Managing in-vehicle distractions - evidence from the Psychological Refractory Period paradigm

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ABSTRACT
Driver distraction by in-vehicle tasks has a negative impact on driving performance and crash risk. This paper describes a study investigating the effect of interacting with a surrogate in-vehicle system task – requiring a two-choice speeded response – in close temporal proximity to a subsequent lead vehicle braking event. The purpose of the study was to determine the 'task-free' interval required before a braking event to ensure safe braking performance. Drivers (N = 48) were split into six groups and randomly assigned an in-vehicle task defined by stimulus (three levels) and response modality (two levels). Four blocks of inter-mixed single- and dual-task trials were presented. The time interval between the two tasks was varied on dual-task trials. Slower braking responses on dual-task trials relative to single-task trials indicated dual-task interference. Driver braking performance demonstrated the psychological refractory period effect – an increase in reaction time with decreasing temporal separation of the two tasks. The impact of in-vehicle task stimulus and response modality on performance is discussed in relation to predictions based on Multiple Resource Theory. This study demonstrates a fundamental human performance limitation in the real-world driving context and has implications for driver response speeds when distracted. Specifically, the presentation of an in-vehicle task in the 350 milliseconds before a braking event could have severe safety consequences. The use of the findings to manage in-vehicle stimulus presentation is discussed. Problems with implementation of the results are reported.

General Terms
Human Factors, Performance, Experimentation, Standardization.

Keywords
driver distraction; driver safety; simulator; in-vehicle tasks; human-machine interface; psychological refractory period;

1. INTRODUCTION
1.1 Driver distraction
Driver distraction is defined as the directing of attention away from the driving task towards an object or event in the internal or external vehicle environment [22]. Distraction from in-vehicle tasks that are unrelated to driving (e.g. tuning the radio or answering a phone call) can have negative effects on driving safety, in particular, reduced longitudinal and lateral vehicle control [2,9,18] and reduced critical event detection [9,14].
Driver distraction is estimated to play a contributory role in up to 25% of vehicle crashes [22], with this figure predicted to rise with future increases in the availability and uptake of in-vehicle driver assistance, communication, and entertainment systems [4,29].

1.2 Task timing and dual-task interference
It is well-established that humans are subject to a performance limitation when performing two tasks simultaneously or close together in time [16,26]. Performance decrements occur even with simple tasks, indicating a barrier to the perfect time-sharing of multiple tasks. The effects of distraction on driving performance are often explained in terms of this difficulty in a multi-tasking situation [13]. The regular need to multi-task in the driving environment means that it is both important and necessary to investigate the impact of additional tasks on performance.
It is proposed that human task performance consists of a linear sequence of three processing stages: perception (A), response selection (B), and response execution (C) [19] (see Figure 1). The central bottleneck (CB) model of task processing postulates that multiple tasks can be processed in parallel at peripheral processing stages (perception and response execution) but that processing can only proceed in a serial manner at the central, response selection stage [16,17,20,26]. This allocation of response selection resources to a single task at a time means that if two tasks require simultaneous access to this processing stage, one is forced to 'wait' until response selection for the other task reaches completion. This results in a delay in the time taken to perform the 'queuing' task, termed the psychological refractory period (PRP) effect (see Figure 1).
The PRP effect is observed under dual-task conditions and refers to the delayed response to a second task that is due to interference from a preceding task. Task responding is delayed relative to its single-task performance, with the magnitude of the effect dependent on the temporal proximity to a preceding task. Stimulus onset asynchrony (SOA) is the time gap between the presentation of the first and second task stimuli. Varying SOA alters the amount of response selection processing overlap between the tasks. The effect – observed in many laboratory

