorrect for unintended drifts in lane position caused by drivers looking proportionally less at roadway centre, a possibility that is supported by previous research on the effects of handheld mobile phones on simulated driving (Reed and Green, 1999).

As expected, the second study hypothesis—that, regardless of road environment, compared to driving alone, driving while text messaging would be associated with significant differences in driving performance measures—was supported. Text messaging was associated with effects on several measures of driving performance that provide an indication of the impact that driver distraction has on driving, including lateral and longitudinal vehicle control, and changes in visual behavior. Compared to baseline driving, both text messaging tasks increased drivers' subjective workload, lane position variability, and speed variability, with the combined task of reading and writing text messages being associated with significantly higher workload, significantly less time looking at the roadway and more time looking at the phone, than reading alone. These results are in accordance with previous simulator research on text messaging while driving, which showed that drivers looked away from the roadway significantly more often when performing text-messaging tasks than in baseline (non-text-messaging) conditions, as well as increases in lane position variability during text-messaging (Drews et al., 2009; Hosking et al., 2009). Contrary to expectations, though, text messaging was associated with reduced vehicle speed only when participants were *reading* text messages. That speed was faster when drivers were *reading and writing* text messages compared to the baseline and 'read only' conditions may, similar to increased speeds on the freeway when writing text messages, indicate that drivers' speed monitoring capacity was compromised in this, more difficult, situation. The increased visual demands of the 'read/write' task, which was associated with significantly fewer glances to the forward scene than the other two conditions, may have induced drivers to monitor their vehicle speed less effectively, which, because of the decline in the road surface's gradient, would result in faster speed.

The finding that lane position variability was greatest when performing the 'read/write' task is consistent with past research showing that increased visual–manual demand increases lane keeping variation (Engström et al., 2005). It is also consistent with the reduced proportion of time drivers spent looking at the roadway when they performed this task. Interestingly, although participants looked less at the roadway in this task condition, and contrary to previous research showing that the visual–manual resources engaged when writing text messages have more significant detrimental effects on drivers' ability to react to traffic signals than does reading messages (Brookhuis et al., 1991; Törnros and Bolling, 2005), a similar proportion of participants in both the tunnel and the freeway environment answered correctly in their written text messages.

Surprisingly, this study is one of the first to investigate subjective ratings of driver workload while performing text-messaging tasks. Therefore, there is no previous research literature with which to compare the observed results. Regardless, due to the similarity between text-messaging and handheld mobile phone use (particularly the dialing sub-task), an increase in subjective workload was predicted. A stepwise increase in subjective workload ratings across the three text-messaging conditions (baseline, 'read only', and 'read/write') was observed, which is consistent with previous research showing increases in subjective mental workload with handheld mobile phone use (Brookhuis et al., 1991), and confirms that the 'read/write' task was more demanding than the 'read alone' condition.

Although not specific to the effects of distraction, differences in longitudinal vehicle control between the two road environments were observed, with tunnel driving being associated with slower speeds and marginally (not statistically significant) larger standard deviation of speed. These results are consistent with previous perceptual research on the relationship between perceived road width and vehicle speed (Manser and Hancock, 2007; Godley et al., 1999; Lewis-Evans and Charlton, 2006), and suggest that drivers in this study may have been more vigilant about maintaining slower speeds in the tunnel, perhaps due to the greater perceived risk of the tunnel environment (Fuller, 2005), or because of the increased rate of optic flow (Gibson, 1979).

Unlike previous reports (Beall and Loomis, 1996; Chatziastros et al., 1999), there were no effects of tunnel driving on measures of lateral vehicle control, nor did drivers in the present study spend a greater proportion of time overall looking at the forward roadway when driving in the tunnel compared with the freeway. It is possible that, in order to demonstrate such effects, drivers would need to be exposed to a tunnel environment for a longer period of time than in the present study. It is also interesting to note that tunnel driving was not reported by participants as being more difficult than was freeway driving; subjective workload ratings between the two simulated environments in this study were the same.

4.1. Limitations and future research

The present study was designed to investigate the contribution of road environment (tunnel *vs.* freeway) to driver distraction associated with text-messaging. Investigation of other potential contributing factors, such as gender and age, was not a priority. Nevertheless, it is possible that other, individual factors influence driver distraction and the ways in which drivers adapt their behavior, and future research should be undertaken to explore this possibility. Likewise, drivers in this study were exposed to the tunnel environment for only a limited amount of time. It is possible that longer exposure to tunnel driving would be associated with selective increases in driver distraction compared to freeway driving. It is also possible that knowing *a priori* that they would be required to perform text messaging tasks while driving, and being monitored while performing them, may have acted to moderate any perceptual influences of tunnel driving on lateral control and visual behavior. Future research should be designed to investigate these possibilities.

The possibility that changes in vehicle speed may be a consequence of drivers' less effective speed monitoring strategies was not investigated in the present study. These issues should be explored in future studies by comparing the frequency of driver brake and accelerator pedal applications across varying levels of driver distraction.

A driver's ability to attend to the driving task, as well as any secondary task(s), would be expected to depend on whether an individual suffered from an attention deficit disorder. Participants were not pre-assessed on this factor; however, it is unlikely that generalized deficits in attention would have contributed to the results, as each participant acted as their own control, and all participants received the same instructions with regards to the study.

The present research design required participants to perform text-messaging tasks while driving in both a tunnel and a highway environment. This design does not allow the prediction of how prevalent text-messaging would be in real world tunnels compared to highways. Further research would be needed to determine drivers' willingness to engage in text-messaging, or other secondary tasks, while driving in tunnels compared to highways.

5. Conclusion

Driver distraction caused by text messaging in a simulated tunnel environment was associated with alterations in driving performance measures, including changes in speed and speed variability, decrements in lateral vehicle control, decreased visual scanning of the roadway ahead, and increased ratings of subjective workload. These effects were also evident in the freeway environment; however, more pronounced reductions in speed associated with text-messaging in the tunnel suggest that drivers may make attempts to compensate more in this road environment than on the freeway. Although driving performance decrements were similar in the two environments, it is critical to remember that, in real world driving, the enclosed tunnel environment can be problematic, and more dangerous, in that it can restrict the evacuation of road users in the event of a collision. The potentially devastating consequences of driver distraction and associated high level of crash risk, therefore, make it a particularly undesirable occurrence in this environment. Drivers should be encouraged not to engage in text messaging or other distracting behaviors when driving in tunnels.

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