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The effect of distraction modality on driver performance

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Abstract

The increased implementation of in-vehicle information systems presented in the different perceptual modalities and the implications this has on driver distraction has prompted a research focus in this area. The present study investigated the effect of attending to a secondary comprehension task in three different perceptual modalities on driver performance. Twenty four students participated. There were three modality conditions (central visual, peripheral visual, auditory) and two difficulty conditions (low and high). The central vision condition presented text in the central visual field, the peripheral visual condition presented text in the horizontal periphery, while pre-recorded texts were played in the auditory condition. Results confirmed that driving performance decreases with concurrent secondary task attention in any perceptual modality. Auditory distraction degrades driver performance the least (~19%) compared to pure driving, followed by central visual distraction (~31%) followed by peripheral visual distraction (~54%). These differences can be attributed to superior time-sharing of the audio-visual dichotomy, as predicted by multiple resource theory.

Keywords: driver distraction; driver safety; in-vehicle tasks; multiple resource theory; human-machine interface.

1. Introduction

Driving is a common activity for many people, making driving safety an important issue in everyday life. Over the 20 years from 1990 to 2011, the number of licensed vehicles in South Africa has grown 53%, from approximately 5.25 million to 9.95 million, while total annual mileage travelled annually in South Africa has increased 27,5% from 1990 to 2008 and reached 129 million kilometres in 2010 (Road Traffic Management Corporation, 2011). However, in spite of safety improvements in road and vehicle design, the total number of fatal crashes still rises. Motor vehicle-related fatalities in South Africa has increased from 11,157 in 1990 to 14,627 in 2010 (Road Traffic Management Corporation, 2011), with a social cost rising to an estimated R306 Billion in 2012, approximately 10% of South Africa's gross domestic product (Ensor and West, 2013). This figure dwarfs estimates from other developing countries, where the cost of accidents is said to consume an average of 2% of GDP. Taken together, these figures demonstrate that driving safety represents a persistent and important issue in transport in South Arica.

Although most motor vehicle crashes are attributed to multiple causes, driver error represents the dominant causal factor, as drivers are responsible for operating vehicles and avoiding crashes (Lee, 2007). Driver inattention was linked to nearly 80% of crashes and 65% of near-crashes in the U.S conducted naturalistic 100-Car Study, with driver distraction estimated to have contributed to 25% of these (Stutts et al., 2001; Klauer et al., 2006). Most of these incidences resulted from the impairment of driver's attention, including distraction associated with secondary tasks, driving-related inattention to the forward roadway, non-specific eye glances, and fatigue. 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 (Stutts et al., 2001).

Recent advancements in in-vehicle information systems (IVIS) (e.g., navigation systems, head-up displays, hands-free cell phone kits, and internet) have been promoted as a possible solution to alleviate driver distraction in situations where there is a competition of attention resources. Reducing distraction by presenting two sets of information in different perceptual modalities might be a viable solution to alleviate driver distraction; however, research suggests that doing so may in fact increase cognitive distraction and reduce the driver's ability to respond to critical signals in the road scene (Lunenfeld, 1989; Mollenhauer, et al., 1997; Srinivasan & Jovanis, 1997, Lee et al., 2008).

The Multiple Resource Theory (MRT) (Wickens 1984; Wickens 2002) accounts for this phenomenon in terms of competition for attentional resources classified by four dichotomous dimensions: processing *stages* (perception or response selection, and response execution), processing *codes* (response (spatial and verbal)), perceptual *modalities* (auditory or visual) (Wickens, 2002), and visual *channel* (focal or ambient vision) (Horrey & Wickens, 2004). These dimensions account for variance in time-sharing performance. Assuming equal resource demand or task difficulty, MRT holds that when two tasks compete for resources at one level of a given dimension (e.g. two tasks demanding visual perception in driving), performance of one or both degrades. This suggests that in a dual-task setting, tasks are better time-shared if each draws on resources from two different perceptual modalities than between two similar modalities i.e. Audio-visual vs. Visual-visual. That is, cross-modal time-sharing is better than intra-modal time-sharing.

Inferences from MRT, along with the trend toward increasing use of IVISs and the abovementioned statistics from Road Traffic Management Corporation (2011), provides strong support to consider the effect that attending to information in different perceptual modalities has on driver behaviour (Alm & Nilsson, 1995).