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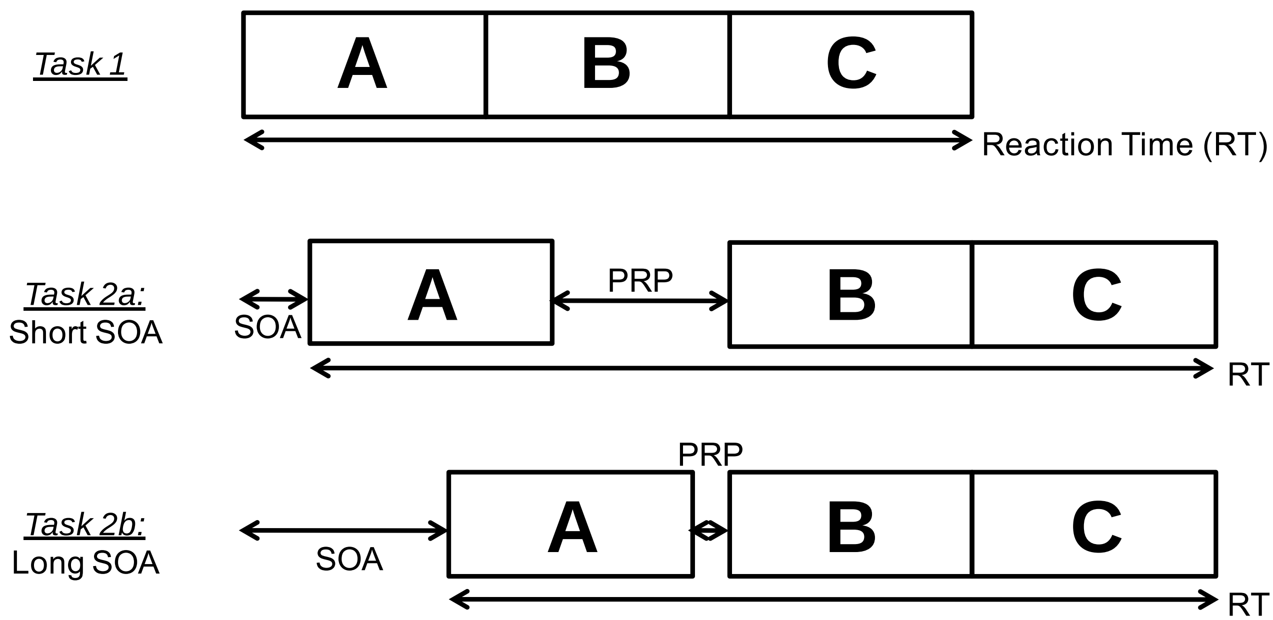

Figure 1 – Psychological Refractory Period effects under dual-task conditions (Task 1 + Task 2). The PRP effect occurs when two tasks produce temporal overlap in their demand for response selection processing resources. The greater the overlap, the longer the delay in Task 2 performance, hence the larger PRP effect for Task 2a (presented at short SOA) compared to Task 2b (long SOA). (PRP: psychological refractory period, SOA: stimulus onset asynchrony, A: perceptual processing, B: central processing including response selection, C: response execution processing).

studies [15,23,26] – is manifested as an increase in Task 2 reaction time with decreasing temporal separation of the tasks. Dual-task interference effects are typically observed between two tasks separated by an SOA of up to 350-500 milliseconds [28-29] with the longest delay in Task 2 performance observed for simultaneous task presentation (0 millisecond SOA). Importantly, the PRP effect is robust to changes in variables such as task modality [3,16], task type, task difficulty [6,8,12], task practice [5], and testing environment [13,16,26], suggesting that it is revealing an underlying limitation in human task performance, namely that two tasks cannot be performed together without interference effects. A further observation from this paradigm is that Task 1 performance is unaffected by the inter-stimulus interval between the two tasks.

The PRP paradigm has rarely been applied to the study of real-world dual-task performance. However, it is likely that dual-task interference effects will exist in everyday settings, such as the driving environment. The PRP effect has been demonstrated in the driving context by way of a delayed braking response following the performance of a surrogate in-vehicle distracter task [13].Participants were required to respond manually or vocally to simple visual or auditory detection tasks, presented between 0 to 1200 milliseconds before a braking response task. Brake reaction time was slower following a distracter task compared to single-task braking performance and increased with increased temporal proximity of the two tasks. Braking task performance was delayed on dual-task trials involving an SOA in the 0-350 millisecond range. The maximum delay was 174 ms, equating to a 4.9 metre increase in stopping distance from an initial speed of 65 mph. There was no effect of distracter task stimulus or response modality on braking task performance.

