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Identifying cognitive distraction using steering wheel reversal rates

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Abstract: The influence of driver distraction on driving performance is not yet well understood, but it can have detrimental effects on road safety. In this study, we examined the effects of visual and non-visual distractions during driving, using a high-fidelity driving simulator. The visual task was presented either at an offset angle on an in-vehicle screen, or on the back of a moving lead vehicle. Similar to results from previous studies in this area, non-visual (cognitive) distraction resulted in improved lane keeping performance and increased gaze concentration towards the centre of the road, compared to baseline driving, and further examination of the steering control metrics indicated an increase in steering wheel reversal rates, steering wheel acceleration, and steering entropy. We show, for the first time, that when the visual task is presented centrally, drivers' lane deviation reduces (similar to non-visual distraction), whilst measures of steering control, overall, indicated more steering activity, compared to baseline. When using a visual task that required the diversion of gaze to an in-vehicle display, but without a manual element, lane keeping performance was similar to baseline driving. Steering wheel reversal rates were found to adequately tease apart the effects of non-visual distraction (increase of 0.5 degree reversals) and visual distraction with offset gaze direction (increase of 2.5 degree reversals). These findings are discussed in terms of steering control during different types of in-vehicle distraction, and the possible role of manual interference by distracting secondary tasks.

1 Introduction

Although driver distraction is regularly cited as one of the leading causes of traffic accidents and near misses, how different types of distraction affect road safety is currently poorly understood. When studying the effect of driver distraction in the laboratory, researchers use a multitude of tasks to simulate distraction, as well as different driving environments and performance measures.

Information processing models (e.g., the Multiple Resource Theory proposed by Wickens, 2002) as well as working memory models (e.g., Baddeley, 1992) predict that the type of distraction used has a differential effect on driving performance, with most disruption seen by tasks which share the same response or processing resource. The majority of the published literature on the subject uses a broad distinction between two main types of distraction: visual distractions, which involve processing of some form of visual information (and therefore can change the natural eye-movement patterns), and non-visual (often referred to as “cognitive”) distractions, which involve processing of information without a visual component.

In terms of their effect on driving performance, visual distractions have been shown to have two main effects: an increase in lateral deviation from the lane centre (e.g. Engström, Johansson, & Ostlund, 2005; Santos, Merat, Mouta, Brookhuis, & de Waard, 2005; Liang & Lee, 2010) and also increased deviation of gaze because the information that needs to be sampled is usually displayed away from the road centre, for example on a central console (e.g. Victor, Harbluk, & Engström, 2005; Reyes & Lee, 2008). Godthelp, Milgram, and Blaauw (1984) argued that the change of gaze from the centre of the road to some place off the road, such as an in-vehicle information system, results in large errors in heading direction, which in turn affect the lateral position of the vehicle.

If the increase in lateral deviation during a visual task is linked to the decrease of gaze concentration towards the road centre, it follows that placing this visual task around the road centre will likely lead to similar, or even better lane keeping performance, compared to baseline driving, as drivers’ eyes will not be diverted towards a distracting in-vehicle task. Understanding how placement of the visual task in relation to the driving scene affects lateral control is of value, and may provide knowledge on the design of future in-vehicle-information systems.

Studying the effect of non-visually distracting (cognitive) tasks on driving performance has produced more mixed results. While some studies have also reported an increase in lateral deviation akin to that of visual tasks (e.g. Salvucci & Beltowska, 2008; Strayer & Johnston, 2001), other studies find the opposite effect, i.e. a *reduction* in lateral deviation (Atchley & Chan, 2011; Cooper, Medeiros-Ward, & Strayer, 2013; Engström et al., 2005; He, McCarley, & Kramer, 2014; Jamson & Merat, 2005; Kubose et al., 2006; Reimer, 2009), and also a reduction in the deviation of gaze (Victor et al., 2005; Reimer, 2009), a phenomenon often called "gaze concentration".

This reduction in lateral deviation under conditions of non-visual distraction is thought to be an indication of better lateral control (Cooper et al., 2013; Medeiros-Ward, Cooper, & Strayer, 2014), which, at face value, it is. However, what drives this behaviour is not currently clear. It has been argued that this improvement in lateral control is due to a hierarchical control system, whereby increased attention to a simple (tracking) task disrupts performance (Cooper et al., 2013; Medeiros-Ward et al., 2014). By the same token, performing a competing and concurrent secondary task removes attention from the simple tracking (lane control) task. Since this improved lane keeping is also accompanied by increased gaze concentration to the road centre during secondary task engagement, a "lock in" state is observed by drivers, where their focus on the road centre affords less attention to peripheral stimuli (e.g. Lee, Lee, & Boyle, 2007; Merat & Jamson, 2008). Kountouriotis et al (2015) showed that fixing gaze direction towards an eccentric target removed any differences in lateral control between visual and non-visual tasks when drivers were negotiating a bend. However, what has not yet been investigated is whether a visual task which mimics the gaze concentration on the centre of the road will result in the same reduced lateral variability as a non-visual task.