This driving simulator study was designed to investigate the effect of attending to a secondary task (surrogate IVIS) presented in three different perceptual modalities on primary (driving) task performance. The difficulty of the secondary tasks was varied in order to ascertain whether any performance decrement was due to a limitation in central processing or due to concurrent demand of one attentional resource.

First, we predicted that that there will be a difference in driving performance during secondary task execution of differing modalities performed under the same difficulty. Second, we anticipated that there would be a difference in driving performance with a change in task difficulty. Finally, driving performance will decrease with an increase in visual eccentricity of the secondary task.

2. Method

2.1 Design and analysis

This study used a fixed-base driving simulator. A repeated measures experimental design was used, involving two parameters: secondary task (surrogate IVIS) modality and secondary task (surrogate IVIS) difficulty. This resulted in a 3 (perceptual modality) x 2 (task difficulty) within-subjects design, with six experimental conditions. Perceptual modality conditions were central visual, peripheral visual and auditory; difficulty conditions were defined as low and high conditions, based on each of the modal conditions. All experimental data were imported into a Statistica (v. 9) table. A general linear model was applied, with 2-way analyses of variance (ANOVA) tests ($p<0.05$) used to calculate statistical effects between differences in the driving performances as well as between the difficulties. Gender was analysed as a covariate throughout. A confidence level of 95% with a corresponding alpha level of 0.05 (5%) was chosen. Post-hoc tukey tests processed the data further, providing specific significant differences ($p<0.05$) between conditions.

2.2 Driving simulator

The driving simulator (Göbel *et al.,* 1998) (Figure 2) was used for the study. The simulator has no motion system, nor is there any torque feedback at the steering wheel. It is based on a mock-up of a right-hand Opel Monza, with a fully intact cockpit. A real-time, minimally textured, 3-d graphical scene of a virtual road is projected on a 2800mm x 1400 mm screen in front of the driver. No realistic sounds of engines or other sounds were used in this study. The projection system consists of one forward channel, at a resolution of 800 x 600 pixels. For this study, the frame rate was fixed to a constant 60Hz. Data were collected at the frame rate. Tracking (driving) speed was kept constant, at a speed low enough to allow for drivers to perform the primary and secondary task in parallel. The geometric positions of the simulation display are shown in Figure 1.

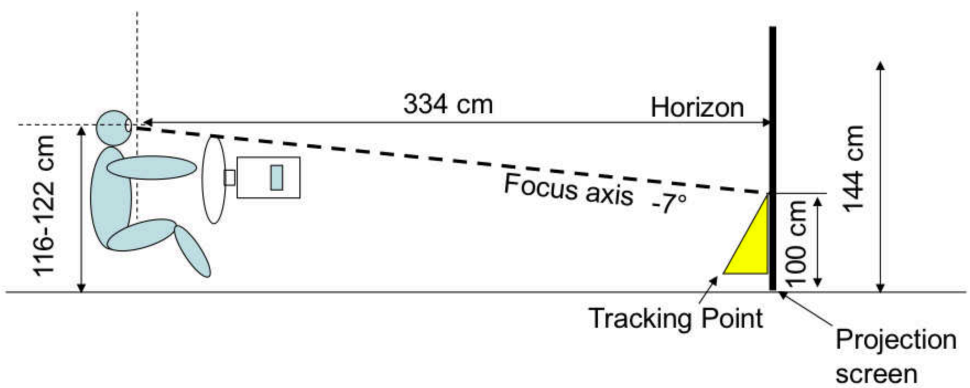

Figure 1. Geometric positions of driver and simulation display.