Determining the magnitude of the PRP effect could allow management of the negative impacts of driver distraction on braking performance; specifically by informing about the timing of in-vehicle task presentation that can prevent dual-task interference effects. This study applies the PRP paradigm in a driving simulator study and attempts to extend previous work [13]. The surrogate in-vehicle task is a two-choice discrimination task. Due to the potential for future in-vehicle haptic stimuli, the choice task stimulus modality manipulation is extended to include a haptic stimulus task presented as a steering wheel vibration. A more extensive consideration of SOA is provided, with a focus on the range known to cause dual-task interference. The intention is to accurately quantify the magnitude of the PRP effect, and its impact on a braking response.

1.3 Task modality and dual-task interference

In addition to dual-task interference localised to response selection processes, peripheral interference effects can also occur when two tasks overlap in time. Multiple Resource Theory [27-28] proposes multiple parallel processing channels at each stage of task processing. Dichotomous processing resources exist whereby visual and auditory stimuli can be processed concurrently, as can manual and vocal responses. Each resource channel is capacity-limited. Task performance decrements occur when the demand for processing resources within a single channel exceeds the available supply. Peripheral dual-task interference effects are predicted when two temporally-overlapping tasks share a common stimulus or response modality. For example, two visual stimulus tasks would be expected to produce greater dual-task interference than a visual stimulus task and an auditory stimulus task presented together.

This theory is relevant to the investigation of dual-task interference effects in the driving context, due to the range of task stimulus and response modalities that are available for use by the driver. The selection of task modality offers another approach to reducing the problem of driver distraction. However, this should be in addition to a consideration of task timing, as dual-task interference effects have been shown in the absence of stimulus or response modality overlap in the laboratory [1,7] and driving domain [21].

1.4 Current study

An understanding of the prevalence and magnitude of dual-task interference in the driving environment is an important step in the management of driver distraction, and thus the improvement of driver safety. This driving simulator study considers the speed of a braking response, both in isolation and in the presence of a preceding two-choice response task (simulating an in-vehicle task interaction). The temporal proximity to the preceding task and its stimulus and response modality are manipulated. The speed and accuracy of the in-vehicle task response is also considered. It is predicted that brake reaction time will increase with decreasing temporal separation of the two tasks – the PRP effect. In-vehicle task modality is expected to modulate this dual-task interference effect, with common task stimulus or response modalities causing increased dual-task interference. The results will be used to provide guidance regarding the management of in-vehicle task presentation, to reduce the effects of distraction on driving performance, in particular on response speed to a lead vehicle braking event. The study targets two aspects of in-vehicle task presentation; task timing and the choice of appropriate task stimulus and response modalities [4].

2. METHOD

2.1 Participants

Forty-eight participants (30 males, 18 females) were recruited, their ages ranging from 19 to 47 years (M = 27.5, SD = 8.2). The criteria for participation were possession of a valid national driving licence and no uncorrected visual or auditory defects. Driving experience ranged from 0.5 to 32 years (M = 7.6, SD = 8.1). The experiment consisted of a single 80-minute testing session. Each participant was rewarded with £10.

2.2 Apparatus

The study was conducted on a fixed-based, medium-fidelity driving simulator, presented via a laptop computer. The simulation was run on a Dual-Core Toshiba laptop with a nVidia workstation-class graphics card. This laptop ran all elements of the simulation, including the vehicle dynamics model, the graphical subsystem and the presentation of the various stimuli. The simulator software consisted primarily of freely available OpenSceneGraph for the rendering process and programs developed by staff at the University of Leeds. The simulator system sampled scenario and driver behaviour parameters at a rate of 60 Hz.

The laptop was connected to an Acer 19" flat-panel display in front of the driver. A real-time, fully-textured and anti-aliased, 3-D graphical scene of the virtual world was displayed. The display was a single 1280 x 1024 resolution channel with a horizontal field of view of 50° and a vertical field of view of 39°. The display showed the forward road scene and a replica dashboard, including realistic speedometer and rev meter function. Background engine noise (60 dB) was presented through the laptop speakers.