When examining the effect of non-visual tasks on lane keeping, many studies show reductions in measures such as the standard deviation of lateral position (SDLP) when performance is compared to baseline (e.g., Atchley & Chan, 2011; Engström et al., 2005; He et al., 2014; Jamson & Merat, 2005; Liang & Lee, 2010; Merat & Jamson, 2008), but the effect of such secondary tasks on steering control is not always clear. For example, high workload (visual and non-visual) leads to irregular/unpredictable steering entropy (how predictable/random steering wheel movements are, Boer et al., 2005). Further work is therefore required to examine the effect of driver distraction using additional metrics of steering performance. Markkula and Engström (2006) proposed that steering wheel reversal rates (SRRs) are a useful metric for assessing the effects of visual and non-visual distractions. Steering wheel reversal rates measure the number of times the steering wheel changes direction by a set angle (and larger) per minute (MacDonald & Hoffman, 1980). Analysis of data from the EU project HASTE (using both simulator experiments and field trials) showed that whilst non-visual distractions led to an increase of “micro” steering corrections (in the range of 0.1 to 2 degrees), visual distractions, where gaze is diverted from the road centre, led to an increase of steering reversals larger than 2 degrees (Markkula & Engström, 2006). It appears, therefore, that SRRs measure two different components of the steering signal, depending on how they are defined. Whilst larger reversals are indicative of a change in direction of heading, it remains unclear whether smaller reversals (particularly reversals smaller than 1 degree) imply fine-tuning by the driver, or simply reflect increased steering activity that have little effect on the vehicle’s trajectory. Therefore, examining SRRs alongside other steering control measures, such as steering wheel acceleration and steering entropy is necessary to compare the effect of different types of secondary task on steering and lane keeping measures.

The aim of the present paper is therefore two-fold: (a) to investigate further the apparent differences between visual and non-visual distractions on steering performance, and (b) to investigate the role of SRRs in identifying different types of driver distraction and its relation to other steering metrics. Three secondary tasks were therefore implemented for this driving simulator study: two visual tasks, one presented on an eccentric IVIS in the vehicle, which is comparable to the type of visual distractions used in the literature cited here, and one presented centrally on the back of a lead car to assess the effect of gaze concentration on the centre of the road, whilst performing a visual task. We argue that a visual task which does not require drivers to take their eyes off the road, but instead mimics gaze behaviour observed during a non-visual task (increased gaze concentration on the road centre) can potentially lead to similar steering control behaviours as a non-visual distraction task (such as improved lane keeping performance), while a visual task that requires changes in gaze direction should deteriorate lane keeping. A non-visual task was also used for comparison with the two visual tasks described.

2 Methods

2.1 Participants

Sixteen naïve participants took part in this study, eight of them males. The mean age was 35.12 ± 9.95 years and all had a valid driving license, with an average 14,887 annual mileage.

2.2 Design and Procedure

2.2.1 Materials

The experiment was conducted in the University of Leeds Driving Simulator which consists of a Jaguar S-type cab with all driver controls operational. The vehicle is housed within a 4 m spherical projection dome and has a 300° field-of-view projection system. A v4.5 Seeing Machines faceLAB eye-tracker was used to record eye-movements at 60Hz. The IVIS display used to display the Remote Arrows was a Lilliput 7" VGA touchscreen display with a resolution of 800 × 480, positioned approximately 28.3° to the left of the centre of the main scene and 25.4° lower of the horizon.

2.2.2 Secondary Tasks

Three secondary tasks (two visual tasks and one non-visual task) were implemented in this experiment, as well as a baseline condition (Baseline) which involved only driving. Both visual tasks were inspired by the European HASTE project (see Jamson & Merat, 2005): participants were required to locate a target arrow (arrow pointing upwards) amongst distractors (arrows pointing in other directions), presented in a 4 × 4 grid. Unlike the manual response used in the HASTE experiments, participants were required to verbally report the position of the target arrow using the letter and number coordinates located around a grid (see Figure 1). Also, in contrast to the HASTE set up, a target arrow was always present in these experiments. The main difference between the two visual tasks was the location of the arrows grids: in one set up the task was displayed on an in-vehicle interface to the left of the driver (Remote Arrows), whilst in the other it was displayed at the back of the lead car (Central Arrows). There was an auditory notification when a new grid appeared, and each grid remained visible until either the participant provided a response or seven seconds elapsed from its onset.

Figure 1. The "Central Arrows" task. In the "Remote Arrows" the arrows grid was displayed on the in-vehicle display (on the screen to the left of the steering wheel, seen in this figure).

The non-visual task was a count back in sevens task (Countback), where the participants would hear a three digit number and would have to count backwards in steps of seven. Each task was presented in two blocks of 30 seconds.

2.2.3 Driving Environment

The experiment consisted of one drive taking place in a rural two-lane road, each lane being 3.65 m wide, with Straight and Curved sections separated by a short urban environment. No data were collected in the urban section. The curved sections consisted of a series of alternating left and right bends, and each bend had a radius of 750m. There was a lead car, which mirrored the speed and acceleration profile of the participant car, in order to maintain a constant distance of 25 m from the participants' vehicle. This was implemented to ensure that the Remote Arrows task was always performed at the same distance.

