Do driver monitoring technologies improve the driving behaviour of distracted drivers? A simulation study to assess the impact of an auditory driver distraction warning device on

Do driver monitoring technologies improve the driving behaviour of distracted drivers? A simulation study to assess the impact of an auditory Driver Distraction Warning device on driving performance.

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ABSTRACT

Being distracted while driving is a major cause of road crashes. To help prevent this particular type of crash, new driver monitoring technologies track ocular and head movement and alert drivers when periods of prolonged distraction are detected, thus preventing hazardous situations on the road. In this mixed-factorial multi-level experiment, the behaviour of drivers was measured as they performed a secondary task while being monitored via an auditory Driver Distraction Warning (A-DDW) device which reminded them to look at the road ahead and cease the activity which was the source of distraction. Here, we evaluated the effectiveness of this type of DDW device by measuring longitudinal and lateral behaviour in situations where the driver is intentionally distracted for a significant period of time, and when the device repeatedly reminds the driver of his/her primary task.

Forty-two participants were randomly stratified into three groups and subjected to the following distraction levels: (i) not distracted (baseline), (ii) distracted, and (iii) distracted but interacting with the A-DDW device. All participants drove in (i) free-flowing and (ii) stable traffic conditions along straight motorway segments. Speed and speed deviation values for distracted drivers were lower than for undistracted ones but they also experienced a significant deterioration in vehicle lateral control. Conversely, drivers assisted by the A-DDW device experienced a considerable improvement in their lateral control even though their speed and speed deviation values were higher. The reaction times of distracted drivers interacting with the A-DDW device deteriorated as revealed in cognitive tests conducted before and after the driving task.

Keywords: crash prevention, distraction, driver behaviour, Driver Distraction Warning device, driving simulation.

1. INTRODUCTION

Driver distraction is a serious road safety issue accounting for up to 25% of road crashes in Europe (ERSO, 2018). In the recent three-year period 2016-2018, distracted driving caused circa 3,000 deaths per year in the United States, with more than a quarter of the distracted drivers in the 20 to 29-year-old age group (National Highway Traffic Safety Administration, 2018; 2019; 2020a). Distraction diverts drivers from primary driving-related activities towards secondary tasks (Regan *et al.*, 2011), which can be driving-related, e.g., focusing on onboard instruments, or non-driving-related, e.g., texting with a smartphone (Stutts *et al.*, 2005). Mind wandering while driving results in poor driver vigilance, and often occurs when the driver is familiar with the route (Baldwin *et al.*, 2017; Burdett *et al.*, 2016). There are four categories of distraction: (i) visual (Bakhit *et al.*, 2018; Kuo *et al.*, 2019), (ii) manual (Stutts *et al.*, 2005; Klauer *et al.*, 2006), (iii) auditory (Strayer *et al.*, 2003; European Road Safety Observatory, 2018), and (iv) cognitive (Strayer *et al.*, 2015). The use of a mobile phone involves a combination of these (Kircher, 2007) as does interaction with the centre console (Kuo *et al.*, 2019), with the driver repeatedly switching attention between the driving (primary) and the secondary task (Kaber *et al.*, 2012). A more demanding secondary task leads to a higher number of off-road glances, both for purely visual (Metz *et al.*, 2011) and visual-manual tasks (Tivesten & Dozza, 2014), while a complex driving task including both visual and auditory stimuli from in-vehicle systems forces drivers to concentrate more on the road ahead and keep their eyes focused spatially on the central part of the road (Victor *et al.*, 2005).

It is well established that distraction affects longitudinal and lateral vehicle control as well as driver reaction times (Papantoniou *et al.*, 2017; Young *et al.*, 2009). Driving simulation studies show that speed (*S*) decreases when the driver is using a cell phone (Alm & Nilsson, 1994; Reed & Robbins, 2008) and the standard deviation of speed (*SDS*) increases as the difficulty of the secondary task increases (Rakauskas *et al.*, 2004). A reduction in speed (Papantoniou *et al.*, 2017) and/or an increase in the distance between the driver and the vehicle in front (Strayer & Drews, 2004) are generally adopted as countermeasures to ensure increased reaction times in response to a potential hazardous event requiring an evasive manoeuvre like steering and/or braking. It should be noted that distracted drivers do not always deteriorate their performance levels. As reported by Oviedo-Trespalacios *et al.* (2018), when the distraction is self-inflicted, drivers select lower speeds to compensate for the risk(s) they are taking.

Regarding transversal control, lateral position (*LP*) and standard deviation of lateral position (*SDLP*) are the most common parameters employed to evaluate the ability to maintain appropriate position and control of the vehicle within the lane (Papantoniou *et al.*, 2017). However, any distractions while driving adversely affect the ability of drivers to maintain their vehicle correctly positioned in the lane (Choudhary & Velaga, 2019; Rumschlag *et al.*, 2015). Furthermore, some studies showed that visual and manual tasks cause more lane deviations, steering errors and higher *SDLP* values than cognitive distractions (Engström *et al.*, 2005; Kaber *et al.*, 2012).

