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SURROGATE IN-VEHICLE INFORMATION SYSTEMS AND DRIVER BEHAVIOUR: EFFECTS OF VISUAL AND COGNITIVE LOAD IN SIMULATED RURAL DRIVING.

A. HAMISH JAMSON and NATASHA MERAT.

Institute for Transport Studies,

University of Leeds,

UK.

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CORRESPONDENCE ADDRESS: Hamish Jamson, Institute for Transport Studies, University of Leeds, LS2 9JT, U.K. (Email: a.h.jamson@its.leeds.ac.uk)

ABSTRACT

The underlying aim of HASTE, an EU FP5 project, is the development of a valid, cost-effective and reliable assessment protocol to evaluate the potential distraction of an in-vehicle information system on driving performance. As part of this development, the current study was performed to examine the systematic relationship between primary and secondary task complexity for a specific task modality in a particular driving environment. Two fundamentally distinct secondary tasks (or surrogate in-vehicle information systems, sIVIS) were developed: a visual search task, designed such that it only required visual processing/demand and an auditory continuous memory task, intended to cognitively load drivers without any visual stimulus. A high fidelity, fixed-base driving simulator was used to test 48 participants on a car following task. Virtual traffic scenarios varied in driving demand. Drivers compensated for both types of sIVIS by reducing their speed (this result was more prominent during interaction with the visual task). However, they seemed incapable of fully prioritising the primary driving task over either the visual or cognitive secondary tasks as an increase in sIVIS demand was associated with a reduction in driving performance: drivers showed reduced anticipation of braking requirements and shorter time-to-collision. These results are of potential interest to designers of in-vehicle systems.

INTRODUCTION

Whilst driver inattention and human error are often linked with vehicle accidents, the true scale of the problem is unclear. At the turn of the last millennium, distraction was linked to as much as 50% of the motor-vehicle accidents on U.S. highways (U.S. Department of Transportation, 1998), whilst in Japan it accounted for 25% (Japanese Traffic Bureau, 1998). In the U.K., the problem appears to be less severe. Stevens and Minton (2001) state that only 2% of fatal accidents between 1985 and 1995 were reported to be caused by in-vehicle distractions. However, during this period less in-vehicle technology was available. Furthermore, as argued by Haigney and Westerman (2001), this figure is likely to be an under-estimate since it is based on self-reports and is potentially biased by under-reporting due to fears of legal ramifications.

Developments in in-vehicle technology, such as navigation displays, telephones and entertainment system undoubtedly offer drivers real benefits, for example, those involved in sales (Eost and Flyte, 1998). However, driving is a complex, safety-critical task. When drivers choose to perform, concurrently, a range of other tasks, there is an associated increase in accident risk (Steven and Minton, 2001; Stutts and Hunter, 2003). There are at least two well-accepted theories to explain this: Multiple Resource models of divided attention (Wickens, 1984; Wickens, 1992) and Working Memory (Baddeley, 1996).

The Multiple Resource model assumes that there are three limited capacity resources: processing stages (ranging from early perceptual to late central processing), modality (auditory and visual) and response (spatial and verbal). Optimal task performance is achieved when the conflict between the resources required for each task is minimised. Given driving as a primary task (a visual-spatial-manual task); auditory secondary tasks produce less disruption than visual secondary tasks (see Parkes and Coleman, 1990). Furthermore, Liu (2001) demonstrated faster response times and more accurate performance to either auditory or audio-visual presentation of information, compared to purely visual presentation of the same information.

Working Memory (Baddeley, 2003) models a system that is responsible for the processing and maintenance of information for short durations. The system has three major components. The central executive describes a supervisory system overseeing two slave systems: the phonological loop and the visuospatial sketchpad. The phonological loop attends to linguistic information and the visuospatial sketchpad serves visual and spatial information. Essentially, the slave systems have the role of information storage. The model forms a basis as to what Atkinson and Shiffrin (1968) referred to as “short-term memory”. Recently, Baddeley (1996) gave the central executive the added functions of selecting and rejecting incoming information as well as selecting and manipulating information from long-term memory. When dual tasks are performed, the working memory model suggests that if those two tasks share the same working memory resource, performance in one or both deteriorates when tasks are performed concurrently as opposed to independently.

These theories, along with the accident statistics mentioned above (U.S. Department of Transportation, 1998; Japanese Traffic Bureau, 1998; Stevens and Minton, 2001), provide a basis for current concerns over drivers’ ability to successfully interact with in-vehicle information systems (IVIS) whilst driving. Presently, various methods of assessment are available to assist designers in achieving minimum distraction with their systems. These include: the HMI Checklist (Stevens, Board, Allen and Quimby, 1999), the EU Statement of Principles (2000), British Standard design guidelines (BSI, 1996; Stevens, Quimby, Board, Kersloot and Burns, 2002) and the 15s rule (SAE, 2000; Green, 1999).

Whilst these checklist methods provide a tool in identifying potential design problems with IVIS, authorities lack useful methods of assessing their actual safety impact. Furthermore, some of the current methods have come in for some criticisms, particularly the 15s rule (Noy, Lemoine, Klachan and Burns, 2004) and the occlusion method used to enforce it during testing (Lansdown, Burns and Parkes, 2004). The development of a valid, cost-effective, reliable and efficient assessment protocol is the underlying aim of HASTE, an EU FP5 project.

Several studies have examined the effect on driving and task performance of the both visual and auditory in-vehicle secondary tasks. Dewing, Johnson and Stackhouse (1995) investigated the effects of three ecologically valid secondary tasks on driving: undertaking simulated cellular phone conversation, finding objects from a closed container and interacting with an in-vehicle system proving both routing and traffic information. Tasks were performed individually and in conjunction with one another. Findings indicated that drivers suffered reduced primary (driving) task performance when interacting with the visual rather than the auditory task. Lui (2002) showed a similar effect.

Further work has revolved around manipulating complexity levels of both primary and secondary tasks, mainly visual/manual and auditory systems, but separately. During an on-road study, Verwey (2001) showed an increasing number of unsafe situations occurring as the complexity of interaction with an in-vehicle information system increased. Radeborg, Briem and Heman (1999) investigated performance on an auditory recall and judgment task with varying levels of primary task complexity. Driving was made more difficult by reducing the grip afforded by the simulated driving surface. An effect of driving was proven but increasing the difficulty of the primary task had no discernable effect on secondary task performance.