2.2.4 Experimental Design

A repeated-measures design was used for this experiment, and there were a total of eight conditions: 2 Road conditions (Straight, Bend) × 4 Task conditions (Baseline, Remote Arrows, Central Arrows, Countback). The tasks were counterbalanced, and each task block lasted 30 seconds, and was presented twice in each drive. Results are reported as the average of the two blocks per task. After providing informed consent, participants completed a 20 minute practice drive before experimental data was collected. The tasks started once the participants left the urban environment and entered the rural road, and there was a 30 second period between each of the tasks.

3 Results

3.1 Secondary Task Performance

In order to ensure participants engaged with the secondary tasks their performance was recorded[1] and the percentage of correct responses was calculated. The performance on the secondary tasks is shown in Table 1. A 2 (Road) × 3 (Task) repeated-measures ANOVA showed a significant main effect of Task ($F(2, 28) = 7.37$, $p = .015$, $\eta_p^2 = .34$), but no significant effect of Road ($F < 1$), and no interaction between Task and Road ($F < 1$).

Table 1. Percent correct responses (±SD) on the secondary tasks

	Central Arrows	*Remote Arrows*	*Countback*
Straight	100% (±0)	99.52% (±1.84)	93.13% (±13.52)
Bend	99.15% (±2.25)	99.33% (±2.58)	93.24% (±10.51)

The main effect of Task was analysed using LSD comparisons since there were only three task conditions. While there was no significant difference between the two Arrows tasks ($p = .782$), the Countback task yielded significantly lower accuracy scores compared to both Central ($p = .016$) and Remote ($p = .015$) arrows. Although the Countback task yielded slightly lower accuracy scores to the two Arrows tasks (~93% compared to ~99%), performance on all three tasks was adequate to assume the participants were engaging with the secondary tasks.

3.2 Gaze Concentration

Twelve of the sixteen participants produced adequate data for eye-movement analysis. Participants with adequate data in terms of eye-movements were defined as producing more than half of the

[1] Responses for one participant could not be scored for accuracy due to technical problems, but that participant was generating responses, and did not come up as an outlier in any of the gaze or steering metrics examined.

frames with a FaceLab rating of 3 (highest quality). Gaze concentration was measured by measuring the Standard Deviation of yaw gaze angle – left/right direction – (SD Yaw) to study participants' eye-movements during the three secondary task conditions.

A 2 (Road) × 4 (Task) Repeated Measures ANOVA was used to analyse SD Yaw. This revealed a significant main effect of Task ($F(3,33) = 108.88$, $p < .001$, $\eta_p^2 = .91$). There was also a significant interaction between Road and Task ($F(3,33) = 3.47$ $p = .027$, $\eta_p^2 = .24$).

The interaction between Road and Task, shown in Figure 2 was analysed using simple main effects. Whilst for the Central Arrows condition there was a significant difference between Straight and Curved roads ($p = .009$), no differences were found for the Road conditions in the other tasks. In addition, while in the Curved roads all differences between the four tasks were significant ($p < .006$), for the Straight roads there was no significant difference between the Central Arrows and Countback ($p = .090$) but the rest of the comparisons reached significance ($p < .003$).

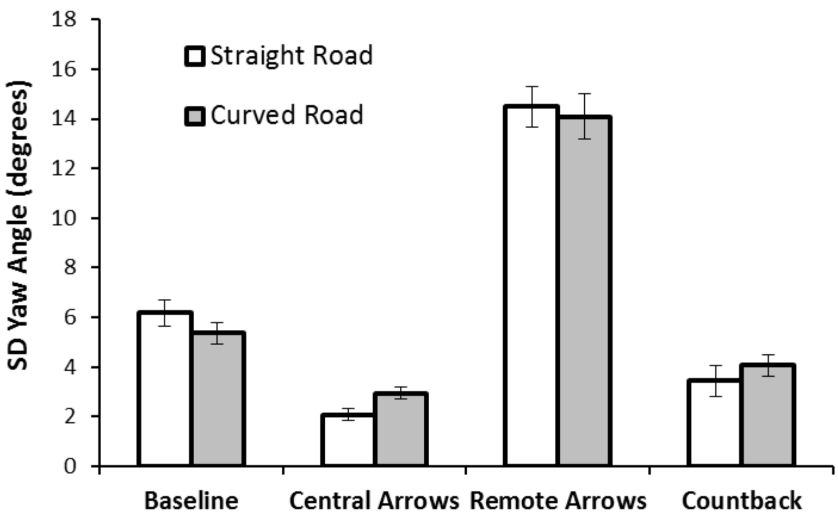

Figure 2. The interaction between Road and Task in SD Yaw. Error bars represent the standard error of the mean (SEM).