Driver monitoring technologies were introduced more than a decade ago, first as a driver behavioural research tool (May & Baldwin, 2009; Taylor *et al.*, 2013), then as in-vehicle technology to alert drivers to inappropriate driving practises and hazardous situations (Reagan *et al.*, 2018; Mase *et al.*, 2020). Recently, the European Parliament (European Parliament & Council of the European Union, 2019) approved Regulation No. 2019/2144 in an effort to protect vehicle occupants and other road users from distraction. The 2019/2144 Regulation imposes the adoption of Driver Distraction Warning (DDW) systems on new vehicles by 2026. These devices were originally introduced to the automotive aftermarket and to new vehicle models afterwards (Doudou *et al.*, 2020). They emit auditory and/or vibratory warnings when the driver is distracted, with the aim of ensuring that the driver is alert and retains or regains full control of the vehicle. The majority of current DDW devices process data relating to the eye region (gaze tracking, eye closure, percentage of eyelid closure over time, etc.) and face monitoring (Sigari *et al.*, 2014). Anti-distraction applications were also introduced on smartphones as low-cost DDW systems (Bergasa *et al.*, 2014). The technical documents in support of the 2019/2144 Regulation (European Parliament & Council of the European Union, 2021) indicate that DDW systems are expected to be more effective outside urban zones, e.g., on motorways, where long-distance driving at a constant speed together with less interesting surrounding environments can result in drivers becoming more distracted (Huemer & Vollrath, 2011).

Despite the effectiveness of DDW technologies in detecting distraction being well recognized (Dumitru *et al.*, 2018; Gallahan *et al.*, 2013), their effects on driver behaviour and performance are still the subject of debate. Donmez *et al.* (2006) investigated the effects of an advisory mitigation strategy used to discourage off-road eye glances while drivers were interacting with an in-vehicle information system, but no relevant advantages in braking and steering performance were observed. Ahlstrom *et al.* (2013) used a seat vibrating DDW system based on a remote eye tracking (AttenD) algorithm to evaluate changes in driving behaviour in field tests under uncontrolled traffic conditions, but it did not result in significant changes in global glance behaviour. The uncertainty regarding the impact of DDW devices on driver performance in controlled traffic conditions suggests that more research is needed.

In this driving simulation study, we evaluated the effectiveness of an auditory DDW (A-DDW) device currently available on the automotive aftermarket, which can track eye and head movements and alert drivers if and when their visual behaviour deviates from the reference front position for at least 3 s. Participants were asked to perform a secondary task which involved a cognitive, visual and manual distraction. We were then able to assess the effectiveness of the warning system by measuring driver behaviour when subject to a state of intentional distraction.

2. METHODS

2.1 Experimental design and hypotheses

A multi-level mixed-factorial design with varying levels of distraction and traffic density was considered. Longitudinal and lateral behavioural indicators were monitored under two different traffic scenarios, while the participants were subjected to one of the following three states: not distracted, distracted, or distracted but with the support of the A-DDW device. This experiment was conducted under the hypothesis that the A-DDW device counteracts the negative impact of the distraction experienced when drivers persist in performing a secondary task.

Although this specific secondary task is not likely in ordinary driving, we considered it because of the conclusions reached by Shinar *et al.* (2005), who observed that solving mathematical operations significantly degraded driving performance compared to a distraction caused by conversation. On the other hand, the simultaneous activation of an alert system that detects distraction and the persistence of a distracted state is likely when A-DDW systems are installed on the next generation of vehicles in 2026.

We also evaluated the effect of the A-DDW device on mental workload by measuring the change in the perception and reaction times (PRT) of participants to visual and auditory stimuli before and after driving. The hypothesis tested in this experiment is that the A-DDW device requires a more demanding driving task, with an increment in the PRT after driving.

The experiment combines distraction as a between-subject factor, and traffic density (i.e., the level of service, LOS) as a within-subject factor (Table 1). The stimulus combined visual, cognitive, and manual distractions and was dispensed along straight segments of 2 km (see Section 2.2).

TABLE 1. Synthesis of the design factors.