A related auditory task, the use of cellular phones while driving, has been the subject of substantial recent research (see Goodman, Tijerina, Bents and Wierwille, 1999; Haigney and Westerman, 2001, for reviews). When using a cellular phone, drivers respond less effectively to events in the driving environment, e.g. braking in response to visual stimuli (Alm and Nilsson, 1994), taking evasive action to avoid objects (Cooper, Zheng, Richard, Vavrik, Heinrichs and Siegmund, 2003), detecting lead car deceleration (Lamble, Kaurenen, Laakso and Summala, 1999) and taking evasive action to a range of traffic scenarios (McKnight and McKnight, 1993). Brookhuis, De Vries and De Waard (1991) found a decrease in variability of lateral position when drivers were using a mobile phone, particularly in a motorway driving environment. Reduced responsiveness to external events may be an involuntary result of increased competition for attentional resources when performing an auditory secondary task. Alternatively, drivers may be aware of threats to performance when dual-tasking and reduced responsiveness may be part of a process of strategic control designed to facilitate timesharing.

However, there is limited evidence that drivers compensate for demands associated with cellular phone use by increasing safety margins. Haigney et al. (2000) and Alm & Nilsson (1994) found speed reductions when taking a phone call. Cooper et al. (2003) found drivers were more cautious in response to changing traffic lights when engaged in a cellular phone task. However, it would seem that cognitive activity associated with 'hands free' phone operations may also have a detrimental effect on driving performance (Goodman et al., 1999; Lamble et al., 1999; Strayer and Johnson, 2001). Parkes (1993) showed that business negotiations made by cellular phone whilst driving suffered in comparison to those conducted when not driving.

In order to develop the HASTE IVIS assessment protocol, it is first important to explore the relationship between secondary task modality, secondary task complexity, primary task complexity and driving environment at a fundamental level. Whilst the studies noted during this introduction provide a useful insight, there is an absence of published work using safety margins to examine the systematic relationship between primary and sIVIS task complexity for a specific task modality in a specific driving environment. The nature of these relationships is the question that the current study attempts to address.

Experimental aims

The current study was designed to investigate the effects of a cognitive (presented as an auditory task) and a visual sIVIS on primary (driving) task performance. Both the demands of the primary task and the complexity of the secondary task were varied systematically in order to try and understand further the relationship of a driver's voluntary or sub-conscious performance trade-off between the two tasks. A further point of investigation was whether the effects of cognitive or visual load differed quantifiably. Since the more demanding secondary tasks were considered to be highly distracting, to limit danger to participants taking part in the investigation, a driving simulator was used.

The null hypothesis was that there would be no effect on either primary or secondary task performance of varying primary task complexity. Similarly, the second null hypothesis was that there would be no effect on either primary or secondary task performance of varying secondary task complexity. The third null hypothesis was that there would be no effect of modality (visual and cognitive) of the secondary task on driving. Driving performance indicators directly related to safety margins were used as dependent variables.

METHOD

Design and analysis

The present study used a fixed-base driving simulator. A repeated measures experimental design was used, involving three factors: primary task difficulty (driving scenarios), secondary task (sIVIS) modality and secondary task (sIVIS) difficulty. Primary task difficulty and secondary task difficulty were within-subjects factors, whilst secondary task modality was a between-subjects factor. This was to minimise learning effects, since some of the simulated scenarios involved unexpected braking to simulated traffic scenarios. Main effects and interactions between the factors were assessed by carrying out a series of repeated measures ANOVA, corrected for sphericity violations where necessary by use of the Greenhouse-Geisser (1959) modification.

Driving simulator

The Leeds Driving Simulator (Figure 1) was used for the study. The simulator has no motion system and is based on a complete Rover 216GTi, with all of its driver controls and dashboard instrumentation still fully operational. A real-time, fully textured and anti-aliased, 3-D graphical scene of the virtual world is projected on a 2.5 m radius cylindrical screen in front of the driver. This scene is generated by a SGI Onyx2® Infinite Reality2 graphical workstation. A Roland digital sound sampler creates realistic sounds of engine and other noises via two speakers mounted close to each forward road wheel. The projection system consists of five forward channels, the front three at a resolution of 1280 x 1024 pixels. The images are edge-blended to provide a near seamless total image, and along with two peripheral channels (640 x 480 each), the total horizontal field of view is 230°. The vertical field of view is 39°. A rear view (60°) is back projected onto a screen behind the car to provide an image seen through the vehicle's rear view mirror. For this study, the frame rate was fixed to a constant 60Hz. Although the simulator is fixed-base, torque feedback at the steering wheel is provided via a motor fixed at the end of the steering column and a vacuum motor provides the brake pedal booster assistance. Data are collected at the frame rate.

FIGURE 1 ABOUT HERE

Primary task complexity (driving scenarios)

The road network was about 30km long with a 96kph (60mph) posted speed limit and took around 20 minutes to complete. There were two 3.65m wide lanes, one in each direction with no verge nor shoulder to the lane. The surrounding virtual environment mimicked a rural road layout with medium density, on-coming traffic. Participant drivers were instructed to drive as naturally as possible, bearing in mind the speed limit of the rural road.

A lead car was introduced at the start of each rural road, and participants were instructed not to overtake this car. At the start of each level of primary task complexity (scenario), the lead car was controlled such that it maintained a headway of 3s in front of the simulator vehicle.

Primary task complexity was split into three levels, each involving lead car following: straight car following, curved section following and discrete events. For straight sections, a following scenario was choreographed such that the lead vehicle began an 864m straight section of virtual roadway at a headway of 3s. After this point, the lead vehicle maintained a constant speed and interaction with the secondary task began automatically. This scenario required minimal driver workload compared to the other scenarios.

During curved sections, the lead vehicle also entered this section at a headway of 3s and then maintained a constant speed as the secondary task commenced. The section of roadway, also 864m, was made up of 18 curved segments making a double s-shaped bend. Curves varied left and right and radius fluctuated between 510m and 750m. This gentle curving scenario required some negotiation by the driver and driver workload was considered to be higher than the simple straight following.