Main effects showed gaze concentration to be lowest during the Remote Arrows (due to the nature of the task) whilst it was significantly lower compared to Baseline during both the Central Arrows and Countback tasks. This similar gaze concentration patterns for the Countback and Central Arrows tasks therefore enables a more direct comparison of the effect of these tasks on steering and lateral control.

3.3 Longitudinal Measures

Since the lead vehicle was set at a constant distance from the participant's vehicle, mirroring its speed and acceleration profile, measuring headway for this study was redundant. Although participants were asked to maintain their speed at around 50mph, drivers could adopt a slower/faster velocity as a result from the distraction tasks (e.g., slow down during more demanding conditions). The mean speed was therefore analysed using a 2 (Road) by 4 (Task) repeated-measures ANOVA. There was a significant main effect on Road ($F(1, 15) = 9.55$, $p = .007$, $\eta_p^2 = .39$), but no significant effect of Task ($F(3, 45) = 1.06$, $p = .358$, $\eta_p^2 = .07$) and no interaction between the two factors ($F(3, 45) = 1.03$, $p = .369$, $\eta_p^2 = .06$). Participants drove at a slower speed during the Curved road sections (mean = 50.34mph, SEM = 0.42) compared to Straight road sections (mean = 52.56mph, SEM = 0.85).

3.4 Standard Deviation of Lateral Position (SDLP)

All 16 participants were included in the analysis of driving measures. Sphericity was taken into account when appropriate for calculating *p*-values, but the uncorrected degrees of freedom are reported for clarity.

A 2 (Road) × 4 (Task) Repeated Measures ANOVA was conducted on SDLP. This analysis showed a significant main effect of Road ($F(1, 15) = 81.20$, $p < .001$, $\eta_p^2 = .84$), and a significant main effect of Task ($F(3,45) = 23.35$, $p < .001$, $\eta_p^2 = .61$). The interaction between Road and Task did not reach significance ($F(3,45) = 1.78$, $p = .164$, $\eta_p^2 = .11$).

The main effect of Road was driven by higher SDLP when negotiating a curved trajectory (mean = 0.200, SEM = 0.011) compared to driving on a straight road (mean = 0.127, SEM = 0.007).

The main effect of Task, shown in Figure 3, was analysed using pairwise comparisons with Sidak corrections. Driving in the Baseline condition resulted in significantly higher SDLP compared to both the Central Arrows and the Countback conditions (p = .002 and p = .001 respectively), but it was not significantly different from the Remote Arrows condition (p = .999). Remote Arrows produced higher SDLP compared to both Central Arrows and Countback (p < .001 for both comparisons), and no significant difference was found between Central Arrows and Countback tasks (p = .832).

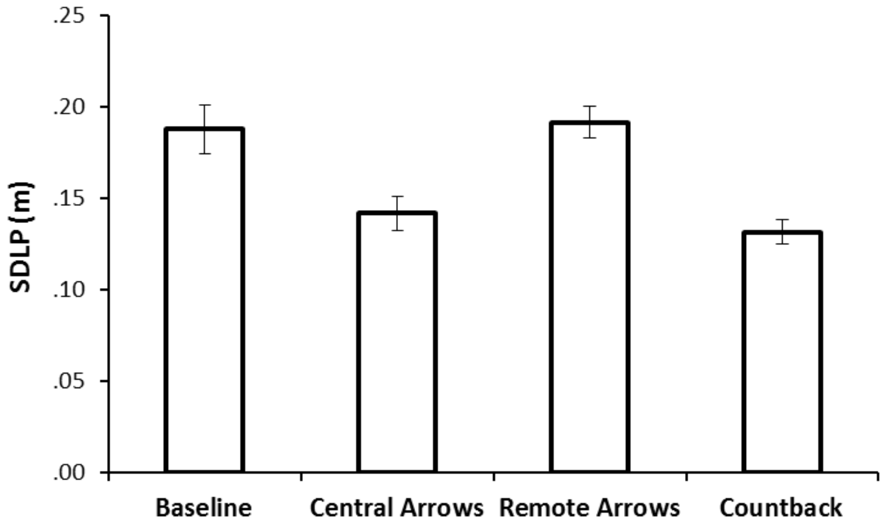

Figure 3. The main effect of Task on SDLP. Both Central Arrows and Countback tasks were significantly lower than Baseline and Remote Arrows. Error bars = SEM.

Therefore, this experiment has shown, for the first time, that the effect of a visual task on lane keeping performance (as measured by SDLP) is similar to that of a 'cognitive' task, when the visual task is presented in the drivers' central visual view, around the road centre. Contrary to our predictions (and previous results), however, the Remote Arrows did not increase significantly SDLP compared to baseline driving. We discuss this below and believe this finding may be due to the absence of a manual element in the Remote Arrows task.

Whilst lower SDLP in cognitive tasks has been seen as a marker of better performance (Cooper et al., 2013; Medeiros-Ward et al., 2014), this assumption needs to be investigated further. We attempted to investigate this further using additional metrics for steering control.

3.5 Steering Wheel Reversal Rates (SRR)

Steering wheel Reversal Rates (SRRs) were measured using a 0.5 degree and 2.5 degree gap size.