Experimental factors	Levels			Type
Distraction level (Group No.)	No Distraction (0)	Distraction (1)	Distraction + A-DDW (2)	Between-subject
Traffic density (Level of Service, LOS)	7 pc/km/lane (A)	14 pc/km/lane (C)	-	Within-subject

2.2 Road scenario

The road scenario consisted of a rural motorway consistent with Italian technical standards (*Ministero delle Infrastrutture e dei Trasporti*, 2001). As the scenario was designed to favour distractions (see Figures 1a and 1b), long straights to increase the feeling of monotony were adopted (Huemer & Vollrath, 2011; Papantoniou *et al.*, 2016; Slootmans & Desmet, 2019). As depicted in Figure 1, the immediate surroundings were slightly hilly with the presence of vegetation, trees, and some buildings in the distance. The weather and visibility conditions for driving were optimal. The carriageway had a width of 7.5 m with 2 lanes (3.75 m each) per direction, a 3 m wide emergency lane, and a 0.7 m wide left shoulder. Horizontal markings and vertical signals conformed to the Italian Highway Code (*Nuovo Codice della Strada*, 1992).

The posted speed limit was set at 130 km/h. A safety barrier of 850 mm in height was selected for the median while the barrier along the right roadside was omitted.

Drivers started the experiment from a lay-by before merging onto the motorway from a direct ramp. After merging, each participant drove on three long motorway tangents connected by circular arcs of 1200 m in radius. The level of service (LOS) was set at A, i.e., free flow conditions, and C, i.e., stable flow with the reduced ability to change lane requiring greater awareness. The randomized order of administration of the LOS along the 2nd and the 3rd straights was adopted. Hence, a number of circulating vehicles corresponding to an average vehicle density of 7 pc/km/lane (LOS A, Figure 1a) and 14 pc/km/lane (LOS C, Figure 1b) was adopted (Transportation Research Board, 2016).

(a) **(b)**

(c)

FIGURE 1. Experimental set-up and scenarios: (a) straight segment under LOS A, and (b) LOS C. Simulation setting (c) with tablet for the secondary task and the A-DDW device.

2.3 Equipment

Experiments were conducted using the fixed-base driving simulator with SCANeR Studio™ software (AV Simulation) at the Road Safety and Driving Simulation (RSDS) laboratory of the Politecnico di Torino (Figure 1c). With this simulator, the driver has a 130° horizontal and around 30° vertical field of view through three 32-inch full HD screens (1920×1080 pixels each). Together with the video card, the monitors update the images at a frequency higher than 50 Hz and are equipped with rear and side view mirrors. The simulator hardware consists of a cockpit complete with steering wheel, manual gearbox, pedals and dashboard. The speedometer, rev counter and other onboard displays are on the small monitor mounted on the back of the steering wheel but in a position where they are always visible to drivers during experiments. The steering wheel is equipped with a force feedback sensor to simulate wheel spin and impacts. Vehicle and traffic sound effects are reproduced through five speakers located behind the screens and a subwoofer under the driver's seat. The simulator repeatedly reached relative validation for longitudinal (Bassani *et al.*, 2018), transversal (Catani and Bassani, 2019), and driving operations (Karimi *et al.*, 2020).

An A-DDW device available in the automotive aftermarket (Figure 1c), i.e., an infrared camera that detects eye pupil and head movements, was used. It determines whether pupils dilate or blink, and if the head position changes with respect to the initial calibration. As soon as any such change is detected, the sensor alerts the driver in real-time to help maintain a condition of safe driving. When the gaze is directed downwards or the pupils constrict, a continuous beep sounds and alerts the driver in less than 2 s. Following 3 s of persistent distraction, i.e., head and gaze not directly focused on the road, a warning voice message informs the driver that he/she has to look ahead. Preliminary tests established that the ideal camera position is close to the rear-view mirror and at a distance of 60 ± 5 cm from the driver's head (see Figure 1c).

2.4 Participants

A hundred participants were contacted via email, and since the study was conducted in line with the Code of Ethics of the World Medical Association (World Medical Association, 2018), all participants signed an informed consent form before starting the experiments. Based on an expected effect size (f) of .30, a significance level of .05, and a power of .90, forty-two out of one hundred were involved. Drivers were aged between 24 and 63, and were divided into three groups according to the between-subject factor (Table 1) in order to avoid any learning effect in the data, while the duration of a driving session was limited to no more than 15 min along the 25 km of the experimental track, so as to keep any fatigue phenomena to a minimum. Groups were stratified by age and gender, with five females and nine males in each group (Table 2).

TABLE 2. Descriptive statistics for participant characteristics.

Participant characteristics	Group	N	Mean	SD	Minimum	Maximum
	0	14	43.8	11.9	24	64
Driver age	1	14	43.0	11.3	23	61
	2	14	43.4	15.1	23	64
	0	14	14,857	10,516	1,000	30,000
Experience (km/y)	1	14	14,607	12,783	1,500	40,000
	2	14	11,429	9,764	2,000	35,000
	0	14	25.1	11.9	5	45
Experience (license y)	1	14	23.1	10.7	4	43
	2	14	23.7	14.7	4	45

2.5 Protocol

Each participant filled out a pre-drive questionnaire on their general health before driving on a test circuit to get familiar with the simulator commands. Drivers were instructed to drive as they would in a real motorway setting, while respecting traffic regulations. Those supported by the A-DDW device (Group 2) were instructed to complete the secondary task regardless of the fact that they were advised by the device to desist from doing so. After that, each participant drove for a maximum of 20 minutes. Before and after the driving task, participants completed two visual and auditory stimuli PRT tests using the online tool *Cognitive Fun!* (retrieved from https://new.cognitivefun.net/). We collected data with this online platform through a computer with a high-speed internet connection without conducting any validation tests.

