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Distraction from multiple in-vehicle secondary tasks: vehicle performance and mental workload implications

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This study investigates the impact of multiple in-vehicle information systems on the driver. It was undertaken using a high fidelity driving simulator. The participants experienced, paced and unpaced single tasks, multiple secondary tasks and an equal period of 'normal' driving. Results indicate that the interaction with secondary tasks led to significant compensatory speed reductions. Multiple secondary tasks were shown to have a detrimental affect on vehicle performance with significantly reduced headways and increased brake pressure being found. The drivers reported interaction with the multiple in-vehicle systems to significantly impose more subjective mental workload than either a single secondary task or 'normal driving'. The implications of these findings and the need to integrate and manage complex in-vehicle information systems are discussed.

1. Introduction

Advanced in-vehicle systems can now provide the driver with a vast array of additional information. Navigation, road traffic information, mobile telephones and in-vehicle entertainment systems are all becoming widely available to the consumer. However, concerns have arisen over the demands on the driver from secondary information, and the implications of this for safe vehicle operation. Factors shown to produce performance decrements for drivers interacting with in-vehicle information systems have included driving experience (Summala *et al.* 1998), attentional allocation (Matanzo and Rockwell 1967, Liu 1996), and mental workload (Hancock and Verwey 1997). Recognizing the potential impact of secondary information systems on driving, researchers have pursued factors faciliating the development of *safety margins* for driving and ancillary tasks, e.g., experience (Summala 1996), personality (Wilde 1994) and interface design (Zwahlen *et al.* 1988, Wierwille 1993). However, it has been conspicuously difficult to bridge between theoretical and empirical findings to develop safety criterion regarding acceptable in-transit human interface interactions (Green 1999).

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Driving task demands are variable, and at times the driver may be left with considerable spare capacity which can be utilized in undertaking secondary or dual tasks. Some example dual tasks (in-vehicle and driving) include, digit detection (Brown and Poulton 1961) or digit repeat tasks (Wierwille *et al*. 1977, Wierwille and Gutmann 1978), sequence following (Brown 1965), detection of double stimuli (Brown 1965) and rearview mirror traffic monitoring (Wagner *et al*. 1997). Although, Salthouse (1982) suggest that a dual task may be conceptualized as nothing more than a complex single task involving additional information processing. Thus, the dual task performance decrements are suggested to be due to increases in overall task complexity. This theory is known as the *slowing complexity* hypothesis. Kortling (1994) controlled the complexity of dual tasks while manipulating task characteristics and demonstrated that *slowing complexity* does not hold universally true. In a classic representation of dual task performance, i.e., an easy primary task will provide a given level of performance, and one would assume that a harder primary task would result in a reduction in task performance. Introducing a secondary task to the easy primary activity has been stated to impair primary task performance. However, the introduction of the same secondary task to a hard primary task may result in significant decrements to primary task performance, see figure 1 (Gopher 1990). Gopher (1990) suggested that, in a situation when performance during a hard primary task is significantly decreased by the introduction of a secondary task, the operators' central processing capacity has been exceeded, and thus primary performance suffers. Empirical support was provided by Gluckman *et al*. (1988) demonstrating task conflicts during use of in-vehicle