3.5.1 Reversal Rates greater or equal to 2.5 degrees

A 2 (Road) × 4 (Task) Repeated Measures ANOVA was run on 2.5° SRRs, which revealed a significant main effect of Road ($F(1, 15) = 272.46$, $p < .001$, $\eta_p^2 = .95$) and a significant main effect of Task ($F(3, 45) = 9.13$, $p < .001$, $\eta_p^2 = .38$). No significant interaction between these two factors was found ($F(3, 45) = 2.70$, $p = .056$, $\eta_p^2 = .15$).

The main effect of Road was caused by significantly higher 2.5° SRRs in the Curved road segments (mean = 11.60, SEM = 0.76) compared to the Straight road segments (mean = 1.10, SEM = 0.32), which is explained by the demands of the steering task itself.

The main effect of Task (shown in Figure 4) was analysed using Sidak corrections. The Remote Arrows condition resulted in significantly higher SRRs compared to all three other task conditions ($p < .024$ for all comparisons), and no other significant differences were observed ($p > .887$).

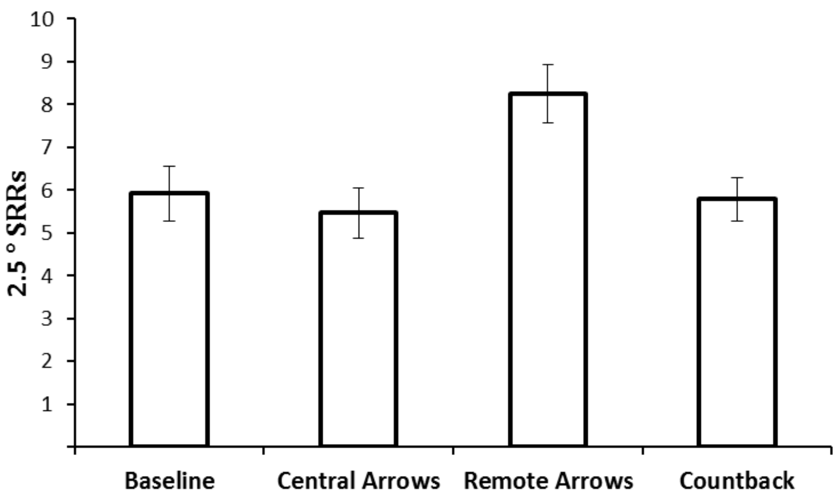

Figure 4. The main effect of Task in 2.5° SRRs. Error bars = SEM.

Therefore, only the task which requires drivers to look away from the road produced a significantly high number of large (greater than or equal to 2.5°) steering wheel reversals.

3.5.2 Reversal Rates greater or equal to 0.5 degrees

The 2 (Road) × 4 (Task) Repeated Measures ANOVA run for the 0.5° SRRs revealed a significant main effect of Road ($F(1, 15) = 57.38$, $p < .001$, $\eta_p^2 = .79$) and a significant main effect of Task ($F(3, 45) = 16.22$, $p < .001$, $\eta_p^2 = .52$). No significant interaction was found between these two factors ($F(3, 45) = 2.32$, $p = .088$, $\eta_p^2 = .13$).

Similar to the 2.5° SRRs, the main effect of Road was caused by higher SRRs in the Curved segments (mean = 40.20, SEM = 3.38) compared to the Straight segments (mean = 25.80, SEM = 2.62) and this difference again can be explained by the demands of the road environment.

The main effect of Task, however, showed a different effect to that seen for the 2.5° SRRs (see Figure 5). Using Sidak corrections, it was revealed that significantly fewer 0.5° SRRs were seen during the Baseline condition, compared to the three task conditions ($p < .031$ for all comparisons). Crucially, the Countback resulted in significantly higher SRRs compared to the other conditions ($p < .034$ for all comparisons), but no significant difference was observed between the Central Arrows and Remote Arrows conditions (p = .915).

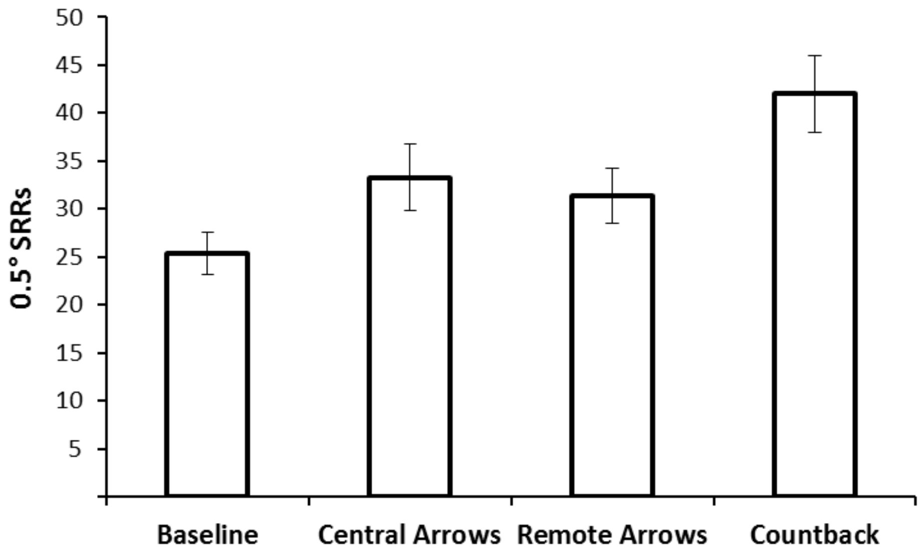

Figure 5. The main effect of Task in 0.5° SRRs. Error bars = SEM.