During the distraction phase, a written message on the central windscreen invited participants to perform simple mathematical operations (Figure 1c). A random sequence of simple, solvable in your head additions, subtractions, multiplications, and divisions was proposed to influence driving performance (Shinar *et al.*, 2005) through *MathGames* (retrieved from https://www.mathplayground.com/math-games.html) installed on a 7" tablet positioned 55 cm to the right of the steering wheel (Figure 1c). The A-DDW device was activated each time drivers looked at the tablet for more than 3 seconds and it remained active until drivers reverted their gaze from the tablet back onto the road for a while. Once they had regained full control of the vehicle, drivers were able to continue with the secondary task. No driver performed any incorrect manoeuvres, or crashed into road installations or surrounding vehicles.

Finally, each driver filled out a post-drive questionnaire to provide feedback on the simulation and the anti-distraction device. The responses to the questionnaire demonstrated that the presence of the A-DDW device did not irritate or annoy the drivers during the test. Positive responses were received on the realistic nature of the simulation when compared to real driving conditions.

2.6 Observed variables, data collection and statistical analysis

Data for speed and lane position were collected at a frequency of 10 Hz for all testing configurations. Any outcomes relating to sections in which drivers were engaged in lane change manoeuvres were excluded from the database and the results. In accordance with the SAE J2944 standard (Society of Automotive Engineers, 2015), the following dependent variables depicting the longitudinal and lateral behaviour of drivers were measured:

(i) average speed (*S*),
(ii) standard deviation of speed (*SDS*),
(iii) average lateral position (*LP*), and
(iv) standard deviation of lateral position (*SDLP*).

LP indicates the distance from the vehicle centre of gravity to the lane centreline of both lanes in the carriageway. Positive *LP* values signify that the centre of gravity (CoG) was on the left side of the lane centreline. *SDS* and *SDLP* values reflect the ability of the driver to remain in control of the vehicle vis-à-vis use of the throttle and the steering wheel, respectively (Verster & Roth, 2011).

PRT tests were conducted to determine if the cognitive performance of participants suffered during the simulation due to the increased mental workload caused by the distracting secondary task (Group 1) and the simultaneous interaction with the A-DDW device (Group 2).

Linear mixed-effects models (LMM) and the generalized linear models (GLM), in the case of violation of LMM assumptions, were considered. Among the fixed effects of both LMM and GLM, the two experimental factors (distraction level, and level of service) and gender were included as categorical, while age and driving experience (average distance travelled in a year, and number of years holding a licence) were included as covariates. In the LMM, random effects (RE) accounted for the unobserved heterogeneity due to participants' subjective characteristics. Therefore, the *Test driver ID* was used as a cluster variable in the analysis. Clinical research (Pietrzak *et al.*, 2010) demonstrates that the LMM rather than other statistical methods like RM-ANOVA, reduces the standard error in the estimation, and increases the effect size (i.e., lower *p*-value), and the reliability of results, especially in mixed experimental designs. LMM is used with datasets including repeated measurements, as in this investigated case where each driver was monitored under two different traffic density scenarios.

Statistically non-significant variables and relative interactions were removed in accordance with the backward elimination technique. By minimizing the Akaike Information Criterion (AIC, Eq. 1) (Akaike, 1974) and the Bayesian Information Criterion (BIC, Eq. 2) (Stone, 1979):

$$AIC = -2\ln(L) + 2k \tag{1}$$

$$BIC = -2\ln(L) + \ln(n) \times k \tag{2}$$

where L is the model likelihood parameter, k is the number of parameters estimated, and n is the number of observations, the model performance was improved. When statistically significant effects and interactions were detected in LMM and GLM, post-hoc tests with Holm correction were performed. The significance level was always set at 5%. Statistical data analyses and modelling were carried out with Jamovi ver. 2.3.18 (The Jamovi Project, 2021).

3. RESULTS

3.1 Descriptive statistics

Table 3 provides the average and standard deviation of the experimental outcomes. The results have been grouped by distraction level and traffic density conditions.

TABLE 3. Mean (and standard deviation) of outcomes for average speeds (*S*), standard deviation of speeds (*SDS*), average lateral position (*LP*), and standard deviation of lateral position (*SDLP*).