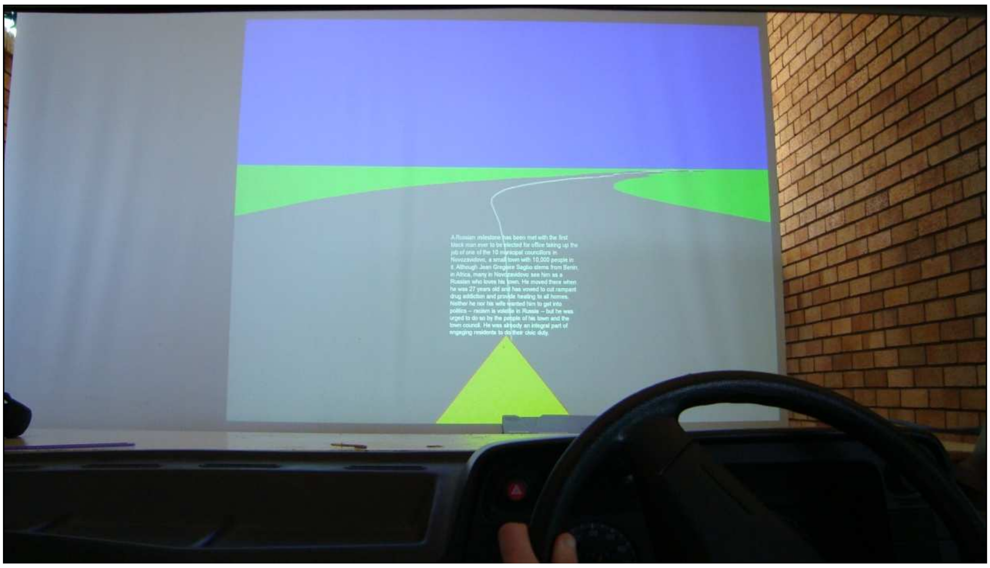

Figure 1. Participants' view of the driving simulator.

2.3 Primary task (driving) and performance measure

The simulator experiment compared vehicle lateral control (driving performance) with, and without secondary tasks that pose visual/auditory and cognitive distraction, displayed in three different modalities. Visual and cognitive distractions have been linked to degraded lateral control (Angell et al., 2006; Carsten et al., 2005). The driving simulator was used to reproduce roadway demands and a comprehension secondary task to reproduce demands representative of IVIS (dual-task approach). The primary task was a tracking task, which allowed every deviation from the target line to be measured. In this way, the driving task required 100% attention, with any reduction in performance was attributable to the secondary task. Driving performance was not considered for the first 1.5 seconds of each condition in order to allow for stabilisation.

2.4 Secondary tasks (sIVIS)

Three distinct in-vehicle comprehension tasks or surrogate IVIS (sIVIS) were designed to imitate methods of stimulus presentation in a real vehicle. The sIVIS tasks used were comprehension tasks that took the form of three modalities of IVIS commonly found in motor vehicles. These included: 1) central visual, as utilized by Heads-Up Display (HUD), 2) peripheral visual, as utilized by Heads-Down Display (HDD), and 3) auditory, as utilized, for example, by navigation systems. The information used in the comprehension tasks consisted of samples of texts (109±10 words) taken from common newspapers. Participants were required to attend to the information in the secondary task while performing the primary (driving) task. In order to ensure the participants were actively engaging with the content of the comprehension texts, following each condition participants were asked questions probing the recall of details from the text. There were three comprehension questions for each text, of which participants were expected to attain two correct answers. Failing this, the driver would repeat the condition at the end of the permutation. In this way, secondary task performance was controlled. A unique permutation of testing order was generated across all participants in order to further nullify learning effects. In addition, the comprehension tests were permutated across all conditions and participants was such that no participants would experience the same content in the same condition.

In terms of instructions for task prioritisation, drivers were encouraged to perform the secondary (sIVIS) task to the best of their ability while not neglecting the primary (driving) task. The degree of intrusion of the secondary task on performance of the primary (driving) task was examined. This would give an indication as to whether driving decrement is due to a real distraction (i.e. central processing limitation) or whether it is due to competing resources as defined by MRT.

In order to compare the effects of modality the secondary tasks contained information of the same nature. Further, the difficulty of each modal condition was varied in order to ensure that the differences between modalities were as a result of modality and not the secondary task characteristic. Therefore, the aim was to induce driver distraction with similar information for the secondary task but in different modalities and measure its effect on driving performance. This would give an indication as to the extent to which changes in performance were due to changes in resource allocation between the information modality and the secondary task.

Reading speed for the central and peripheral visual conditions was self-paced, resulting in a mean reading duration of 60±20 seconds.