Contrary to the results for the 2.5° SRRs, where the largest effect was shown by the Remote Arrows condition, when considering the smaller reversal rates, the largest effect on this measure is shown by the non-visual Countback task. Therefore, although both small and large reversal rates are derived from the same metric (steering wheel angle), their function is not the same since large changes in steering wheel angle result in larger changes in heading angle. This explains the increased number of 2.5° SRRs for the Remote Arrows condition, where participants had to look away from their future path, therefore inducing greater heading errors, compared to the other conditions. Interestingly, although SDLP was higher for Remote Arrows compared to Central Arrows, these two task conditions are similar in terms of 0.5° SRRs. The increase in small reversals for the Countback task could indicate either more careful and involved lane keeping, or random movement which requires correction. The higher number small reversal rates for Countback versus Central Arrows is more difficult to clarify, but could be related to either the non-visual nature of this task, or it could reflect differences in the difficulty of the tasks, which were not directly measured.

3.6 Steering Wheel Acceleration

Steering wheel acceleration, the mean angular acceleration of the steering wheel, can be used to indicate steering smoothness (e.g. Cloete & Wallis, 2011). The 2 (Road) × 4 (Task) Repeated Measures ANOVA run for SWA indicated a significant main effect of Road ($F(1, 15) = 268.78$, $p < .001$, $\eta_p^2 = .95$) and a significant main effect of Task ($F(3, 45) = 9.56$, $p < .001$, $\eta_p^2 = .39$), but no significant interaction between these two factors ($F(3, 45) = 2.50$, $p = .071$, $\eta_p^2 = .14$).

Similarly to the SRRs, Curved segments resulted in higher SWA (mean = 1.969, SEM = 0.116) compared to Straight segments (mean = 0.851, SEM = 0.075), a finding which again is explained in terms of the driving scenario requirements.

The main effect of Task (shown in Figure 6) was analysed using Sidak corrections. SWA in the Baseline drive was significantly lower than the Remote Arrows ($p = .002$) and Countback task ($p = .008$), but not significantly different from the Central Arrows task ($p = .238$). Central Arrows resulted in lower SWA compared to Countback ($p = .029$) but not significantly different to Remote Arrows ($p = .608$). The difference between the Countback and Remote Arrows was not significant ($p = .571$).

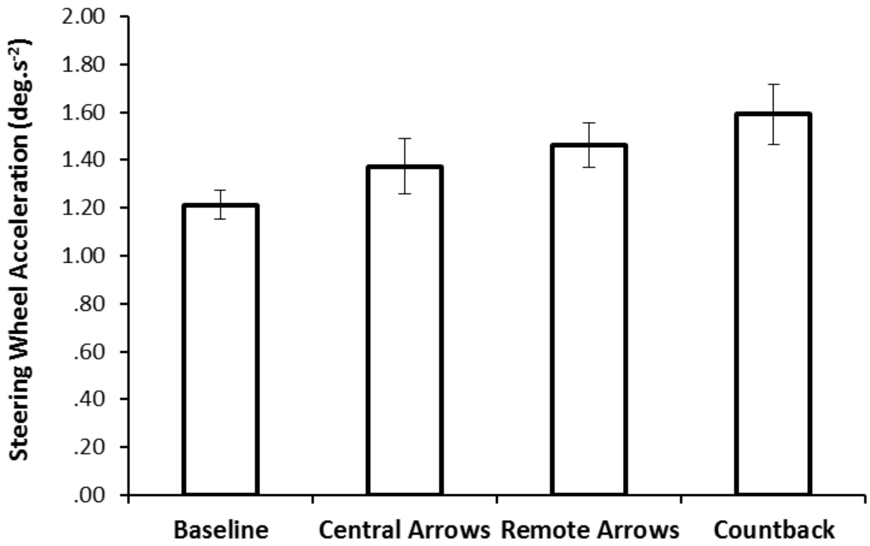

Figure 6. The main effect of Task on SWA. Error bars = SEM.

Results from steering wheel acceleration measure followed a similar pattern to that shown for 0.5° SRRs. Participants were found to have more steering activity (as shown by the 0.5° SRRs) and also higher steering wheel acceleration (as illustrated by SWA), during a cognitive, non-visual, task. This is further investigated with steering entropy, below.

3.7 Steering Entropy

Steering entropy, a measure of high-frequency steering corrections (Boer et al., 2005), was used in addition to steering wheel acceleration. Steering Entropy measures how consistent or random the steering wheel angle is in a certain condition compared to baseline driving.