Groups No. (Distraction level)	**Level of Service (LOS)**	***S*** (km/h)	***SDS*** (km/h)	***LP*** (m)	***SDLP*** (m)
0 (Baseline)	A	123.3 (9.1)	4.71 (1.45)	0.123 (0.199)	0.223 (0.076)
	C	122.5 (11.9)	4.14 (2.42)	0.124 (0.245)	0.217 (0.063)
1 (Distraction)	A	114.4 (18.3)	2.81 (2.23)	0.175 (0.413)	0.344 (0.140)
	C	114.8 (15.3)	3.01 (1.68)	-0.061 (0.407)	0.420 (0.235)
2 (Distraction + A-DDW)	A	123.3 (18.9)	5.14 (4.35)	0.176 (0.375)	0.315 (0.130)
	C	128.3 (20.8)	3.39 (2.70)	-0.055 (0.335)	0.330 (0.169)

3.2 Models estimation

Table 4 shows the estimated parameters for the four dependent variables investigated. *S* and *LP* data were used to calibrate LMM, while *SDS* and *SDLP* data were used to calibrate GLM since (i) no significant impact of the *Test driver ID* as a cluster variable was observed after a preliminary analysis with LMM, and (ii) to avoid any violation of assumptions on residuals for LMM. In Table 4, all models have the lowest AIC and BIC values possible. The assumption checks carried out by the Kolmogorov-Smirnov test confirmed the normality of residuals of the LMM for *S* and *LP* (*p*-values always higher than .05).

TABLE 4. LMM and GLM for driver behavioural outcomes.

		Estimate (*p*-value)			
		LMM		**GLM**	
		S **(km/h)**	***LP*** **(m)**	***SDS*** **(km/h)**	***SDLP*** **(m)**
Factors, covariates (fixed effects):	Effect				
Intercept		119.884 (<.001)	0.0810 (.057)	3.8654 (<.001)	0.3082 (<.001)
Distraction level	1-0	-8.4658 (.119)	-0.0638 (.497)	-1.3988 (.045)	0.1462 (<.001)
	2-0	1.9054 (.726)	-0.0655 (.522)	-0.0778 (.910)	0.0894 (.014)
LOS	C-A	-	-0.1574 (.018)	-	-
Gender	F-M	-8.4705 (.097)	-	-	-
Gender * Distraction level	F-M*1-0	0.8575 (.937)	-	-	-
	F-M*2-0	-23.3404 (.054)	-	-	-
LOS * Distraction Level	C-A*1-0	-	-0.2311 (.148)	-	-
	C-A*2-0	-	-0.2255 (.158)	-	-
Driver age (y)		-0.5621 (.019)	-	-	0.0197 (.001)
Experience (km/y)		$7.64 \cdot 10^{-4}$ (.010)	-	-	-
Experience (licence y)		-	-	0.0607 (.011)	-0.0162 (.008)
Cluster variable for LMM (random effect):					
Test driver ID		(<.001)	(.109)	-	-
Summary statistics					
AIC		649.64	63.50	402.25	-95.20
BIC		660.04	101.16	414.41	-80.61
R^2 marginal		.339	.082	-	-
R^2 (conditional for LMM)		.879	.314	.139	.349
Observations / Drivers		84/42			
Kolmogorov-Smirnov test for normality of residuals		.457	.913	-	-

3.3 Longitudinal behaviour

Regarding *S* (Table 4), the LMM explains around 88% of the total variance, with most of this ascribable to the random effect associated with the *test driver ID* (54% of the total variance in the data), thus indicating the predominant effect of subjective behaviour. Distraction level and LOS were not significant in explaining

S. In fact, LMM did not reveal any significant differences when comparing undistracted drivers with both distracted groups. Estimated marginal means revealed that distracted drivers ($M_1 = 113.6$ km/h, $SE_1 = 3.67$ km/h) adopted lower speeds than undistracted ones ($M_0 = 122.1$ km/h, $SE_0 = 3.79$ km/h), and that drivers who interacted with the A-DDW device drove at speeds similar to those of the undistracted drivers in Group 0 ($M_2 = 124.0$ km/h, $SE_0 = 3.86$ km/h). A post-hoc test revealed that distracted males supported by the A-DDW device (Group 2) drove at significantly higher speeds than male drivers in Group 1 ($S_{1M} – S_{2M} = -22.47$ km/h, $t_{37} = -3.26$, $p\text{-value}_{Holm} = .037$). Moreover, when distracted while under the influence of the A-DDW device, females drove at lower speeds with respect to males ($S_{2M} – S_{2F} = 24.32$ km/h, $t_{37} = 2.97$, $p\text{-value}_{Holm} = .069$), a fact that explains why gender and distraction level interact in the model (Table 4). LMM results also indicate that participants used to driving more kilometres per year also drove faster than those used to driving less, while older drivers behaved more cautiously than younger ones.