Discrete events lead to a major reduction of speed by the lead vehicle due to some obstruction of the roadway ahead. The simulator driver, blocked in by oncoming traffic, was hence forced to brake in order to avoid a collision. The initial deceleration of the lead vehicle was $5m/s^2$ for 2s, followed by a more gentle slowing over the rest of the 30s event. The scenarios took place over the same curved section described above and from a headway of 3s. As well as requiring a reasonable degree of interaction with the simulator and the lead car, this type of scenario was also thought to impose maximal workload, compared to the other two scenario levels.

Secondary tasks (sIVIS)

Two fundamentally distinct in-vehicle tasks or surrogate IVIS (sIVIS) were designed. The visual search task ("arrows") was based on Treisman's Feature Integration Theory (Treisman, 1988). It was designed such that it only required visual processing/demand and minimal cognitive processing. A group of arrows were displayed on a touch-screen LCD mounted in the vehicle. The requirement of the driver was to make a manual yes/no response via the touch-screen if a "target" arrow (one pointing directly upwards) was present.

The auditory continuous memory task (aCMT) was designed to cognitively load drivers without any visual stimulus. Adapted from a visual version (Veltman & Gaillard, 1998), the task required drivers to maintain a count of their "target" sound, heard randomly amongst a sequence of non-target presentations. The counting response was given verbally. A count of each target sound was kept separately, and non-target sounds were not tallied up.

Secondary task difficulty

To create three levels of difficulty for the "arrows task", six different arrangements of arrows were presented on the touch screen LCD, each for 5s, forming a 30s 'burst'. On some occasions the upward pointing 'target' arrow was present and on others it was not. The actual presentations of the displays are shown in Figure 2.

FIGURE 2 ABOUT HERE

The auditory continuous memory task involved the presentation of fifteen complex sounds at a rate of one every 2s. To create the three difficulty levels, participants were required to keep a separate count of two, three or four target sounds (see Table 1).

TABLE 1 ABOUT HERE

Participants

Drivers were drawn from a database of experienced simulator drivers: each had between one and five hours of previous experience of the simulator. This provided a stable level of simulator-specific driving familiarity and skill, and minimized the possibility of simulator sickness, whilst ensuring that participants were not over-exposed to the simulated environment. Participants had not been involved with previous 'technology-based' studies, such as those related to cellular phone use.

In total, forty-eight drivers aged between 25 and 50 years old participated, twenty-four with each of modality of secondary task (type of sIVIS). Driver demographics are show in Table 2.

TABLE 2 ABOUT HERE

Procedure

Data collection took around one and half hours per driver. On arrival, they were first briefed on the requirements of the investigation. Once they had read and understood this, they signed informed consent. They were allocated to one of the two modalities of sIVIS.

First, they performed a 20-30 minute practice period, split into three phases. The first phase was designed simply to enable them to re-acquaint themselves with the controls and handling of the simulator. This took around 10-15 minutes and involved driving in a rural environment at around 50-60mph over around 15km of winding, virtual road. In the second phase, participants learnt to interact with the sIVIS, without any driving required. This was done in order to stabilize any learning effects and ensure that they could perform without errors (allowing the measurement of secondary task performance in terms of response time to correct answers). Once comfortable with the sIVIS, they were allowed to continue to the third and final phase of the practice period. This combined the two tasks (driving + sIVIS interaction) in a 10-min practice drive involving a car following scenario.

After a short break, they completed the experimental session that included three components. The first was a measure of static sIVIS response performance. For this, participants were seated in the simulator with a static view of the virtual scene and were required to interact with the sIVIS without any driving. The second component was a 20-minute driving session on either *route 1* or *route 2* (Table 3), both with and without sIVIS, i.e. baseline driving data were recorded from a separate drive. Each route include nine 'events', consisting of the three primary task levels (driving scenarios) for each of the three levels of difficulty of secondary task. The order of presentation of the secondary tasks was counterbalanced across participants to nullify any learning effects. The order in which participants performed these components was also counter-balanced.

TABLE 3 ABOUT HERE

RESULTS

Effects of experimental manipulations of demand on both the primary (driving) and secondary (sIVIS) tasks were examined separately using a series of repeated measures ANOVA. Designs varied across analyses, as indicated below. For the baseline driving data, three repetitions of each level of driving complexity were recorded. The mean of these three measurements were used in the ANOVA. A degree of non-normality was apparent in some of the data and consequently the effects of various transformations were explored, as was exclusion of extreme scores. However, non-transformed analyses of the full dataset provided very similar if somewhat more conservative results. Therefore it is these analyses that are reported.

Secondary (sIVIS) task performance

Auditory task. As response to the auditory task was given verbally and recorded manually, no measure of reaction time was possible. Hence, the percentage of correct answers (both target sound recognition and correct count) was the main index of auditory task performance (see Figure 3). A 4 x 3 (four levels of driving complexity, including baseline x three levels of sIVIS difficulty) repeated measures ANOVA was carried out on the data. There was a strong main effect of both driving demand; $F(3,69)=4.52$, $p=.006$ and of sIVIS demand; $F(2,46)=15.6$, $p<.001$. Trend analysis confirmed a significant effect located in the linear component of both main effects: driving demand, $F(1,23)=4.35$, p=.030; sIVIS demand, $F(1,23)=31.1$, p<.001. The percentage of correct responses grew worse as both driving and sIVIS demand increased. There was no interaction; $F(6,138)=.91$, $p=.49$.

FIGURE 3 ABOUT HERE

Along with correct responses, errors were also recorded. Errors were defined as either an incorrect count given to a target sound, missed responses to a target sound or a false positive response to a non-target sound. A 4 x 3 (four levels of driving complexity, including baseline x three levels of sIVIS difficulty) repeated measures ANOVA was carried out on the data. Results are shown in Table 4. There was no effect of driving demand on incorrect counts; $F(3,69)=.30$, $p=.83$. However, a strong effect of sIVIS difficulty was shown; $F(2,46)=15.1$, $p<.001$. Contrast analysis showed a significant linear trend of this effect: $F(1,23)=30.6$, p<.001. As sIVIS demand grew, the number of incorrect counts increased. There was no interaction of driving complexity and sIVIS demand; $F(6,138)=.89$, $p=.51$.

For missed responses, results were similar. There was an effect of both driving demand; $F(3,69)=5.79$, $p<.001$ and of sIVIS difficulty; $F(2,46)=5.42$, $p=.038$. There was no interaction; $F(6,138)=.61$, $p=.72$.