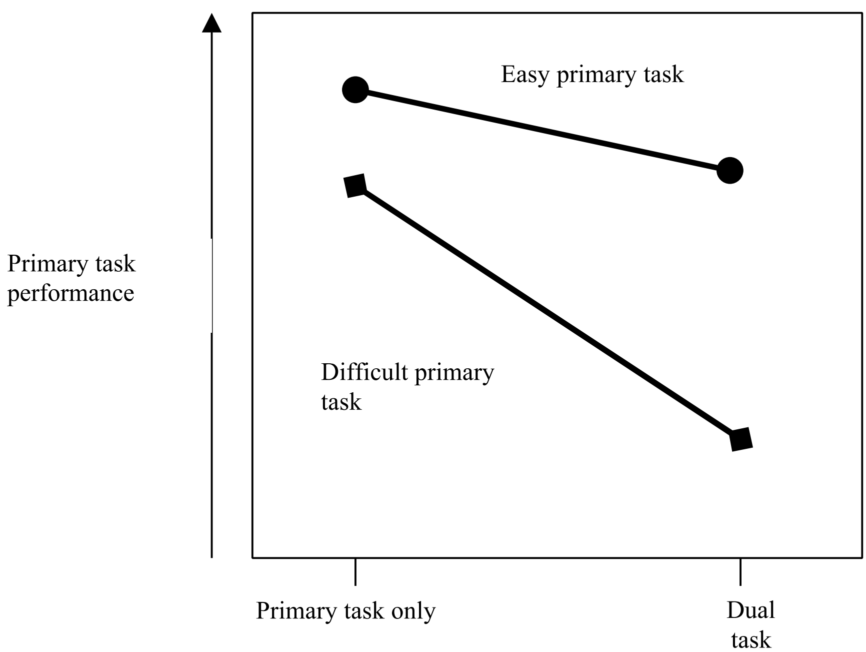

Figure 1. Theoretical dual task performance.

information that resulted in primary task performance decrements. Further, their study suggested dual task performance decrements for both simultaneous and successive presentations of a primary and secondary task. Other research has further supported Gopher's ideas, e.g., in a study presenting a secondary peripheral detection task in addition to simulated driving (Janelle *et al.* 1999). Results demonstrated both primary and secondary task decrements associated with increased anxiety. Factors associated with a decline in information processing have been shown to negatively influence dual task performance, for example, age (Broadbent and Gregory 1965, Brouwer *et al.* 1991, Korteling 1994).

Pertinent to this study are situations where the driver is required to respond to more than one secondary task whilst at the same time maintaining safe vehicle control. For example, route guidance systems and congestion warning devices may simultaneously interrupt the task of controlling the vehicle. Driving performance has been shown to be adversely affected by attempts to undertake multiple secondary tasks (Dewing *et al.* 1995). In their study drivers were asked to undertake simulated cellular telephone conversations, find an object from an enclosed container and/or interact with a complex in-vehicle display. The participants performed one, two or all three of these secondary tasks during simulated driving. The emphasis of the study was on ecologically valid tasks and the drivers were instructed to complete the secondary tasks in a particular order when they were undertaking more that one secondary activity. Consequently, the relative complexity of the tasks undertaken may have been inherently different. The study intentionally blurred the relative importance of the primary and secondary tasks and consequently in a simulated environment may have led to greater investment in the secondary task performance than would have been observed in a public road trial. Findings indicated age-related performance decrements that are well established in the literature and it identified that the visual task (map and text display interaction) as the most disruptive of driver performance. Previous work (Michon 1993) suggests that integrating systems and therefore managing unnecessary interruptions from secondary tasks may reduce such risks.

In-vehicle secondary task demands vary in complexity in much the same way as primary task demands. Some are predictable in their presentation of outputs, for example, some route guidance systems offer turn by turn advice at a pre-determined distance from junctions. Whereas, others can appear random in the selection of when to present information. The consequence of this may be to startle the driver, for example when receiving a call on a mobile phone. Klemmer (1957) found that if the presentation of stimuli is constant (paced) then over time reaction times become predictable and short. However, if the presentation of stimuli is unpredictable, reaction times are likely to be longer than unpredictable stimuli. Available time for in-vehicle secondary tasks is limited and therefore tasks requiring extended interaction times are likely to increase the workload that is experienced by the driver. Those tasks with high mental workload may result in distraction for the operator from the primary task of vehicle control (Wierwille 1993).

The development of in-vehicle interfaces has led to a number of strategies emerging for users to interact with the systems. The users' responses to these interfaces are effected by the design and can be shown to vary considerably (Rockwell 1988, Wierwille *et al.* 1988, Lansdown and Burns 1997). Some tasks may be force-paced, requiring an immediate response from the driver, for example, congestion warning information necessitating an immediate change of road. Whereas, other self-paced tasks may be carried out at the operators' convenience, for example changing radio stations. In terms of the potential to distract, forced paced tasks are considerably more likely to interrupt the driver at times when their attentional allocation should be on the control of the vehicle and interaction with the roadway.

The present study builds on the work of Dewing *et al.* (1995) by investigating the impact on the driving task of *simultaneous* information conflicts caused by interacting with more than one secondary task. Simultaneous presentation is important because the predictability, frequency and nature of secondary tasks may be unknown to the driver. This uncertainty in combination with the variability of primary task demands has raised concerns regarding potential disruption of safe driving behaviour. Dewing *et al.* (1995) presented task combinations that were visual, auditory or manual. Multiple resource theory (Wickens and Hollands 2000) suggests that simultaneous tasks can be processed by the participants using different and non-interfering channels with consequently lower workload. This may have accounted for the relative lack of task-specific findings in their experiment. In this study, participants were presented with simultaneous visual tasks to address concerns with task conflicts that are comparable with in-vehicle information systems.