SDS was marginally influenced by distraction. Distracted drivers reduced speed variation more than non-distracted drivers did ($SDS_0 – SDS_1 = 1.40$ km/h, z = 2.04, $p\text{-value}_{Holm} = .134$). However, distracted drivers supported by the A-DDW (Group 2) device exhibited speed variations similar to undistracted ones ($SDS_0 – SDS_2 = 0.8$ km/h, z = 0.11, $p\text{-value}_{Holm} = .910$). Experienced drivers also exhibited greater speed variations than novice drivers. As before though, no significant differences were imputable to the LOS.

3.4 Lateral behaviour

The LMM for *LP* revealed that it was significantly influenced by LOS ($LP_A – LP_C = 0.157$ m, $t_{41} = 2.44$, $p\text{-value}_{Holm} = .019$), and marginally by the driving style of participants (p-value = .141) which, nevertheless, accounts for circa 23% of the total variance in the model. As shown in Table 3, distracted participants generally drove more on the right side of the centreline under denser traffic conditions (i.e., LOS C) than those undistracted and those distracted but operating under free-flow conditions (LOS A) did. However, LMM did not reveal a significant difference in *LP* ascribable to distraction levels and the covariates.

Conversely, *SDLP* was heavily influenced by distraction levels, driver age and experience. Distracted drivers increased their *SDLP* notably more than undistracted ones ($SDLP_0 – SDLP_1 = -0.146$ m, $t_{37} = -3.97$, $p\text{-value}_{Holm} < .001$). However, Group 2 drivers showed only a marginally better level of lateral control whilst performing the secondary distracting task than that shown by their Group 1 counterparts ($SDLP_1 – SDLP_2 = 0.057$ m, $t_{37} = 1.57$, $p\text{-value}_{Holm} = .125$), albeit not enough to reduce their *SDLP* values to those of undistracted drivers ($SDLP_0 – SDLP_2 = -0.089$ m, $t_{37} = -2.44$, $p\text{-value}_{Holm} = .039$). LMM revealed that free- and stable-traffic conditions had no significant effect on *SDLP*. As shown by the estimates for model coefficients, younger drivers maintained better lateral control than older ones, thereby demonstrating the significant effect of age on *SDLP* ($p\text{-value}_{Holm} = .002$). However, more experienced drivers performed fewer corrections along the trajectory, i.e., had lower *SDLP* values.

3.5 Visual and auditory PRT tests

The comparison between data for the visual and auditory PRT tests carried out before and after the driving test for the three groups of participants is shown in Figure 2. For each group of drivers (i.e., undistracted, distracted, and distracted but interacting with the A-DDW device), PRT data were found to be Gaussian distributed according to outputs from Kolmogorov-Smirnov tests for normality (all *p*-values larger than .05). The average visual and auditory PRT values after the experiments were always higher than the PRTs measured before. Moreover, data confirmed that the visual stimuli led to longer PRTs, because of the longer time required for the transmission of the photoreception signal to the brain compared to that required for the auditory stimulus (Kemp, 1973).

The results obtained revealed no significant differences between before and after visual and auditory PRT values for the undistracted drivers (Group 0). In contrast, significant statistical differences were observed for the distracted drivers in Groups 1 and 2. While the change in PRT within Group 1 was only significant for the auditory values (t_{13} = -2.37, *p*-value = .017), both visual and auditory tests revealed that distracted drivers who interacted with the A-DDW device experienced a statistically significant change in their PRT values after the driving test (visual: t_{13} = -3.49, *p*-value = .004; auditory: t_{13} = -4.17, *p*-value = .001).