Results of the ANOVA on false positive responses did not show any reliable effects, although there was a general fall in these responses with an increase in the number of target sounds. This was expected, however, due to the fall in the number of non-target sounds from difficulty level 1 to 3.

TABLE 4 ABOUT HERE

Visual task. A manual response (yes/no) was given to the visual task and hence a measure of reaction time for correct responses to the visual task was possible and was the main index of secondary task performance. A 4 x 3 (four levels of driving complexity including baseline x three levels of sIVIS difficulty) repeated measures ANOVA was carried out on the data and results are shown in Figure 4. There was a strong main effect of driving demand; $F(3,69)=13.4$, $p<.001$. Trend analysis showed this effect to be located in the quadratic component: $F(1,23)=19.8$, p<.001. There was also a strong main effect of sIVIS demand;

F(2,46)=65.0, *p*<.001. This was a significant linear trend; *F*(1,23)=117, p<.001. Response time to the visual "arrows" task increased with both driving and sIVIS demand.

There was also an interaction between the two factors; *F*(6,138)=2.40, *p*=.031. Reaction time was found to increase with both driving difficulty and sIVIS demand. However, the increase in reaction time with sIVIS difficulty was less with the demand of driving than when static. Potentially, levels 2 and 3 are both so difficult that drivers simply give up on the secondary task when driving, whereas they have no such resource allocation pressures when stationary.

FIGURE 4 ABOUT HERE

Subjective driving ratings

Auditory task. After each 'event', i.e. interaction with either sIVIS, drivers were required to rate their self-assessed quality of driving performance on a linear scale between 1 ("I drove very badly") and 10 ("I drove very well"). A high score equated to a good self-rating of primary task performance. A 3 x 4 (three levels of driving complexity x four levels of sIVIS difficulty including baseline, i.e. no sIVIS) repeated measures ANOVA was carried out on the data and results are shown in Figure 5. There was a main effect of both driving demand; *F*(2,46)=12.9, *p*<.001 and of sIVIS demand; *F*(3,69)=14.8, *p*<.001. Trend analysis confirmed a significance of the linear component of both main effects: driving demand, *F*(1,23)=21.6, p<.001; sIVIS demand, *F*(1,23)=21.9, p<.001. Drivers rated their own performance worse both for more complex driving scenarios and with more difficult sIVIS interactions. There was no interaction; *F*(6,138)=1.43, *p*=.21.

Visual task. Similarly, a 3 x 4 (driving complexity x sIVIS difficulty including baseline) repeated measures ANOVA was carried out on the data and results are also shown in Figure 5. Participants reported their worse with visual rather than auditory distraction. There was a main effect of both driving demand; *F*(2,46)=23.3, *p*<.001 and of sIVIS demand; *F*(3,69)=36.5, *p*<.001. A significant linear trend was demonstrated for both main effects: driving demand, *F*(1,23)=6.75, p=.016; sIVIS demand, *F*(1,23)=93.7, p<.001. There was no interaction; *F*(6,138)=1.47, *p*=.19.

FIGURE 5 ABOUT HERE

Primary task performance

Mean speed. Mean driving speed was recorded during each 30s 'burst' of sIVIS and during corresponding baseline driving events. Since drivers had to slow down during discrete events due to their very nature, two separate 2 x 4 (two levels of driving complexity: straight and curve x four levels of sIVIS difficulty including baseline) repeated measures ANOVAs were carried out on these data for both types of sIVIS. Results are shown in Figure 6. There was a main effect of driving demand for both secondary tasks: auditory task *F*(1,23)=4.74, *p*=.040; visual task *F*(1,23)=4.30, *p*=.05. Driving speed was slower on curves than on straights.

There was also a main effect of sIVIS demand: auditory task *F*(3,69)=4.22, *p*=.008; visual task *F*(3,69)=12.0, *p*<.001. There were significant linear trends for both secondary tasks: auditory task *F*(1,23)=9.76, *p*=.005; visual task *F*(1,23)=17.45, *p*<.001. Driving speed reduced along with an increase in sIVIS demand. However, there was no interaction in either case: auditory task, $F(3,69)=1.26$, $p=.29$; visual task, $F(6,138)=.094$, $p=.963$. As speed decreased, the resulting increase in following headway was also demonstrated.

Figure 6 ABOUT HERE

Mean of TTC minima. Time to Collision (TTC) reflects the time safety margin adopted by drivers for taking action if the lead car brakes suddenly; the less TTC, the less safety margin. It was defined as the time that would elapse, if both the simulator car and lead car maintained their current speeds, before a collision occurred between them:

$$TTC = \frac{s}{\Delta v}$$

where s = distance between the two vehicle,
Δv = relative velocity of the two vehicles.

Since TTC is most pertinent during events where the lead car is forced to brake and drivers must slow down to avoid a collision, the analysis considers only the discrete events. Therefore TTC data were analysed using a single factor (sIVIS demand) ANOVA. The minimum value of all TTC minima under 15s during each event was used as the dependent variable (Figure 7). One participant was removed from the analysis of visual sIVIS as they collided with the lead vehicle during each of the three baseline discrete events. There was a main effect of auditory sIVIS demand: auditory task $F(3,69)=5.17$, $p=.003$ and a trend towards an effect of the visual task $F(3,66)=2.28$, $p=.087$. Trend analysis confirmed a significant effect located in the linear component of driving demand; auditory task, $F(1,23)=8.85$, p=.007; sIVIS demand, $F(1,23)=6.37$, p=.019. Drivers became closer to colliding with the lead vehicle the more complex the sIVIS demands. Similar results based on brake reaction time, minimum time and distance headway were also demonstrated.

FIGURE 7 ABOUT HERE

Lane position variation. Lane position was defined as the distance between the offside edge of the front or rear right wheels to the left hand edge of the lane boundary (U.K. style). The lane boundaries were defined as the inner edges of the lane markings. Lane position variation was defined as the standard deviation of lane position over the duration of each straight or curved event. Discrete events were not considered for analysis since they involved an inherent slowing down of the vehicle, where lateral control is much more straight-forward. Therefore lane position variation data were analysed by two separate 2 x 4 (two levels of driving complexity: straight and curve x four levels of sIVIS difficulty including baseline) repeated measures ANOVAs. Results are shown in

Figure 8.