The null hypothesis for this study is that there would be no significant differences in vehicle control, mental workload or emotional state during interacting with multiple in-vehicle tasks when compared to single tasks or normal driving. A secondary null hypothesis is that unpredictable (unpaced) task interruptions would not be significantly different to predictable (paced) task interruptions for vehicle control, mental workload or emotional state.

1.1. *Design*

A repeated measures design was used in this study. The between participants factor was task type (paced, unpaced, and paced and interruption, subsequently described in more detail).

1.2. *Participants*

Twenty-three participants were involved in this study. They were selected from the Transport Research Laboratory (TRL) database of participants. This resource contains over 1000 members of the general public. Each individual has underdone a familiarization exercise with the driving simulator utilized in this study. The age of the participants ranged from 18–59 years, average age was 40.17 years. The sample consisted of 11 males and 12 females. The average annual distance driven of the sample was 23 800 km per annum. The average percentage estimate of distance driven on motorway was 30.2%. The average number of days driven during the week was 6.4 days.

1.3. *Apparatus and materials*

- TRL Driving Simulator. A full size car is surrounded by three screens to the front providing 210° horizontal × 40° vertical field of view and one similar sized screen to the rear providing a 70° horizontal × 40 vertical field of view, enabling use of all three of the vehicle's mirrors. The scene is updated at rates between 30 and 60 Hz. The car body is mounted on hydraulic rams that supply motion to simulate the tilt and roll experienced in normal braking, acceleration and cornering. The rams provide; roll, pitch and heave with displacements of $\pm 7^{\circ}$, $\pm 4^{\circ}$ and 200 mm respectively. A further ram provides steering force feedback to the driver. The car has simulated engine noise and has external noise of passing traffic and road tyre noise. Main hardware includes an Indigo2 XL Graphics, Ony × 2 Infinite reality, NEC GT2000 LCD projector, 3 × Barco 800 Projectors.

- In-vehicle 'lanscape' displays (100 × 75 mm) presented either side of the steering wheel at 'ten to two' with respect to the steering wheel.
- Steering wheel buttons were used for interaction with the systems, up/down buttons on the right side, and left right buttons on the left side, also positioned at 10 to 2 with respect to the steering wheel. The in-vehicle displays provided a visual reminder of the buttons to be used in each experimental task, see figure 2.
- Paper-based NASA Task Load Index (TLX), subjective mental workload assessment. TLX is a multidimensional scale eliciting overall mental workload ratings. It is composed of sub-scales for mental demand, physical demand, temporal demand, performance, effort and frustration. For further information concerning this measure, see Hart and Staveland (1988).
- Paper-based UMIST, mood adjective checklist. This measure provides an indication of emotional state along three factors, energetic arousal (active–passive), tense arousal (anxious–relaxed) and hedonic tone (cheerful–sad). For further information concerning this measure, see Matthews *et al.* (1990).

1.4. *Procedure*

1.4.1. *Training task*: Participants were read a description of the aims of the study. All participants had previously driven the simulator for 15 min. On this occasion, they were asked to drive the simulator as they would their own vehicle, and told that this was a familiarization task. The simulated environment was one of a section of the UK M3 motorway. It has three lanes and was populated with other vehicles such that between four and eight cars, vans or lorries would be within the 200 m ahead or behind the driven car. The training session lasted between 5 and

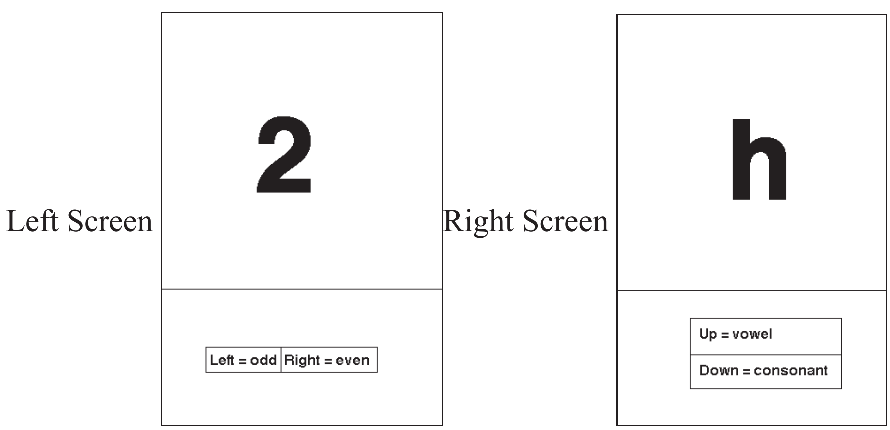

Figure 2. Example Screen Displays.