Steering entropy was calculated using the Boer et al. (2005) method; higher values represent an increase in control effort. A 2 (Road) × 4 (Task) Repeated Measures ANOVA run for steering entropy, which revealed a significant main effect of Task ($F(3, 45) = 14.01$, $p < .001$, $\eta_p^2 = .48$), but no significant effect of Road ($F(1, 15) = 2.02$, $p = .175$, $\eta_p^2 = .12$), and no significant interaction between these two factors ($F(3, 45) = 2.60$, $p = .063$, $\eta_p^2 = .15$).

The main effect of Task, shown in Figure 7, was analysed using pairwise comparisons with Sidak corrections. It was found that Baseline had significantly lower entropy compared to the Remote Arrows ($p = .002$) and the Countback task ($p < .001$), but it was not significantly different from the Central Arrows ($p = .108$). Although the difference in Central Arrows and Countback was significantly different ($p = .019$), no other significant differences were observed between any of the other task conditions (Remote Arrows vs Central Arrows, $p = .211$; Remote Arrows vs Countback, $p = .441$).

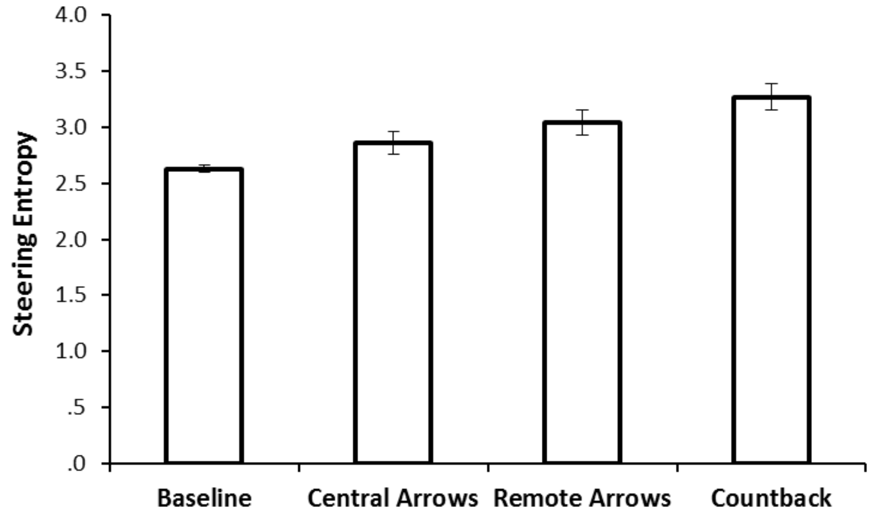

Figure 7. The main effect of Task for steering entropy. Error bars = SEM.

Results from the steering entropy data therefore show a higher level of steering control during the Countback task and follow the pattern shown by the 0.5° SRRs and Steering Wheel Acceleration data.

4 Discussion

In this paper, we examined the effect of two main types of driver distraction (visual and non-visual) on lateral control in a driving simulator study, and also investigated whether position of the visual task has an effect on lateral control of the vehicle.

Previous research has demonstrated that, compared to baseline driving, non-visual cognitive tasks result in lower SDLP, whereas higher SDLP is seen during visually distracting tasks. Here we show, for the first time, that rather than being attributed to the processing resources required by such tasks, this difference, could (at least in part) be attributed to differences in gaze direction required by each task. In our "Central Arrows" manipulation, where participants' gaze concentration towards the centre of the road was similar to the gaze behaviour observed in the non-visual task, SDLP was lower than baseline, and similar to that observed for the non-visual task. Certainly, it can be argued that

that there is a correlational (rather than causal) relationship between SDLP and gaze concentration towards the road centre, with both influenced by the cognitive demand of the Central Arrows task. However, since higher levels of SDLP were observed during performance of the Remote Arrows task, which was equal in demand to that of the Central Arrows, but required gaze away from the road centre, further studies are required to resolve the relationship between gaze position, cognitive load and SDLP measures.

In line with previous studies in this context (e.g., Victor et al., 2005; Reimer, 2009), a non-visual distraction task showed higher gaze concentration towards the centre of the road, and lower SDLP, compared to baseline. In addition, during the non-visual task, participants had higher levels of steering wheel acceleration, steering wheel reversal rates (at the 0.5° level), and steering entropy, when compared to baseline. Although the reduction in SDLP does indicate better lane-keeping performance, the rise in the other steering metrics needs further investigation, and a better understanding of the relationship between these metrics is also warranted. For instance, steering entropy was “developed to quantify the increase in high frequency steering corrections that result after periods of diverted or reduced attention” (Boer et al., 2005: p 25); on the other hand, studies suggest that such increases in steering metrics are the direct cause of the lowered SDLP (Cooper et al., 2013; Medeiros-Ward et al., 2014; He et al., 2014). We argue that, at least for SRRs, different gap sizes show different categories of distraction.