There was a main effect of driving demand for both secondary tasks: auditory task $F(1,23)=63.0$, $p<.001$; visual task $F(1,23)=89.0$, $p<.001$. There was also a main effect of sIVIS demand: auditory task $F(3,69)=6.19$, $p=.001$; visual task $F(3,69)=4.89$, $p=.004$. These effects showed significant linear trends; auditory task $F(1,23)=13.2$, $p<.001$; visual task $F(1,23)=13.3$, $p<.001$. For the auditory task, lane position variation decreased with an increase in sIVIS demand, whereas for the visual task the opposite was true: lane variation increased with an increase in sIVIS difficulty. There was also an interaction for the auditory task, $F(3,69)=3.82$, $p=.014$, that was not apparent for the visual task $F(6,138)=1.33$, $p=.27$. On straight sections, lane variation decreased with increasing auditory task demand, whereas on curved sections lane variation decreased less sharply. Similar results were shown for minimum time to line crossing.

Figure 8 ABOUT HERE

Steering reversal rate. Due to attentional demands of secondary in-vehicle tasks, drivers may not pay continuous attention to the lane-tracking (steering) task. Steering-reversal rate (McLean & Hoffmann, 1975) can record this phenomenon quantitively. Reversal rate is defined as the number of changes in steering wheel direction per minute. At least an angle difference of 1° between steering end values is required for the reversal to count. Higher reversal rate indicates a higher level of driver workload. As with variation in lane position, steering reversal rate was recorded on both straight and curved event. Results are shown in Figure 9.

There was a main effect of driving demand for both secondary tasks: auditory task $F(1,23)=121$, $p<.001$; visual task $F(1,23)=87.5$, $p<.001$. There was no main effect of sIVIS demand for the auditory task; $F(3,69)=.77$, $p=.51$; whilst increasing demand from the visual task showed significantly increased steering reversals; $F(3,69)=24.5$, $p<.001$. This effect showed a significant linear trend; $F(1,23)=59.2$, $p<.001$. The more complex the visual task, the greater the number of small steering corrections made. There was no interaction for either secondary task; auditory $F(6,138)=.47$, $p=.71$; visual $F(3,69)=.64$, $p=.59$.

FIGURE 9 ABOUT HERE

An analysis was also made on the number of rapid steering wheel corrections that were made during concurrent driving and sIVIS interaction. Rapid steering wheel corrections were defined as the number of occasions that the rate of change of steering angle exceeded 20° per second. Results were identical to those for steering reversal rate.

DISCUSSION

This experiment examined the effects on driving performance of two concurrent secondary tasks, designed to reflect the processing demands associated with both visual (“arrows” visual search) and cognitive (auditory continuous memory) load. Performance was assessed in simulated conditions varying in both primary driving and secondary task demand.

It appears, consistent with previous studies (Alm and Nilsson, 1994; Brookhuis, De Vries and De Waard, 1991) that drivers, either consciously or subconsciously, developed a strategy to reduce primary task load whilst performing concurrent secondary tasks. This was shown by a significant reduction in driving speed during interaction with both the auditory and visual tasks. In essence, drivers appear to be attempting to free-up resources for the secondary task by simplifying the primary task. Consistent with theories of both Working Memory and of Multiple Resource, this strategy was much more pronounced during interaction with the visual task, which conflicted more directly with the demands of driving and maintaining a safe headway to the lead vehicle. The success of this strategy is questionable as, in the longitudinal domain, an increase in secondary task demand was associated with a decrease in time to collision during scenarios in which a lead vehicle braked unexpectedly. This effect was shown to the same order of magnitude for both auditory and visual concurrent tasks. Furthermore, the most complex sIVIS tasks that required the most central resource and were the most detrimental on driving performance.

In the lateral domain, the effects of the secondary tasks were in opposite directions. Drivers demonstrated more steering wheel corrections (reversal rate) to both increasing visual and auditory task demands, consistent with the additional required workload as suggested by McLean and Hoffmann (1975). Whilst this effect was more pronounced for the visual task, again in all likelihood due to its direct interference with the visual driving task, an increase in variation of lane performance was only demonstrated with an increase in visual load. An increase in auditory load showed the opposite effect: the greater the auditory load, the less the lane variation. This 'improvement' in steering performance has also been associated with an increase in gaze concentration towards the road centre (Engström, Johansson and Östlund, this issue). It is suggested that increasing auditory task demand may lead to a 'cognitive narrowing' where visual resources are focussed more to the area of most interest and potential hazard to a following driver: the lead vehicle. This, indirectly, leads to a superior perception of the roadway, allowing an improvement to the lane keeping performance of the driver. Whilst improved lane keeping can be associated with this cognitive narrowing, the downside is likely to involve a reduction in peripheral hazard perception and situational awareness. Unfortunately, as no peripheral object perception task was used in this study, this intuitive conclusion cannot be further elaborated.

Drivers' self reports showed their ability to recognise reduced primary task performance when performing concurrent secondary tasks. Furthermore, drivers appeared able to recognise further reduced driving performance whilst interacting with the visual task over the auditory task. Whilst it is promising that drivers seem to hold this ability, there is evidence to suggest that, in reality, they underestimate the potential severity of these distractions and continue to multi-task without fear of reduced responsiveness (White, Eiser and Harris, 2004). It is cause for concern that drivers' overconfidence can override their own ability to recognise their shortcomings whilst performing concurrent secondary tasks whilst driving.

One criticism that could potentially be levied at this study is the fact that rather abstract, esoteric secondary tasks were selected. It is legitimate to suggest that both the paced nature of the tasks and their structure bear little relevance to real world in-vehicle systems. However, the intention of this study was to investigate secondary tasks that varied in demand for two fundamentally different modalities. The goal was to investigate the effect, individually, of each of these modalities. This criterion forced our hand in the selection of rather abstract tasks.

A further question is the suitability of a driving simulator in this type of investigation when more accurate results may be obtained from real world studies. Driving simulator studies could potentially suffer from lack of driver motivation where drivers' priorities may differ from reality or conversely over-estimate distraction due to the increased workload in maintaining control over the simulator. Theoretically, drivers could have less spare resource available to them in a simulator study as more is used up in the handling of the simulator. The first reason for the selection of the simulator was that a wide range of secondary task demand was required since experimental design constraints only allowed the selection of three levels of secondary task complexity. By selecting the highest level of demand that varied considerably from the lowest level, it was hoped that the trade-off between primary and secondary task demand may have been more clear. Secondly, previous real world studies on mobile phone use (Brookhuis et al., 1991) have shown similar results to simulator studies (Alm and Nilsson, 1994). Finally, other partners involved in HASTE who performed the same rural road, sIVIS study with real world driving using an instrumented vehicle road, found similar results to those reported here.