10 min. After the training, pre-test levels of subjective mental workload (Hart and Staveland 1988) and emotional state (Matthews *et al.* 1990) were obtained.

1.4.2. *Experimental trial*: The order of the conditions was counterbalanced to prevent order or learning effects.

Paced task Participants were asked to drive the simulator as they would their own vehicle. Numbers were presented at the same time in the left screen. If the number presented was even, the participants were asked to press the right key. If the number presented was odd, the participants were instructed to press the left key. In this condition the numbers were presented at a regular interval (approximately 30 s apart). Participants were given the following instructions: Dismiss the numbers as quickly as you feel it is safe to do so, but your priority should be to maintain safe control of the vehicle.

Unpaced task During this task, participants experienced the same type of stimuli as in the paced task except, the numbers were presented at an irregular or unpaced rate. The minimum duration between tasks was approximately 15 s, while the maximum was approximately 3 min. Participants were given the following instructions: Dismiss the numbers as quickly as you feel it is safe to do so, but your priority should be to maintain safe control of the vehicle.

Paced and interruption task During this task, participants experienced the same type of stimuli as the paced task, except letters were also presented on a right screen. If the letter presented was a vowel, the participants were asked to press the up key. If the letter presented was a consonant the participants were instructed to press the down key. During this task letters were presented at an unpaced or irregular rate, interrupting the number task. Participants were given the following instructions: Dismiss the numbers as quickly as you feel it is safe to do so, but your priority should be to maintain safe control of the vehicle. Please try hard to dismiss the letters as quickly as possible. Your performance will be rated on how quickly you achieve this. No individual performance ratings were calculated, the instructions were presented to suggest that the information appearing in the right screen was of higher priority than the left.

Control task Participants were asked to drive the simulator as they would their own vehicle.

The secondary tasks adopted in this study may be considered artificial with respect to commercial in-vehicle information systems. Efforts were made to simulate task elements that are requisite in any information processing exchange, i.e., perceive, process and respond. The rationale for this was to make findings generalizable to numerous in-vehicle information devices rather than one type of system.

After each task type the participants were administered the NASA TLX questionnaire and the Mood Checklist. At the end of the study the participants were de-briefed, paid £30 and thanked for participation.

2. Results

Unless otherwise indicated analysis of variance was applied in the statistical analysis of the experimental data and Tukey's HSD (honesty significant difference) used for *post hoc* testing. $P < 0.05$ was adopted as criterion level for significance.

2.1. *Mental workload*

Mean mental workload (overall) was found to be significantly different between task types ($F = 21.88$, df = 3, $p < 0.001$).

Figure 3 shows that lower overall mental workload was experienced in the control than in the secondary task conditions. The task type involving both a paced and interruption task was found to be the most taxing. *Post-hoc* testing revealed a significant difference between the paced and interruption task and the paced and unpaced tasks. The control task imposed significantly lower overall mental workload than either the unpaced ($p < 0.01$) or paced and interrupt ($p < 0.05$) task types.

Participants reports revealed the following sub-components to be significantly different between task types: Mental Demand ($F = 22.59$, df = 3, $p < 0.001$), Physical demand ($F = 12.53$, df = 3, $p < 0.001$), Temporal Demand ($F = 23.53$, df = 3, $p < 0.001$), Effort ($F = 22.83$, df = 3, $p < 0.001$), and Frustration ($F = 8.2$, df = 3, $p < 0.001$). *Post-hoc* testing showed mental demand and temporal demand to be significantly lower in the control task in comparison to the paced ($p < 0.05$), unpaced ($p < 0.05$), and paced and interrupt ($p < 0.05$) task types. The paced and interrupt task was found to impose significantly more physical demand ($p < 0.05$), effort ($p < 0.001$) and frustration ($p < 0.05$) than the control task. No significant differences were observed for the subjective ratings of performance between the four task types.