The central visual modality was simulated by projecting the text as a "HUD" on to the focus area of the tracking task (Figure 1), with difficulty being manipulated by setting text character spacing to 1pt for low difficulty and 4pt for high difficulty. In order to isolate the effects of the peripheral visual modality text was present in the horizontal field of view, peripheral (left) to the focus area of the tracking task. For the low and high conditions, eccentricities were set at 10 and 20 degrees of arc, respectively. In the auditory condition the pre-recorded texts were played to the participants via a set of headphones.

The auditory sIVIS task was designed to cognitively load the participants without demanding any additional visual resources. Audio readings of the comprehension texts used in the visual tasks were used as sIVIS for the auditory modality conditions. These were recorded with a SHURE® SM57 unidirectional dynamic microphone using Adobe® Audition 3.0 in a soundproofed professional recording studio. The low difficulty level condition consisted of the information presented at a sound pressure level of 68dB with no distracting background sound, while the high difficulty level condition consisted of the information being played back at a sound pressure level of 68dB with white noise overlaid at a sound pressure level of 74dB. These parameters were set to comply with current in-vehicle stimulus guidelines (ISO, 2002).

2.5 Participants and procedures

In total, twenty-four participants (12 males, 12 females) were recruited, their ages ranging from 18 to 24 years (M = 19.43 years, SD = 1.86). Drivers were drawn from volunteer undergraduate and post-graduate students at Rhodes University. All participants held a valid driver's license for a mean duration of 2.52 years (SD = 1.24). Participants with visual impairments were required to wear corrective lenses as indicated by their driver's license. The experiment consisted of a single 40-minute testing. Participants were not given any reward for partaking in the study.

2.6 Procedure

Experimentation was conducted in the Ergonomics Laboratory in the Department of Human Kinetics and Ergonomics at Rhodes University. On arrival, the aim of the research was explained, after which the subjects were introduced to the simulator with specific instructions explaining the primary (driving) and secondary task. Once they understood this and agreed to take part in the study, they signed informed consent. Data collection took approximately one hour. Subjects were required to participate in one testing session during which two repetitions of six conditions were assessed.

Each participant performed 20 minutes of free driving habituation on the simulator 24 hours before testing. The first 10 minutes consisted of a normal tracking task, excluding any secondary tasks. In the second 10 minutes, participants were familiarised with the sIVIS, while performing the primary driving task. Before the main test, each participant performed a 5-minute pre-test control condition. This consisted of a pure primary (driving) task, and accounted for the baseline driving measure. For the main testing session, each participant performed all conditions in one session, which ranged from 30 - 40 minutes in duration. Each participant performed an additional 5-minute control condition following the testing session, this was combined and analysed along with the pre-test drive to account for the baseline driving measure. Each condition was repeated twice to account for any learning effects during the course of testing. A unique permutation of testing order was generated across all participants in order to further nullify learning effects.

3. Results

The results obtained in this study provide insight into the perceptual and cognitive resource requirements placed on drivers attending to secondary tasks in the sensory modalities most often used in IVIS. Effects of experimental manipulations of difficulty and modality of the secondary (sIVIS) tasks were examined separately using a series of repeated measures ANOVA and Tukey post-hoc comparisons. For the baseline driving data, two repetitions of 5-minute pure driving pre and post-test were recorded. The mean of these two were used in the ANOVA. All results were calculated with gender as a covariate. However, no gender effects were observed across all analyses.

A 3 x 2 (three levels of sIVIS perceptual modality x 2 levels of sIVIS difficulty) repeated measures ANOVA was carried out on the data. Consistent with the basic model of resource allocation (Wickens, 2002), there was a main overall effect of any configuration of sIVIS conditions on tracking performance (computed as a performance index relative to baseline driving (=100%)) (Figure 3) [$F(2,22) = 71{,}45$, $p < .01$]. Attending to a secondary task, regardless of modality or difficulty, significantly degrades tracking performance by a minimum of ~19% (Auditory Low condition).