Participants were seated approximately 1.0 m from the computer screen. The simulator was equipped with a Logitech G25 force-feedback steering wheel, spring-loaded foot pedals (accelerator, brake and clutch) and a manual shifter unit. The steering wheel provided force feedback to simulate the aligning torque of the wheel. There were two manual response paddles located on the left and right rear of the steering wheel. Participants were required to operate the steering wheel, accelerator, and brake pedal only. Both pedals were operated with the right foot. Participants were allowed to adjust the position of the pedal unit to obtain a comfortable driving position.

2.3 Tasks

The driving simulation used was a car-following scenario (Figure 2). A single lead vehicle (black Mitsubishi Shogun) maintained a fixed speed of 40 mph on a single-carriageway, rural road. No other vehicles were present. The speed of the experimental vehicle was fixed at 40 mph by a controller system, which maintained constant time headway (1.5 seconds) to the lead vehicle. The absence of speed control was explained to the participants as the functioning of a cruise control system. The driving scenario was only presented when accelerator pedal depression exceeded 50%. This was to ensure that braking responses involved a foot movement from the accelerator to the brake pedal.

Participants were presented with two types of task: an 'in-vehicle task' and a braking task. The in-vehicle task was presented as a two-choice, speeded response task, in which participants responded to one of two possible stimuli presented for a short duration. This task simulated an in-vehicle system task that drivers could encounter during everyday driving. The discriminability of each stimulus pair was confirmed through pilot work with all tasks being simple and having highly detectable stimuli and short response actions. Stimuli were presented from the front in the visual, auditory, or haptic modality, and required a manual (hand) or vocal response. In-vehicle systems can make use of three sensory channels to present information to the driver; sight, hearing, and touch. The three stimulus modalities were chosen to reflect these possible modes of presentation. The braking task required the driver to brake in response to the presentation of the lead vehicle brake lights. Participants were shown catch trials in which the lead vehicle left indicator flashed eight times. No response was required to this stimulus. These trials (n = 16) were included to avoid response performance on each trial, which could create an artificially high level of driver vigilance. Participants experienced each task type under both single-task and dual-task conditions. The in-vehicle task always preceded the braking task on dual-task trials, to allow the investigation of in-vehicle distraction on subsequent braking performance.

Figure 2 – The simulated driving environment including road scene with lead vehicle and in-vehicle dashboard

2.4 In-vehicle task interface

The in-vehicle task interface was designed to imitate methods of stimulus presentation in a real vehicle. Tasks were simple to learn and perform. Practice was given to reduce differences in task difficulty across task modality combinations. The visual task stimuli were blue or yellow-coloured rectangles (128 x 135 pixels) presented centrally on the dashboard for 400 milliseconds. Stimulus colours were selected to avoid confusion with the centrally-presented, red brake light stimulus. The auditory stimulus was a 300 Hz or 900 Hz saw-tooth wave file presented through the laptop speakers for 200 milliseconds. Stimulus intensity was fixed at 75dB to allow detection during background noise and to fit with current in-vehicle stimulus presentation guidelines [11]. The haptic stimulus was a steering wheel force feedback vibration with variable amplitude (0.8 and 0.4 Nm). Stimulus period (100 ms), torque (0.0 Nm) and duration (200 milliseconds) were fixed. The haptic stimulus was presented so that it did not interfere with steering control or the operation of the response paddles.

The in-vehicle tasks involved a single response action to one of two stimuli. Manual responses were performed on the left and right response paddles located on the rear of the steering wheel. Simple response actions were selected to fit with current international in-vehicle system advice [10]. Dependent measures for manual responses (in-vehicle task and braking) were recorded by the simulator system. Vocal responses involved single word vocalisations (‘one’ or ‘two’) and were recorded using an Olympus WS-321M Digital Voice Recorder attached to a Griffin Lapel Microphone. Dependent measures for vocal responses were collected manually using Pratt, an audio play-back program allowing spectral analysis of sound data.

2.5 Braking task interface

The braking task interface simulated a real-world braking event. The braking task stimulus was the illumination of three lead vehicle brake lights (two side brake lights and a centre high-mounted stop light) for 3 seconds, accompanied by a constant lead vehicle deceleration (-5 m/s^2). Participant responses were performed using the foot pedal unit. The correct action was the removal of the foot from the accelerator pedal and the depression of the brake pedal. The participants were required to decrease the speed of the experimental vehicle to 0 mph.