In this experiment, engagement in the two visual tasks did not increase SDLP, when compared to Baseline, an outcome in contrast to previous work in this area. We predicted that, (a) if the increase in SDLP observed during a visual task is due to a re-direction of gaze away from the road towards an in-vehicle display, then Remote Arrows should increase SDLP compared to Baseline, and (b) if the decrease in SDLP observed during a non-visual task is due to the increased gaze concentration towards the centre of the road, then SDLP will decrease in the Central Arrows task, compared to Baseline. Whilst point (b) was observed, point (a) was not, with SDLP showing similar results between the Remote Arrows and Baseline conditions. We suggest that the reason for the contrast between our results and previous studies (e.g., Engström et al., 2005; Kountouriotis & Merat, 2016; Liang & Lee, 2010; Merat & Jamson, 2008; Santos et al., 2005) is that at least some of the increase in SDLP induced by visual tasks in previous studies may well be due to the manual element of these tasks, since response to our remote Arrows was verbal.

As we were unable to source any other published work which has considered the distinction between visual-manual and visual-only distracting tasks on driving performance, and in order to examine whether the manual element of the task in particular was responsible for the incongruences observed between the present and past experiments, data were pulled from two additional experiments conducted in our laboratories, (see Figure 8), which matched the current experiment in terms of the simulator used, driving scenario, lead car presence, and sample size. In all cases, results from the visual tasks are displayed as the difference from the respective baseline data for comparison.

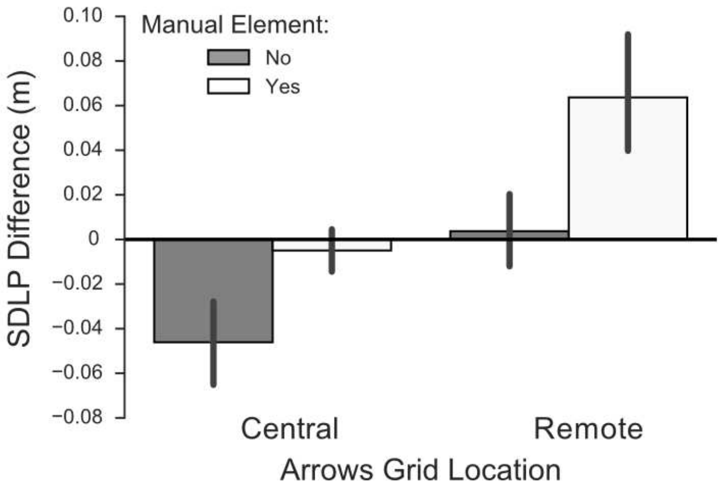

Figure 8. Comparative results from the current experiment and two additional experiments using different variations of the visual task on SDLP. Each task condition is displayed as the difference between the task and its respective baseline score (Baseline – Task Condition), therefore negative values indicate lower SDLP in the Task condition compared to Baseline, positive values higher

SDLP in the Task condition compared to Baseline, and values close to zero indicate no difference. Error bars display the 95% Confidence Intervals.

As illustrated above, an increase in lateral variability imposed by a visual task is driven by two separate components. Firstly, when there is no change in gaze direction (Central Arrows) and no manual response is required (No Manual), the visual task decreases SDLP compared to baseline driving (presumably due to gaze concentration). When either a manual element is added to the task (Central Arrows with Manual element) or a change in gaze direction is required without a manual element (Remote Arrows without Manual element), lateral variability is similar to that of Baseline. Finally, when both a gaze direction away from the road *and* a manual response is required (Remote Arrows with Manual element), similarly to the majority of experiments using a visual (manual) task, then lateral variability increases considerably compared to baseline driving.

Therefore, it can be concluded that the differential results often reported between visual and “cognitive” distractions in driving are not purely due to the different cognitive demands of these tasks, but could be attributed to the task demands in terms of gaze direction and manual interference. In terms of further research in this area, it would be very interesting to consider the effects on performance of a non-visual task, which requires similar changes in gaze direction to a visual task, and also has a manual component. According to the data presented in this paper, such a task would result in higher lateral deviation compared to baseline driving.

Finally, while in most previous studies in this context, steering wheel reversal rates are measured using just one gap size, (usually at 1 degree), in this experiment two levels of SRRs were used, with each being sensitive to different secondary tasks. Small reversal rates, in general, identified the non-visual task, and larger reversals were observed only for the task that required diverted gaze direction. This differentiation was firstly acknowledged by Markkula and Engström (2006), and this distinction can be attributed to the fundamentally different behaviours these metrics measure. Larger reversal rates (in this experiment defined as 2.5 degrees and above) indicate steering which attempts to correct heading errors, while smaller reversal rates could indicate either fine-tuning of the steering response or erratic steering. Future studies should therefore use steering wheel reversal rates in a manner that separates overall steering activity from large changes in heading direction.

In conclusion, we have shown in this study that the detriments in lane keeping performance during a visual task can be attributed to changes in gaze direction and possibly manual interference, and that steering wheel reversal rates can distinguish between non-visual and visual distractions.

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