2.2. *UWIST Mood Checklist*

No significant differences were observed between task types for this measure.

2.3. *Headway*

A repeated measures ANOVA was carried out on the headway data. This information is collected by the driving simulator automatically when a vehicle is closer than 200 m ahead. A significant difference was found in headway between the different task types ($F = 18.12$, df = 3, $p < 0.001$). Greatest headway was maintained in the control task and the least headway in the unpaced task. *Post-hoc* testing revealed minimum headways for the control task (mean = 9.67 m) to be significantly longer than the paced (mean = 6.12 m) and unpaced (mean = 2.4 m) task types. A significant difference was not observed between the control task and

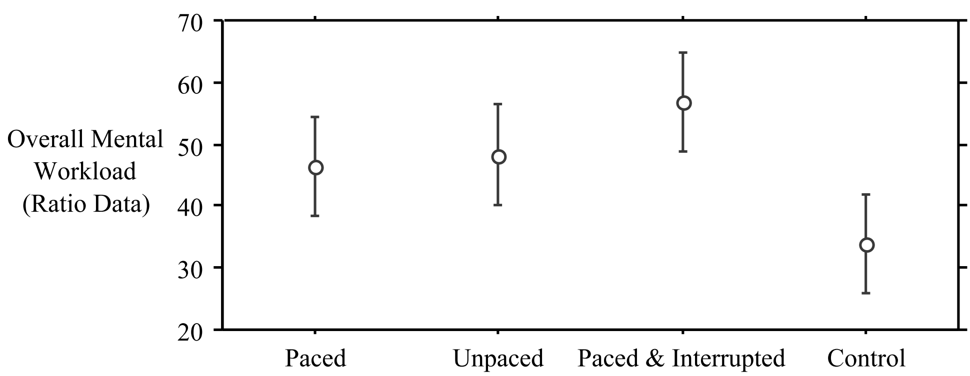

Figure 3. Subjective mental workload by task type (error bars indicate 95% confidence interval for the mean).

the paced and interrupt task type (mean = 7.85 m). No significant differences were observed between any of the three task types involving a secondary task.

2.4. *Brake pressure*

During driving participants normal use of the vehicle brakes in response to other vehicles was found to be significantly different. Standard deviation of brake pressure was significantly different between task types ($F = 4.3$, df = 3, $p < 0.01$). Figure 4 illustrates that brake pressure was higher in the unpaced task in comparison with the other three task types. *Post-hoc* testing revealed significant differences between the unpaced task and the other three task types. No significant differences were found between the paced, paced and interrupt, and the control task types.

No gender effects or interaction effects between gender and task type were observed for brake pressure.

2.5. *Mean speed*

A significant difference was observed for mean speed between the task types ($F = 7.14$, df = 3, $p < 0.001$). Participants maintained a higher mean speed in the control task (32.0 mph) in comparison to the paced (30.0 mph), unpaced (30.2 mph) and paced and interrupted (29.4 mph) tasks. *Post-hoc* testing revealed significant differences between the control and the other three task types. However, no significant differences were observed between the task types involving a secondary task.

A significant difference was observed between the mean speeds of males and females ($F = 6.037$, df = 1, $p < 0.05$). As illustrated in figure 5, males maintained a higher average speed in comparison to females.

The ANOVA revealed no interaction effects between gender and condition for the mean speed data.

2.6. *Lane position and movement in lane*

No significant differences were observed between the steering wheel adjustments made in each task type. Nor were any significant differences found for exceeding the boundaries of the lane, deviating position in lane or mean lane position between task types.