2.6 Design

The experiment was a mixed ANOVA design with manipulation of three factors. Two in-vehicle task factors were varied between subjects: stimulus modality (visual, auditory, haptic) and response modality (manual, vocal). Participants were randomly assigned to one of six groups (n = 8) with each group allocated a different in-vehicle task type (Table 1).

The within-subjects factor was manipulated on dual-task trials only. Stimulus onset asynchrony (SOA) was varied across eight levels: 0, 50, 150, 250, 350, 450, 850 and 1000 milliseconds. Each SOA was experienced an equal number of times (n=4). The order of SOA presentation was counterbalanced within each of the six participant groups. The range of SOA selected was based on previous research.

Table 1 – Participant groups based on the between-subjects manipulation of in-vehicle task stimulus modality and response modality.

Participant Group	Stimulus Modality	Response Modality
1	Visual	Manual
2	Visual	Vocal
3	Auditory	Manual
4	Auditory	Vocal
5	Haptic	Manual
6	Haptic	Vocal

2.7 Procedure

Participants were presented with a four-page briefing sheet to read. The experimenter answered questions before completion of a consent form and a driver demographic information questionnaire. The study commenced with a short practice drive, to allow participants to become familiar with the operation of the simulator. The participants were then taught the correct responses to the in-vehicle and braking tasks. The participants practiced the in-vehicle task until eight consecutive correct responses were produced (M = 12 trials). Participants then performed four trials of each type (single in-vehicle task, single braking task, dual-task).

The experimental phase consisted of 112 trials (32 dual-task, 32 single braking task, 32 single in-vehicle task, 16 catch), divided into four blocks (n = 28). Each block was followed by a two-minute rest to avoid participant fatigue. All four trial types were possible on any trial. Trial type, in-vehicle task stimulus, and task onset time were randomised to ensure procedural unpredictability. Task onset was randomised within the range 8 to 23 seconds (M = 15) after trial onset. Total trial length ranged from 12.5 to 29.5 seconds (M = 20.5).

Each trial began when the accelerator pedal was depressed, with both vehicles travelling at 40 mph in the left-hand lane. The participants were instructed to press the accelerator until the end of the trial or until braking was required. Early release of the trial resulted in an auditory tone warning and restarting of that trial. The trial ended with a fade-out of the driving scene five seconds after the final stimulus presentation.

Participants were instructed to respond as quickly as possible to all task stimuli and to focus on driving safely i.e. drive in the left-hand lane and avoid collisions. The braking task was explained as the lead vehicle approaching a traffic jam. Participants drove with their fingers on the manual response paddles to minimise individual differences in movement time that could confound measurement of response speed. A light grip was advised to prevent resistance to haptic stimulus presentation.

2.8 Dependent measures

In-vehicle task performance was assessed via measures of stimulus reaction time and stimulus response accuracy. Braking task performance was assessed via brake reaction time. All reaction times were measured from the onset of the task stimulus until the moment a response was commenced. The analysis of in-vehicle task response accuracy was performed on the entire data set. Stimulus response accuracy was based on the first response provided and accuracy was calculated as the number of correct responses to the in-vehicle task (max. 32 per trial type).

3. RESULTS & DISCUSSION

All trials for which an incorrect response was produced were excluded from the reaction time analysis. Reaction times within the range 100-3500 milliseconds were included. Dual-task trials were checked for response grouping (RT2-RT1 < 100 ms) – a strategy that would mask dual-task interference effects and that is unlikely in the more unpredictable real-world setting. No exclusions were necessary. Data from three participants was excluded entirely due to questionable task understanding. Dual-task data only was excluded for six further participants due to a high incidence of reversed response orders (>50%).