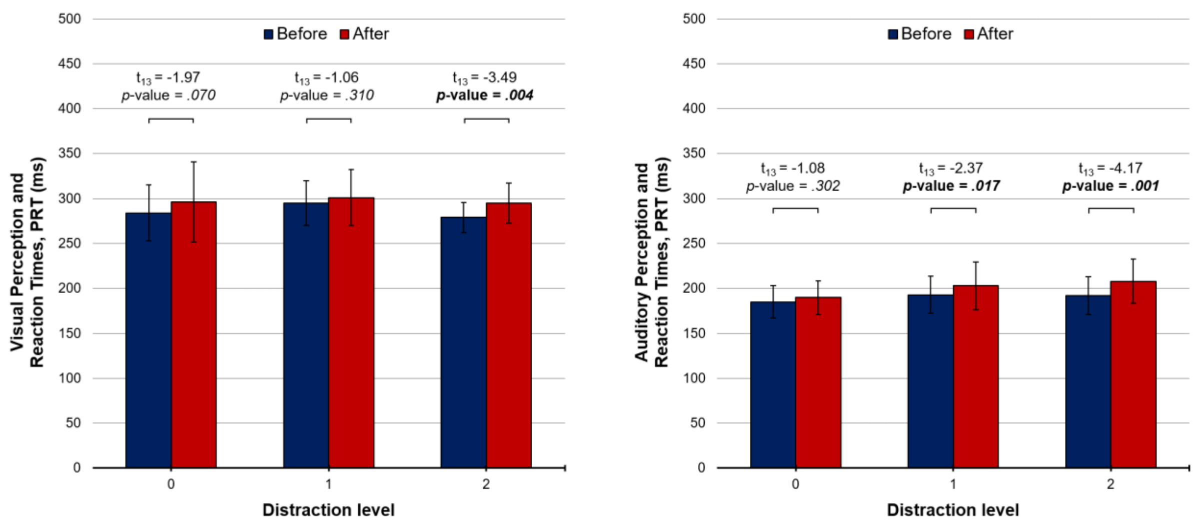


FIGURE 2. Visual and auditory perception and reaction times (mean and standard deviation) before (blue bars) and after (red bars) the driving session.

4. DISCUSSION

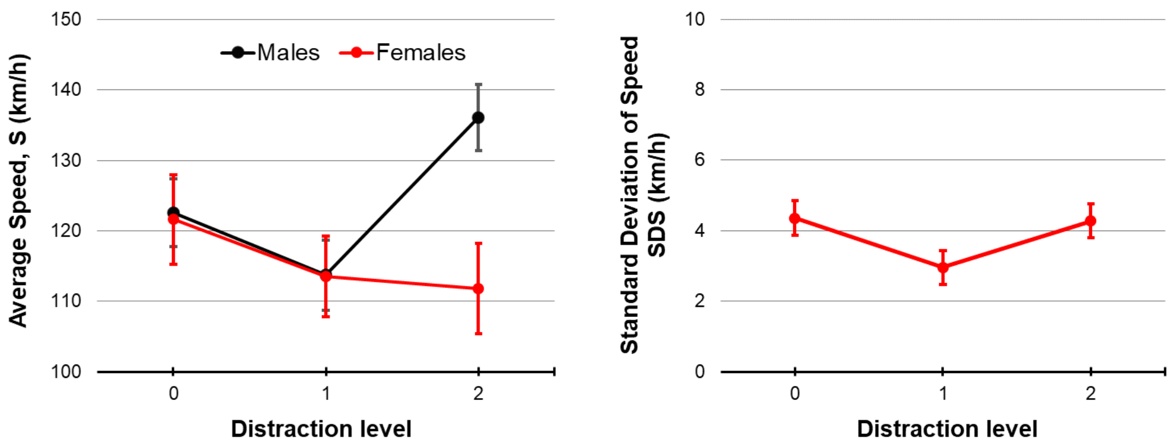
We examined the effect of an A-DDW device on driver performance while he/she is distracted by having to perform a secondary task along a motorway. In doing so, we took the performance of drivers distracted by the same task and non-distracted drivers as benchmarks.

The results with the LMMs and GLMs indicate that along motorways the personal characteristics of drivers have a significant influence over speed and a marginal influence over lateral position in the lane. In contrast, longitudinal and transverse control ability are mainly influenced by the level of driver distraction and age.

As depicted in Figure 3a, drivers slightly reduced their speed when distracted to compensate for the risk associated with continuing to perform the secondary task. In this study, this reduction did not prove to be statistically significant, while the same trend but statistically significant in difference was observed by Choudhary and Velaga (2019) in a driving simulation study on a four-lane (two lanes per direction) undivided carriageway with a posted speed limit of 110 km/h. Similar outcomes were registered by Rakauskas *et al*. (2004) for a simulation study in a two-lane rural road setting. Based on our results, we can confirm that, when distracted, drivers prudently maintain a lower speed than they do when focused on the primary driving task only.

We also observed that the behaviour of distracted drivers interacting with the A-DDW device differed with gender. Whereas males drove significantly faster than the distracted-only drivers in Group 1, females reduced their speed to levels lower than males operating under the same conditions. The prudent nature of female drivers was observed by Onate-Vega *et al*. (2020), while Choudhary *et al.* (2022) confirmed that females demonstrated a greater perception of the risk associated with distracting secondary activities than their male counterparts. However, care must be taken not to generalise this result, as the study had an unbalanced composition of males (65%) and females (35%). LMM outcomes also reveal that drivers with greater driving experience in terms of distance travelled adopted higher speeds. This is consistent with the results from Oviedo-Trespalacios *et al.* (2017), who observed that inexperienced drivers reduced their speed more than experienced ones when distracted.