There are two main practical significances of the present study. Firstly, whilst stationary, performance on both secondary tasks decreased linearly with respective demand of both modalities. This 'static' performance accurately predicted the reduction in secondary task performance with its increasing demand whilst driving. In relative terms, the reduction in secondary task performance with increasing secondary task complexity mimicked that demonstrated with the additional demands of driving. In absolute terms, the addition of a driving demand further degraded secondary task performance. Secondly, even though drivers attempted a strategy of slowing down, freeing up valuable resources for the secondary task, a reduction in primary task performance could still be detected. In essence, drivers seemed incapable of fully prioritising the primary driving task over either visual or cognitive secondary tasks. An increase in demand of either secondary task was demonstrated by a reduction in task performance. However, and more worryingly, the increase in demand was also associated with a reduction in primary task performance, most noticeable in time to collision. These results are of potential interest to designers of in-vehicle systems.

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Table 1: three levels of difficulty of each 30s ‘burst’ of auditory sIVIS

Difficulty level 1	3 repetitions of one target sound, 12 non-target sound
Difficulty level 2	3 repetitions of two target sounds, 9 non-target sounds
Difficulty level 3	3 repetitions of three target sounds, 6 non-target sounds

Table 2: age, driving experience and mileage of participant drivers

Secondary task	**Age**	**Driving experience**	**Annual mileage**
Auditory	37.8 years, SD = 8.2	9.4 years, SD = 3.9	12800 miles, SD = 10623
Visual	31.7 years, SD = 7.2	7.2 years, SD = 3.3	8800 miles, SD = 5094

Table 3: event order for virtual driving routes

Event	**Route 1**	**Route 2**
1	Straight	Straight
2	Discrete event (sheep blocking one carriageway)	Discrete event (roadworks blocking one carriageway)
3	Curve	Curve

4	Discrete event (HGV turning into junction across driver)	Discrete event (car turning into junction across driver)
5	Curve	Curve
6	Straight	Straight
7	Straight	Straight
8	Discrete event (HGV emerging from junction in front of driver)	Discrete event (car emerging from junction in front of driver)
9	Curve	Curve

Table 4: percentage errors (and standard error) to auditory task

	sIVIS	None	Straight	Curve	Event
Percentage incorrect	2 target sound	8.57 (1.77)	5.56 (2.78)	6.25 (3.73)	9.03 (2.83)
	3 target sounds	14.5 (2.70)	10.2 (2.21)	12.6 (3.23)	12.0 (3.53)
	4 target sounds	13.3 (1.30)	18.8 (3.06)	16.1 (2.89)	18.6 (3.17)
Percentage missed	2 target sound	8.33 (2.57)	9.03 (4.37)	8.33 (4.37)	16.7 (5.31)
	3 target sounds	9.41 (1.99)	8.80 (2.91)	10.6 (3.24)	21.5 (4.96)
	4 target sounds	15.4 (2.73)	17.1 (4.15)	16.5 (3.60)	21.2 (4.49)