3.1 Braking task

3.1.1 Dual-task interference

Brake reaction time data was subjected to repeated measures ANOVA with trial type as a within-subjects factor and in-vehicle task stimulus and response modality as between-subject factors. All repeated measures ANOVA analyses were tested for spherical data. The Greenhouse-Geisser correction was applied where necessary. There was a significant effect of trial type on brake reaction time [$F(1,33) = 4.751$, $p = .037$, $\eta^2 = .126$] with faster responding in the single-task condition [M = 964 ms, SE = 22] than the dual-task condition [M = 987 ms, SE = 22]. This supports the hypothesis that brake reaction time would increase with prior in-vehicle distraction. This dual-task interference effect increases in magnitude with the removal of the two longest SOA conditions, suggesting that the absence of task processing overlap on these trials dilutes the overall dual-task interference effect.

Dual-task interference was observed regardless of in-vehicle task stimulus or response modality. The stimulus modality of the in-vehicle task had a significant effect on brake reaction time on dual-task trials [$F(2,33) = 4.739$, $p = .016$, $\eta^2 = .223$]. Reaction times were faster after the haptic [M = 922 ms, SE = 36] and auditory [M = 936 ms, SE = 39] in-vehicle tasks than the visual in-vehicle task [M = 1084 ms, SE = 37]. This result fits with predictions based on Multiple Resource Theory, where two tasks sharing a common stimulus modality are more likely to impair each others' performance than two tasks with dissimilar stimulus modalities. In this case, when visual processing resources are required for both tasks, the visual processing channel may become overloaded, thus resulting in a decrement in braking performance relative to braking after an auditory or haptic in-vehicle task. It is important to note that there was also a significant main effect of in-vehicle task stimulus modality on single-task brake reaction time. This is entirely unexpected because modality is a redundant variable in this case. It suggests that modality effects could reflect a fundamental difference in the samples randomly assigned to each task stimulus type.

There was no effect of response modality on brake reaction time, although there was a tendency for faster responses following a vocal response task [M = 935 ms] compared to the manual response task [M = 1015 ms]. This fits with similar predictions based on Multiple Resource Theory.

3.1.2 PRP effect

Investigation of the PRP effect used brake reaction time data from dual-task trials only. Repeated measures ANOVA was conducted with SOA as a within-subjects factor and in-vehicle task stimulus and response modality as between-subject factors. A significant main effect of SOA on brake reaction time was observed [$F(7,231) = 53.561$; $p = .000$, $\eta^2 = .619$], with brake reaction time increasing with decreasing SOA between the two tasks (see Table 2).

Table 2 – Brake reaction time data from dual-task trials. All data in milliseconds.

SOA	Mean Brake Reaction Time	S.E.	95% Conf. Intervals	
0	1137	25	1087	1187
50	1092	24	1042	1141
150	1033	28	976	1091
250	979	26	927	1031
350	947	26	894	999
450	921	24	873	970
850	888	26	836	941
1000	897	25	846	947

In support of the previous study [16], the PRP effect is therefore observed in the driving context. This result – and the prior dual-task interference result – fit with a central bottleneck theory of human information processing whereby temporal overlap in the demand for response selection resources results in an enforced delay to Task 2 processing until these resources are released from Task 1 processing. The increased delay in Task 2 reaction time at short SOA can be explained in terms of increased time 'queuing' for access to central, response selection resources. At longer SOA, the response selection stages of the two tasks are subjected to less temporal overlap, and thus Task 2 processing experiences less of a delay, reducing the dual-task interference effect relative to short SOA trials.

Post-hoc pairwise comparisons revealed that brake reaction time was affected by changes in SOA in the range 0-350 ms (see Figure 3). Above this, changes in SOA had little impact on brake reaction time, as shown by the plateau on the graph.

There was also significant effect of stimulus modality on brake reaction time [$F(2,33) = 4.375$, $p = .021$, $\eta^2 = .210$]. Brake reaction time was slower following a visual in-vehicle task [M = 1080 ms, SE =39] than an auditory [M = 943 ms, SE = 41] or haptic in-vehicle task [Mean = 936 ms, SE = 38]. Further analysis revealed that these modality effects were confined to short SOA trials only (as shown by the converging lines at long SOA on Figure 4). This implies that modality-specific interference relies on close temporal overlap of the tasks. There was a non-significant tendency for slower brake reaction times after a manual response task [M = 1021 ms, SE = 31] compared to a vocal response task [953 ms, SE = 33].