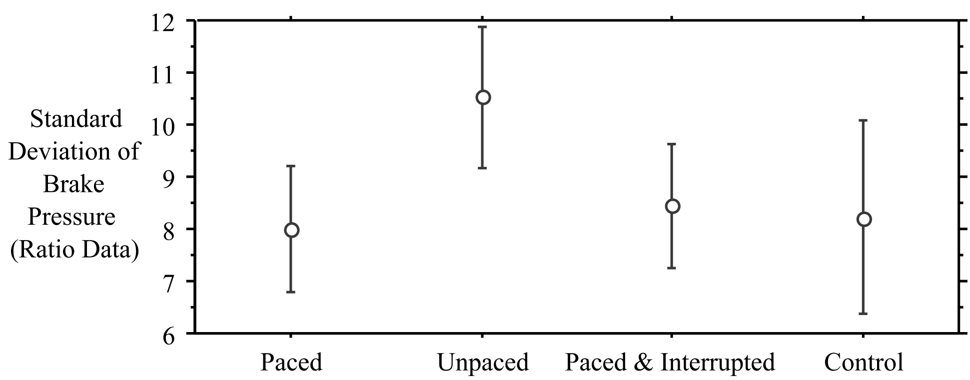

Figure 4. Summary of brake pressure by task type (error bars indicate 95% confidence interval for the mean).

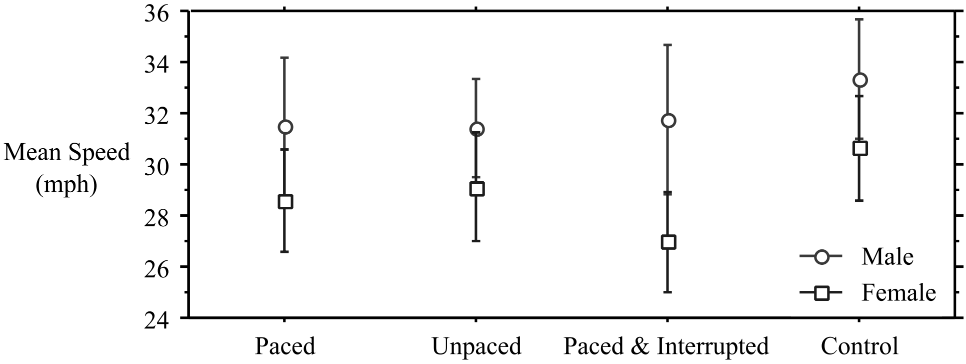

Figure 5. Speed and Gender by Condition (error bars indicate 95% confidence interval for the mean).

2.7. *Secondary task reaction times*

A significant difference was observed between the mean reaction times for correct responses to the tasks ($F = 717$, df = 1, $p < 0.001$). As shown in figure 6 when responding correctly, participants were quicker during the interruption task, which they were asked to give priority. Incorrect mean reaction times were found to be significantly different between the four secondary tasks, ($F = 20.173$, df = 1, $p = 0.001$). Figure 6 shows incorrect mean reaction times were also quicker in the interruption task.

2.8. *Secondary task performance*

Friedman tests were carried out on the secondary task response data. The percentage of correct responses to the secondary tasks was significantly lower in the interruption task, to which participants were asked to respond immediately, ($\chi^2 = 32.353$, df = 3, $p < 0.001$). However the distraction of the interruption task did not degrade performance of the paced task, as no significant difference was observed between the percentage of correct responses made in the paced, unpaced, or paced with an interruption, task types.

The percentage of incorrect responses to the secondary tasks was significantly higher in the interruption task type, to which participants were asked to respond immediately, ($\chi^2 = 41.899$, df = 3, $p < 0.001$). However, similar to the correct response data, the interruption task did not significantly degrade paced task performance with respect to the percentage of incorrect responses made in the paced, unpaced, or paced with an interruption, tasks (figure 7).

3. Discussion

The findings of this study support the research suggesting that the introduction of a secondary task tends to have a detrimental effect on driving performance. The distraction imposed by a secondary task increased the overall self-reported workload experienced by the drivers, decreased headways were observed with correspondingly increased brake pressures applied. Interaction with the two distinct secondary tasks was found to be significantly more demanding that one secondary task alone. Responses to the in-vehicle task that had been assigned a high priority/urgency resulted in significantly quicker reaction times than the other secondary tasks,