Figure 1: The Leeds Driving Simulator

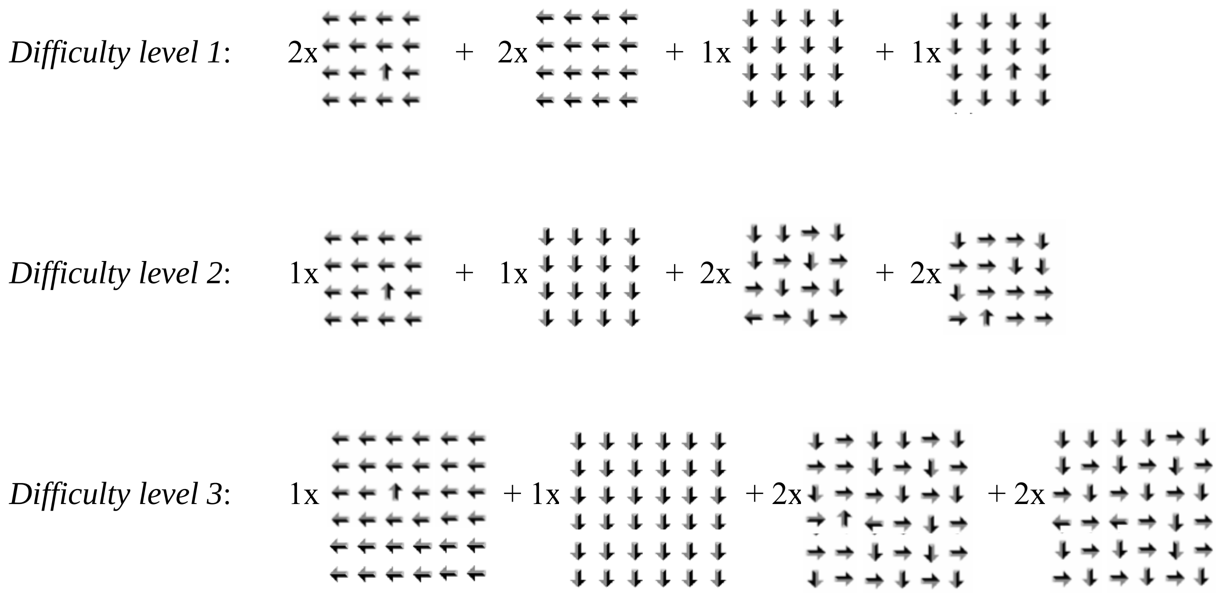

Figure 2: Three levels of difficulty of each 30s ‘burst’ of visual sIVIS

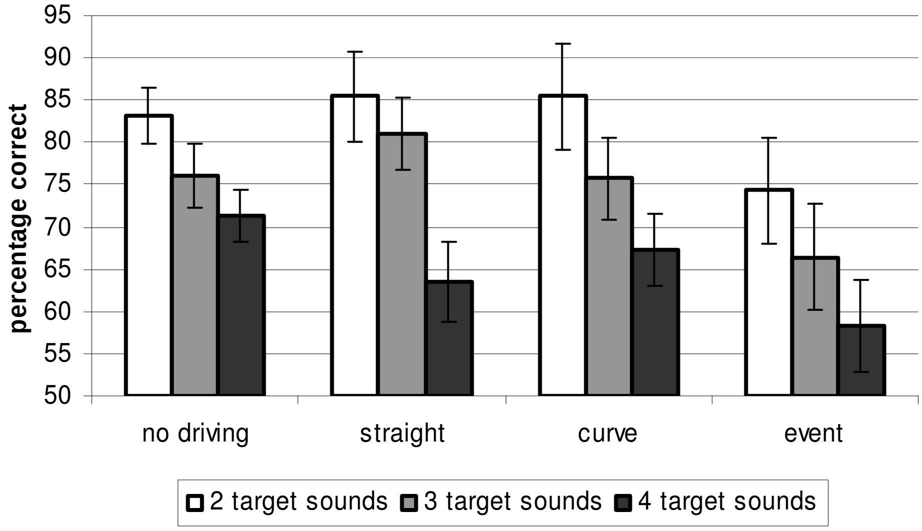

Figure 3: Percentage correct responses to auditory task (standard error bars)

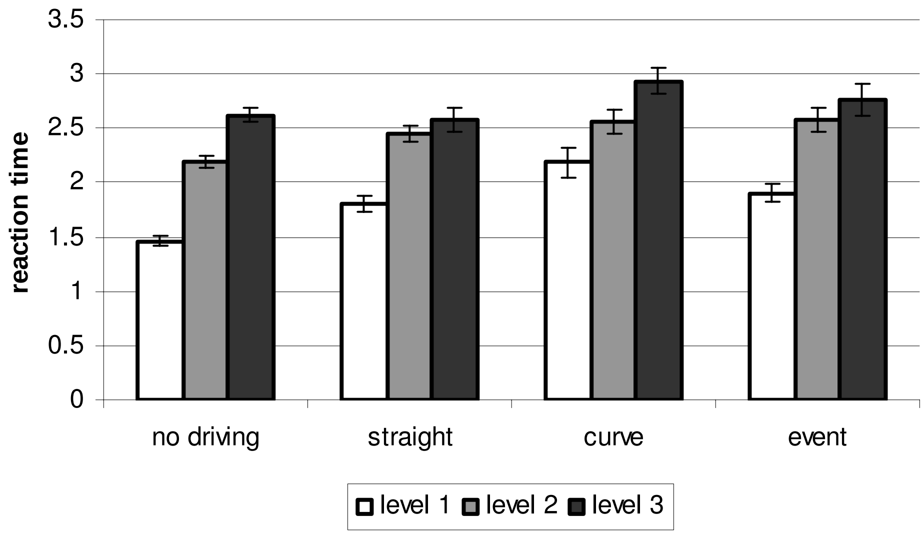

Figure 4: Reaction time to the visual task (standard error bars)

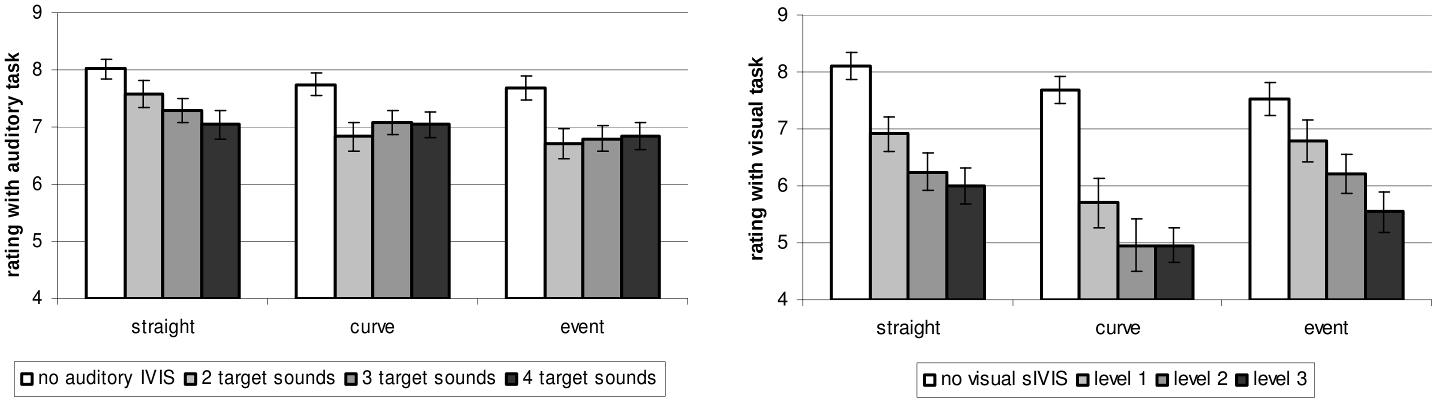

Figure 5: Subjective driving ratings for both sIVIS tasks (standard error bars)

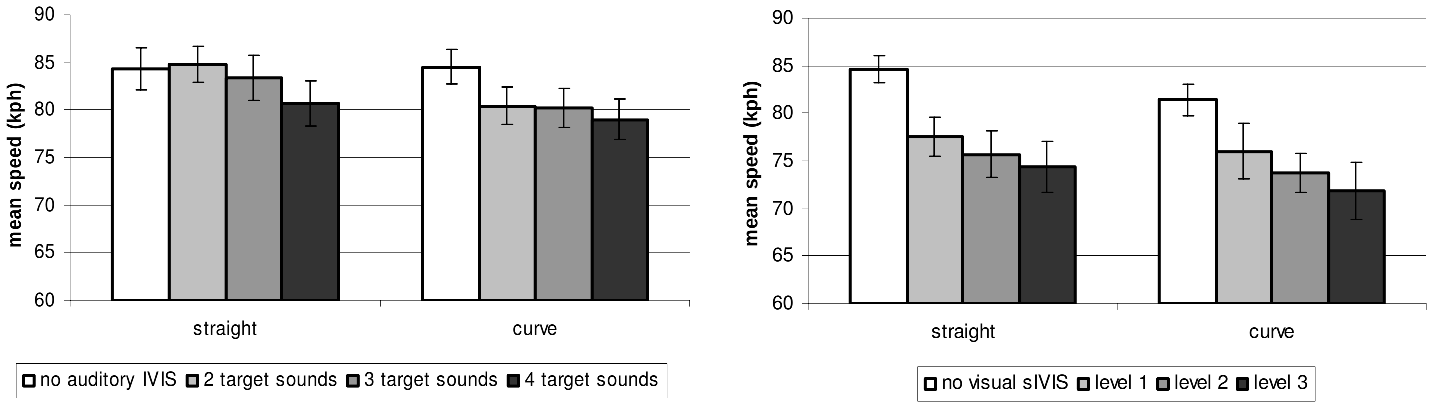

Figure 6: Mean speed for both sIVIS tasks (standard error bars)