There were trends towards modality differences in the magnitude of the PRP effect i.e. the SOA range over which a delay in brake reaction time is observed. These effects are broadly consistent with those predicted by Multiple Resource Theory, whereby tasks that share a common processing demand produce greater dual-task interference effects. Future experiments will be designed to consider cross-modality differences in PRP effect magnitude in more detail.

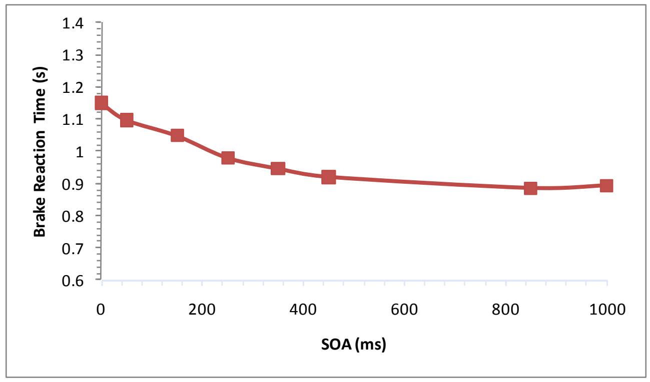

Figure 3 – Brake reaction time data for dual-task trials at each level of SOA.

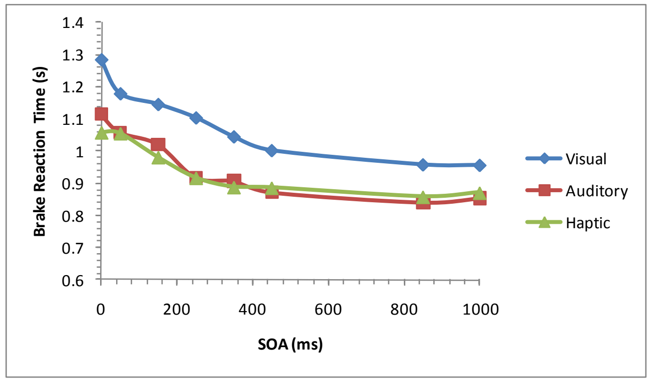

Figure 4 – Brake reaction time at each SOA; data plotted separately for each in-vehicle task stimulus modality.

3.2 In-vehicle task

3.2.1 Dual-task interference

The in-vehicle task data was subjected to the same analyses as the braking task data. There was a significant effect of trial type on stimulus response time [$F(1,33) = 14.303$, $p = .001$], with faster responses in the dual-task condition [Mean = 647 ms, SE = 12] than the single-task condition [Mean = 670 ms, SE = 13]. This is an unexpected result because task type is a redundant variable for the in-vehicle task as it is always presented first. It appears that the presentation of a subsequent braking task can speed up the processing of the earlier in-vehicle task. Further analysis revealed that this effect was restricted to participants performing the haptic-vocal in-vehicle task only.

3.2.2 PRP effect

As expected, there was no effect of SOA on in-vehicle task stimulus response time on dual-task trials [$F(7,231) = 0.899$, $p = .508$] (see Figure 5). This supports previous demonstrations of the absence of dual-task interference effects on the task presented first in a PRP paradigm. This argues against the demonstration of backward crosstalk effects in a previous study.

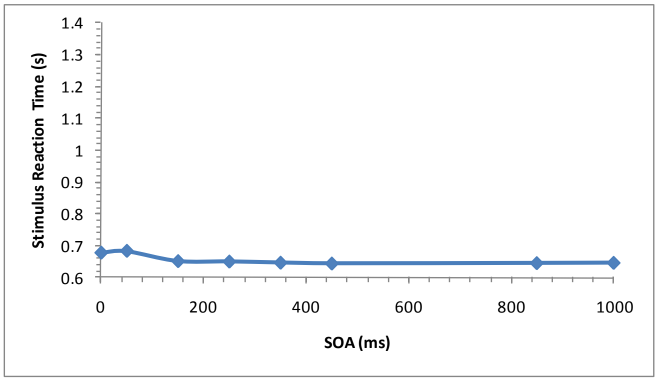

Figure 5 – The relationship between in-vehicle stimulus reaction time and SOA (dual-task trials only).