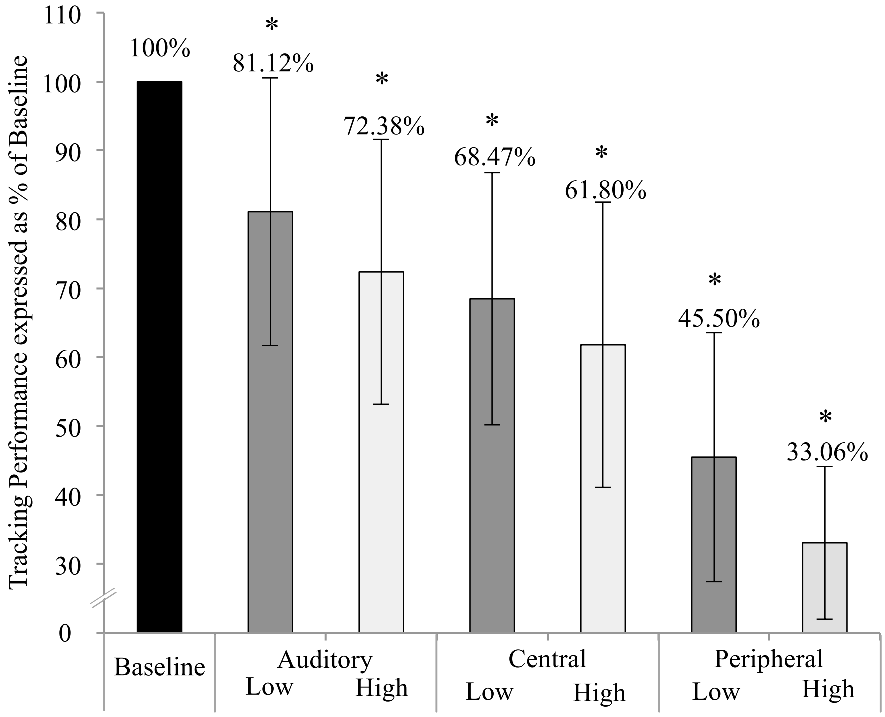

Figure 2. Mean deviation responses expressed as a percentage of the baseline drive for each condition and difficulty. Vertical bars denote standard deviation (* denotes statistically significant difference to baseline, $p<0.05$).

3.1 Effect of modality

When considering the modal distinctions laid out by MRT, tracking performance differed significantly across and between all modalities [$F(2, 22) = 71.45$, $p < .01$]. The auditory modality elicited the lowest overall decrement in tracking performance (~19%), followed by the central visual modality (~31%), followed by the peripheral visual modality (~54%).

3.2 Effect of difficulty

The main focus of this investigation was the effect of information modality on driving performance, therefore difficulty of the secondary task was manipulated in order to ensure that the differences between modalities was as a result of modality and not secondary task characteristic. There was an overall significant decrement in tracking performance between the low and high difficulty conditions [$F(1,44) = 38.95$, $p < .001$], which reflected variations in difficulty of perception of the secondary task within each modality. Post-hoc tukey analysis of pairwise comparisons revealed that there were significant differences between low and high difficulties for the auditory and peripheral vision modalities (Table 1). However, there was no evidence for a significant difference between the low and high difficulty conditions for the central visual modality. Modality was shown to not have any effect on these results, which means that they hold true for the range of difficulties as defined in the current study.

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Table 1. Statistical effects for all comparisons of primary (driving) task performance across all conditions. Values in BOLD represent comparisons of intra-modal differences in difficulty, values in ITALICS represent comparisons of inter-modal differences for the low difficulty condition (* denotes a statistically significant difference; p<0.05).

	Audio High	Central Visual Low	Central Visual High	Peripheral Visual Low	Peripheral Visual High
Audio Low	**0.027621***	*0.003994**	0.000147*	0.000147*	0.000147*
Audio High		0.981345	0.011265*	0.000147*	0.000147*
Central Visual Low			**0.067942**	*0.000147**	0.000147*
Central Visual High				0.000173*	0.000147*
Peripheral Visual Low					**0.000422***

3.3 Effect of repetition

There was a main effect of repetition between the first and second trial over all conditions [$F(1,22) = 4.53$, $p < .01$]. However, post hoc analysis revealed no interaction between trial one and two within each modality. That is, while there was a significant overall difference found between trial 1 and trial 2, this trend was not observed in any of the conditions individually.

3.4 Effect of eccentricity

In order to consider eccentricity as an influence on primary (driving) task performance, the low difficulty central visual condition is referred to here as 0° eccentricity, while the peripheral visual conditions of low and high difficulty are referred to here as 10° and 20° of eccentricity, respectively.