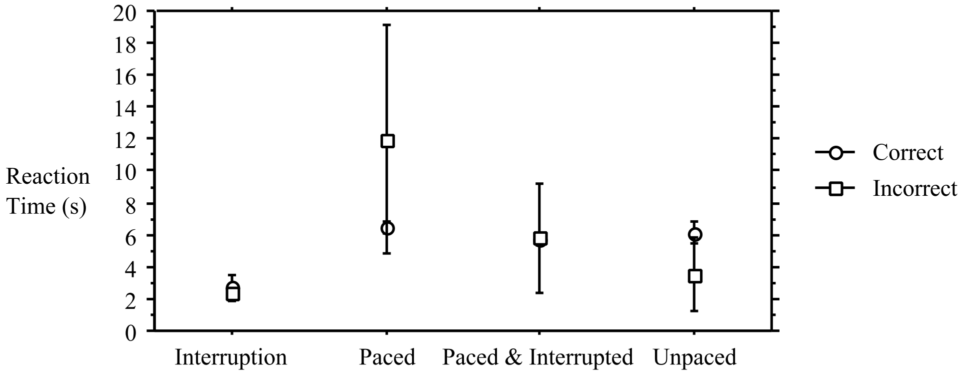

Figure 6. Mean correct and incorrect secondary task reaction times by secondary tasks (error bars indicate 95% confidence interval for the mean).

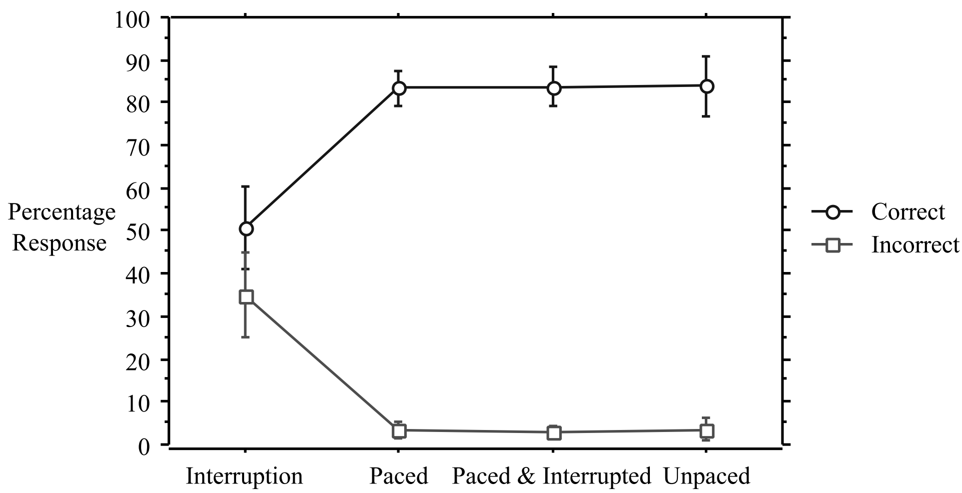

Figure 7. Percentage of correct and incorrect responses by secondary tasks (error bars indicate 95% confidence interval for the mean).

suggesting that drivers were attempting to comply with instructions. However, their task performance was less accurate in the high priority/urgency task (vowel/consonant discrimination) than the comparable (odd/even discrimination) other tasks.

The mean speed was significantly faster during *normal* driving in comparison to the conditions with interaction with secondary tasks. Drivers appear to have been compensating for the increased workload imposed by the secondary tasks by reducing vehicle speed, hence reducing the workload imposed by the primary task of vehicle operation. Previous research has supported this behaviour, most notably, the paper by Matanzo and Rockwell (1967), in which visual occlusion and vehicle speed were used interchangeably as independent and dependent variables. Rockwell found that participants compensated for task demands by attempting to control the available information to achieve a comfortable task difficulty level. The broader theoretical implications of such task compensation behaviour are discussed in some detail in the review text by Wilde (1994). Headway was reduced when interacting with a single secondary task (paced or unpaced), suggesting that participants were distracted by the secondary task, therefore failing to maintain a comfortable headway when compared with their 'normal driving'. The visual nature of the dual tasks may have been responsible for the increased workload experienced by the participants. Spatial uncertainty during concurrent visual tasks has been shown (Liu 1996) to produce greater task interference than concurrent verbal tasks and these findings are consistent with multiple resource theory (Wickens and Hollands 2000). The greater headway adopted during the multiple secondary task condition (paced and interrupted) is assumed to be a response by the drivers to back off to compensate for the difficulty of this activity. Such behaviour would be consistent with the additional demands for divided attention. Drivers may have been adopting a *selective* attentional allocation strategy during interaction with a single secondary task, but multiple simultaneous secondary tasks could have switched their strategy to one of *divided* attentional allocation. Such behaviour may have prompted conscious re-appraisal of the task complexity leading to the headways adopted (comparable with normal driving). During the paced and unpaced conditions (significantly shorter headway) the drivers' ability to control the vehicle was disrupted but the tasks may not have been perceived to be so taxing that they warranted a more cautious driving style. Use of vehicle brakes supports this view, as pressure was significantly increased during the introduction of the unpaced task, indicating an interruption of the drivers' task scheduling. These findings provide evidence that interacting with multiple in-transit in-vehicle tasks can affect the drivers' ability to control the vehicle, and therefore potentially compromise vehicle safety.