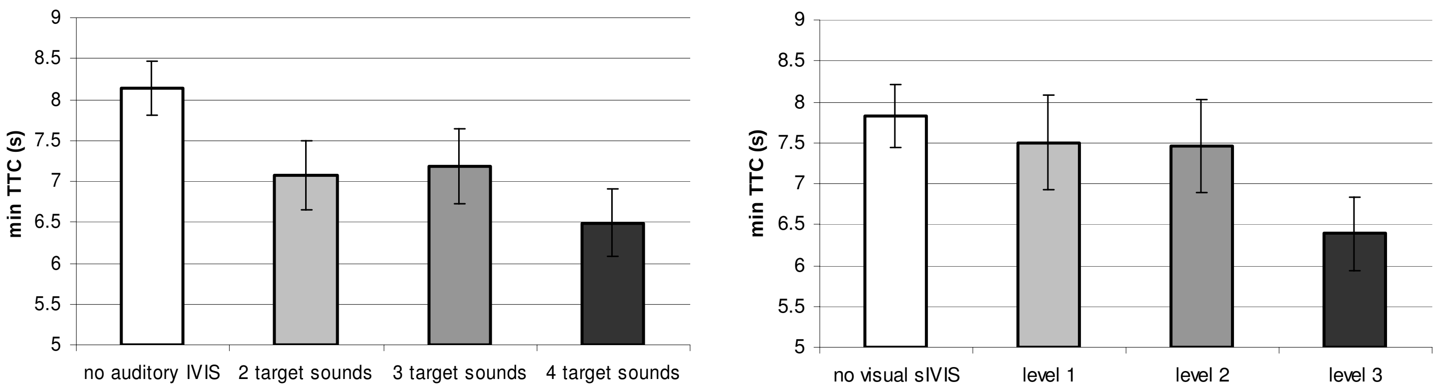

Figure 7: Mean of TTC minima for both sIVIS tasks (standard error bars)

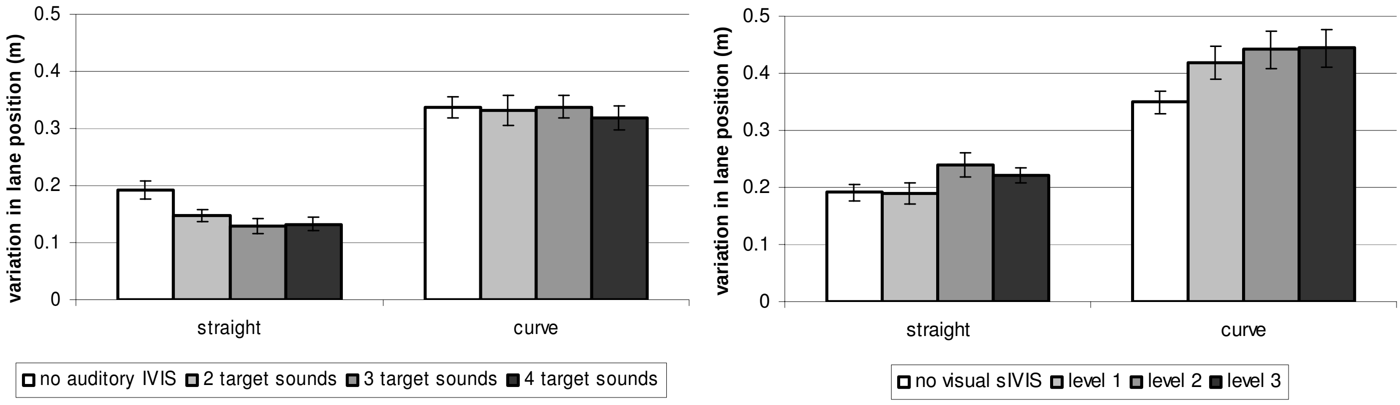

Figure 8: Variation in lane position for both sIVIS tasks (standard error bars)

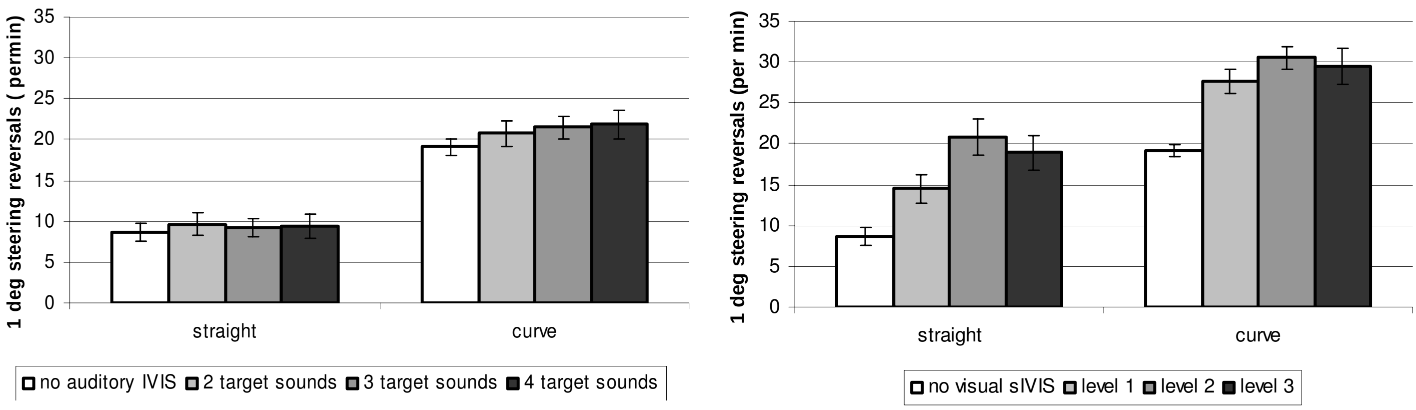

Figure 9: 1° steering reversals for both sIVIS tasks (standard error bars)