Tracking performance degraded significantly as the text display for the secondary (sIVIS) task increased in eccentricity. Figure 4 illustrates a significant overall main effect established between the eccentricities of 0°, 10°, and 20° ($F(2,44) = 74.3$, $p<.001$). That is, the greater the eccentricity the greater the primary (driving) decrement. The analysis of pair wise comparisons was not considered in this context as the conditions were considered as part of a spectrum of a continuous data set (eccentricity). More appropriate though, is an estimation of the performance characteristic across this visual spectrum, which shows that tracking performance is predicted to decrease as the displays for the two tasks are progressively separated.

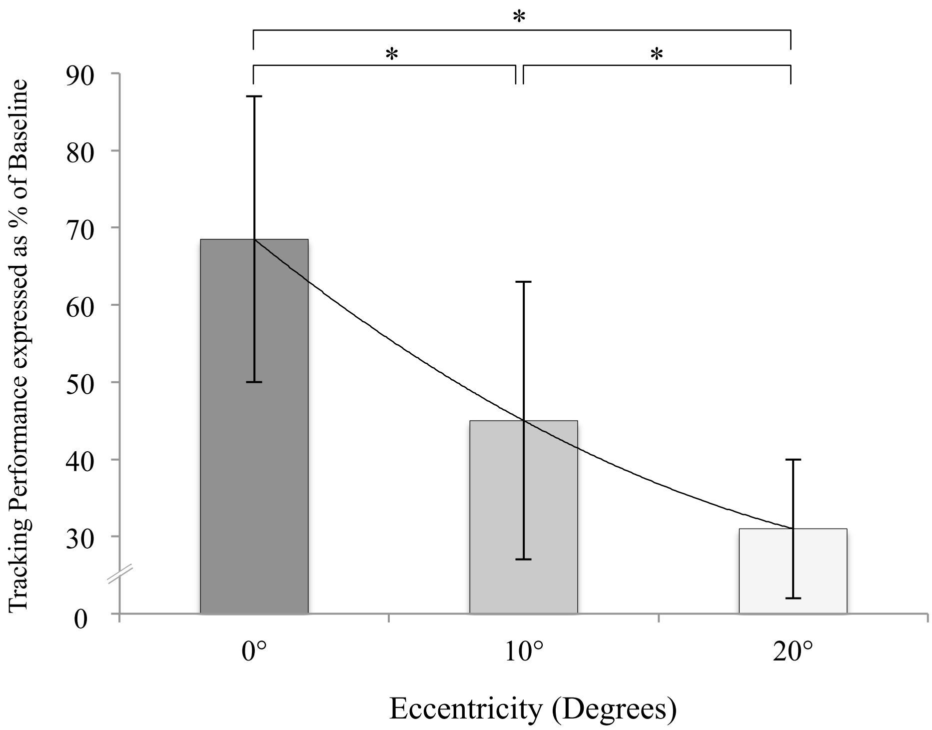

Figure 3. Overall mean deviation of low and high difficulties between eccentricities (0°, 10°, and 20°) expressed as a percentage of baseline performance, with a polynomial approximation overlaid. Vertical bars denote standard deviation (* denotes statistically significant difference, p<0.01).

4. Discussion

This study explored the effect of attending to a secondary task in different perceptual modalities on primary (driving) performance. From theoretical perspective, this study examines the resource allocation responses of three sensory modalities most used in a dual-task driving setting, at maximal cognitive and perceptual attention. The results provide support for Wickens' (2002) MRT that in dual-task situations, attention is shared more effectively across different perceptual modalities. Consistent with the hypothesis, driving performance attributed to a secondary task degrades significantly, irrespective of the modality through which that task is attended to. Therefore, performing a secondary task whilst driving, places additional strain on the perceptual and cognitive resources, in excess of that imposed by the driving task itself.

This result answers questions pertaining to human information processing at the most basic level. Given that tracking performance corresponds to resource allocation and information processing capacity (Bubb, 1993), the results of this study suggest that that driving performance is directly affected by the availability of resources. Further, this overall degradation indicates that driving in the context assumed herein is for the most part a conscious activity, which intimates that in a dual task context there is a limitation in the processing of information in the higher centres of the nervous system. This places the bottleneck of performance at the perceptual encoding stage of information processing, as this is where the stimulus is matched with previously learned neural codes in the brain and elicits stimulus perception or recognition (Wickens, 1980). This is in line with MRT, which states that even if the perceptual modality is different the tasks will interfere if both require central processing (Wickens, 2002).