Overall mental workload was significantly lower during *normal* driving in comparison to the secondary (dual) task conditions. This finding is in agreement with the emerging research regarding in-vehicle secondary task performance (Zwahlen *et al.* 1988, Dingus *et al.* 1989, Gopher 1990, Fairclough *et al.* 1993, Lansdown 1996). The introduction of a secondary in-vehicle task can be seen to degrade driver performance in a quantifiable fashion. Findings from this study provide new data indicating that simultaneous interaction with multiple secondary tasks has the potential to compound this effect. Further that both primary and secondary task performance is impaired when drivers are tempted to respond to several non-essential driving activities in addition to driving.

It has been suggested (Michon 1993) that if multiple driver information systems are to be present within the modern vehicle, the most practical solution (aside from switching such devices off) to contend with the demands these systems impose, it to integrate and manage the presentation of information. This view is supported by findings from this study, which show vehicle control decrements during the use of multiple in-vehicle systems. The additional (vowel/consonant) discrimination task was designed to introduce a conflict during the (odd/even) discrimination task and required an immediate response by the user.

It was the aim of this study to control for any effects associated with gender. However, male drivers were found to adopt significantly higher average speed than their female counterparts. These findings are consistent with the published research regarding profiles of male drivers as more sensation seeking (Jonah 1997) and risk taking (Harre *et al.* 1996), e.g., close following behaviour and higher average speed (Rajalin *et al.* 1997).

The high urgency task, which appeared from the results to be appropriately given a high priority by the users, was interesting in that although responses were significantly quicker than the other tasks, they were less accurate. If the scenario is compared to a poorly timed motorway diversion message, requiring a rapid response from the driver, it is of some concern that the quality of the decisions undertaken may be compromised. Message type has been shown to significantly influence the comprehension and usefulness of information presented to the driver (Wagner *et al.* 1997). It should be considered though, that the current likelihood of multiple in-vehicle distractions is currently low.

Results did not support entirely Klemmer's (1957) findings (predictable short reaction times to regular stimuli) in that quickest reaction times were found during the multiple (paced) secondary task condition. No significant reaction time differences were found between the paced or unpaced tasks alone.

The secondary tasks were conceived to utilize basic information processing components in a manner that may be considered similar to the use of current driver information system. That is, perception of stimuli, recognition and retrieval from memory, problem solving and output of an appropriate response. Thus, it was hoped that the findings might be generalizable to the modern driving task. If anything, the tasks were simplistic by comparison to commercially available information systems.

Findings suggest rejection of the null hypothesis for; vehicle control in that speed was significantly greater during the control condition (normal driving); mental workload which was significantly greater during the multiple task condition than the other conditions. Results suggest accepting the null hypothesis for emotional state as none of the experimental conditions presented significant differences. Findings indicate the secondary null hypothesis be rejected for vehicle control, where the drivers adopted significantly longer headways when interacting with unpredictable tasks than predictable ones. Mental workload and emotional state data do not support this view as no significant differences were established between paced and unpaced tasks.

4. Conclusions

This study investigated the influence of multiple non-driving tasks on vehicle and secondary task performance. The simultaneous exposure to in-vehicle distractions from two separate tasks was found to impose significantly greater mental workload on the driver than the other conditions. Drivers compensated for high task demands by electing significantly lower vehicle speeds when interacting with simultaneous multiple secondary tasks. Further, the in-vehicle distractions resulted in reduced headways with respect to lead vehicles and significantly greater brake pressure being applied. Considered together, it is suggested that these finding present evidence of a specific and previously unquantified safety risk associated with simultaneous use of more than one in-vehicle information system. The prevalence of in-vehicle technology from cellular telephone, navigation, and mobile office applications will increase the frequency of situations where the 'information overloaded' driver must mediate the distraction from not only one in-vehicle information system but from several devices. Integration and management of driver information is advocated as the most practical solution to mediate this risk, although regulation, market forces and the acquisition of secondary dual task skills may mediate the safety risk from such situations.

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