3.2.3 Modality effects

Single in-vehicle task trials were used to allow a pure consideration of the effects of stimulus modality and response modality on in-vehicle task response time. A two-way ANOVA with stimulus modality and response modality as between-subject factors was performed. There was a significant effect of response modality on stimulus reaction time [$F(1,39) = 5.254$, $p = .027$]. Participant responses were faster on manual in-vehicle response tasks [Mean = 658 ms, SE = 20] than vocal response tasks [Mean = 720 ms, SE = 18]. This could be explained by the greater familiarity with using the manual response modality in the driving environment. There was no main effect of stimulus modality or interaction of stimulus and response modality on stimulus reaction time. It is important to exercise caution when interpreting these modality effects. It cannot be assumed that the only difference between task types was stimulus or response modality. There are potential confounds such as task difficulty or stimulus duration.

3.2.4 Response accuracy

Repeated measures ANOVA was conducted with trial type (single vs. dual-task) as a within-subjects factor and stimulus modality and response modality as between-subject factors. There was no effect of trial type on response accuracy. This suggests that participants perform the in-vehicle task equally well, regardless of whether it is presented alone or with a subsequent braking task.

The effect of stimulus modality was significant [$F(2,42) = 4.823$, $p = .013$], with better performance on visual stimulus tasks [M = 30.4, SE = 0.677] compared to haptic stimulus tasks [M = 27.4, SE = 0.677]. There was an effect of response modality [$F(1,42) = 6.284$, $p = .016$] with lower response accuracy on manual response tasks [M = 28.0, SE = 0.552] than vocal response tasks [M = 29.9, SE = 0.552]. Considering the previous finding that responding was faster on manual response tasks than vocal response tasks, it could suggest that drivers prioritise rapid performance rather than accuracy of a manual response, perhaps to prevent interference with a subsequent braking response.

4. CONCLUSIONS

This study has demonstrated the existence of dual-task interference between a surrogate in-vehicle task and a braking task. The PRP effect was observed, whereby responding to the braking task was delayed in an SOA-dependent manner – increasing brake reaction time with decreasing temporal separation of the two tasks. Specifically, presenting an in-vehicle task within the 350 millisecond period before a lead vehicle braking event has a negative impact on the speed of response to the safety-critical event. The maximum delay in braking response due to the presence of a preceding in-vehicle task was 173 milliseconds. This equates to an increase in stopping distance of 5.41 metres when travelling at an initial speed of 70 mph. These results are comparable to the findings from a previous study [13], where a 174 millisecond delay in braking response was observed with a prior choice response task. These figures highlight the potential impact on driver safety from the presentation of a distracting task in the interval immediately before a braking event. In-vehicle task timing should therefore be managed to prevent distraction from the primary driving task. Implementation of this result is difficult due to the unpredictability of lead vehicle braking events. Also, it cannot be assumed that the results generalize to driver reactions to other safety-critical events. However, this study does offer an early indication of the necessary 'task-free' interval required to encourage optimal response to a lead vehicle braking event.

The stimulus and response modality of the in-vehicle task influences the magnitude of the interference effect on the braking task. As predicted, a preceding in-vehicle task that does not share a common stimulus or response modality with a subsequent visual-manual braking task has a tendency to interfere less with braking performance. This implies that design stage choices of an appropriate task stimulus and response modality can reduce potential distracting effects from an in-vehicle task. These modality effects have not been reliably observed in prior studies [13].

This study has provided a demonstration of the PRP effect in a non-laboratory setting, following extensive task practice, and without specific instructions about dual-task response order. This suggests that the PRP effect is robust to changes in conditions and has a noticeable effect on aspects of everyday human performance.

Future work will further explore the impact of in-vehicle tasks on braking performance. The inclusion of additional dependent measures (e.g. maximum braking force, accelerator release time, number of collisions, minimum time-to-collision, and minimum distance headway) and a wider range of driving scenarios (e.g. variable braking event severity, variable road geometry) would allow a more thorough investigation of the PRP effect in the driving domain, with the potential for more precise guidelines regarding in-vehicle task presentation. Improved realism of the driving scenario (e.g. task frequency, in-vehicle task type, method of haptic stimulus presentation) would enhance the validity of the conclusions.

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