While there have been no studies to date considering performance characteristics of all modalities in a worst-case scenario, this finding confirms the principle underlying multiple resource theory (MRT). That is, secondary tasks that compete for the same resources as driving will degrade driving performance (Horrey & Wickens, 2004).

As follows from Wickens' (2002) prediction, there are significant modal differences in driving performances, with the auditory modality proving to affect driving performance to a significantly lesser extent as compared to both visual modalities. However, auditory tasks are force-paced, as opposed to visual tasks that are self-paced, which means that drivers may miss vital information. The most pressing suggestion of these results is that even the most modest distraction supports the distinction between visual and cognitive distraction made by Victor (2005), with visual distraction described as "eyes-off-road" and cognitive distraction describes as "mind-off-road".

The reduction of driving performance even in auditory condition can be accounted for by one or two mechanisms. The first is that a tracking task (even though considered as highly automated) uses the central executive, which is postulated to be responsible for the selection, initiation, and termination of processing routines (e.g., encoding, storing, and retrieving). Baddeley (1986, 1990) equates the central executive with the supervisory attentional system (SAS) described by Norman and Shallice (1980) and by Shallice (1982). The second is that decrement in tracking performance is due to a depletion of attentional resources, suggesting that there is a compensatory mechanism controlling the allocation of attentional resources within intra-modal time-sharing. Indeed, these two mechanisms may both have contributed to performance decrement observed in the current study.

5. Conclusions & Recommendations

In terms of resource allocation, the data collected here has helped to define characteristics of modalities used in the design of IVISs. Statistical analyses performed on the data collected indicate that performing a tracking task with a secondary task of varying modalities and difficulties results in additional strain on the perceptual and cognitive resources, over and above that imposed by the driving task itself. Additionally, it was found that these performance characteristics differed significantly among modalities and were independent of task difficulty and should therefore be taken into consideration in the design of IVIS. The most crucial finding of the study was that performing a secondary task in the auditory channel opposed to either of the visual modalities reflected the smallest decrement in driving performance (~19%). Generally, results from this study support the key assumptions of MRT, but also suggest that cognitive resources are not completely independent from each other. To be able to better detect differences and effects of modality and difficulty, more stringent secondary tasks may need to be applied. The information obtained through the designed experimental methods is aimed at aiding the design of IVIS so that they can be attended to safely.

Recommendations based on this study's findings therefore include the modality in which IVIS are attended to by the driver and the extent to which the IVIS demands attention. With regard to these findings, the peripheral visual field should be avoided, due to the high demand of resources this channel requires. The high difficulty secondary task (IVIS) should also be avoided where possible, yet if necessary, the difficulty should be kept to a minimum. It is essential that these findings be considered in the design of IVIS, as the prevalence of IVISs will continue to rise. If the IVISs that utilise similar conditions to those studied herein, continue to be designed and employed in motor vehicles, this will place strain on the central processing of both tasks, which will increase crash risk due to driver inattention.

6. Research Directions

Further laboratory studies are necessary in order to gain a greater understanding of the underlying mechanisms of resource allocation during driving in all settings:

- Analysis of the relationship between age and resource allocation in different modalities, as utilised in driving.
- Future analysis could focus on the responses of the modalities used in this study when the information attended to in the secondary task is relevant to the driving task.
- Resource functions were not examined between 0° and 10°. Given the increasing prevalence of HUDs, future research could focus on the resource functions within the central visual field, the 0 ° to 10° range.
- Further research could examine the distinction between peripheral and central visual information processing, and the characteristic of the relationship between this processing.
- The results from this study cannot necessarily be extrapolated from non-fatigued, highly concentrated drivers to drivers with low levels of cognitive activation. As the cause of those low activation levels can be two-fold (fatigue or monotony) potential distractions could affect driving performance in two different ways: If the low activation results from fatigue it is hypothesised that the driver will be distracted more easily and driving performance will decrease, while in the case of low activation levels due to the monotonous nature of the task, distractions could actually have a positive effect on driving performance because the reduce monotony and therefore can counteract the down-regulation of activation. Therefore, future studies could consider the effects of auditory and visual distraction in fatigued and monotonous conditions.

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