Figure 3b shows the impact of the different distraction levels on the standard deviation of speed (*SDS*). Distracted drivers reduced their speed variation, while those distracted but interacting with the A-DDW assumed speed variation values comparable to those of undistracted drivers. This outcome contrasts with that observed by Rakauskas *et al.* (2004) who measured an increment of 0.5-1 mph (0.8-1.6 km/h) in the *SDS* of drivers talking on their cell phones in realistic driving conditions. The differences between these two studies are attributable to the difference in distraction type, which was solely cognitive in Rakauskas *et al.* (2004), while cognitive, manual and visual in the present study. However, the not statistically significant increment observed for drivers interacting with the A-DDW device with respect to those simply distracted is consistent with the results from Rakauskas *et al.* (2004) who observed larger speed variation values in tasks requiring a higher mental workload such as participation in mobile phone conversations. Furthermore, the higher *SDS* values recorded for more experienced drivers indicate that they tended to adjust speed more frequently when alerted by the A-DDW device, which emitted a “beep” sound and some warning messages. This result is in line with that of Donmez *et al.* (2006), who observed that older drivers accept and trust strategies to combat distraction more than young drivers do.

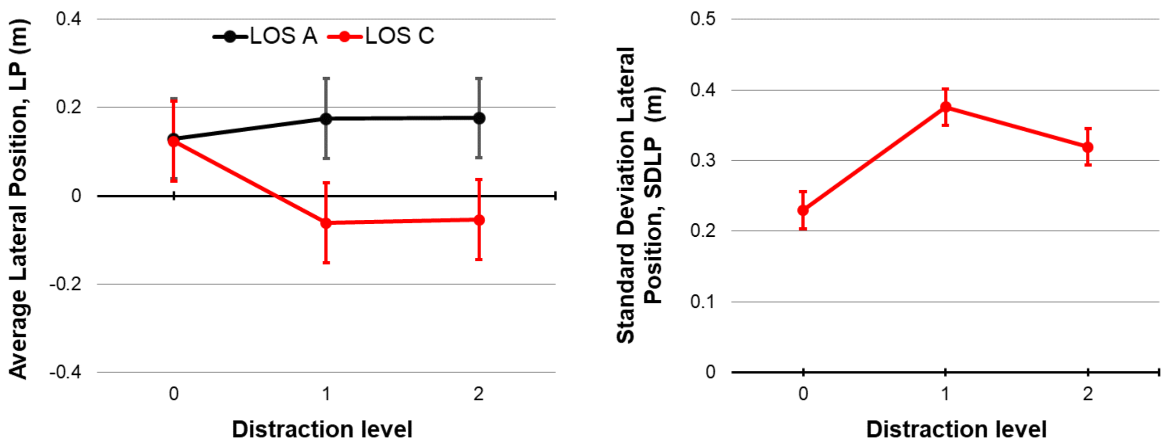


(a) (b)

FIGURE 3. Effect plots of the LMM and GLM analyses for the effect of distraction level on (a) average speed (*S*), and (b) standard deviation of speed (*SDS*), respectively. Bars indicate the standard error.

Significant differences in lane position were attributable to traffic density, as supported by the observations from Mecheri *et al.* (2017) and Dijksterhuis *et al.* (2011), although their studies were conducted on two-lane rural roads. In the case investigated here (Figure 4a), the average lateral position values for distracted drivers in both Groups 1 and 2 were negative under LOS C conditions (see Table 3). The higher the traffic density (Figure 1b), the farther to the right the position of the vehicle driven by distracted participants. This clearly indicates the propensity of distracted drivers to occupy the right side of the lane to limit the degree of interaction with any faster vehicles arriving from behind when occupying the rightmost lane, or to increase the distance from a fixed installation like the traffic barrier when driving in the leftmost lane. This can be seen as a risk compensation strategy to counteract the impact of distraction in a more dangerous environment with vehicles on a multi-lane road, a strategy which was also observed by Oviedo-Trespalacios *et al.* (2020).

In terms of lateral control, distracted drivers exhibited higher *SDLP* values than undistracted ones (Figure 4b) consistent with the studies of Engstrom *et al.* (2005) and Kaber *et al.* (2012), who claimed that tasks combining visual and manual actions like texting with a smartphone cause more lane deviation and result in higher *SDLP* values than distractions which are purely cognitive in nature. Nevertheless, when comparing distracted drivers, the A-DDW device improved lateral behaviour (i.e., lower *SDLP*). Although distracted, Group 2 drivers were invited by the A-DDW device to look at the road ahead, thus maintaining better lateral control. The observation study carried out by Wang *et al.* (2019) in real driving conditions corroborates this hypothesis, with distracted drivers reducing the number and duration of glances required to perform the secondary distraction task so as to remain more focused on the road ahead.



(a) **(b)**

FIGURE 4. Effect plots of the LMM and GLM analyses for the effect of distraction level on (a) the average lateral position (*LP*), and (b) the standard deviation of lateral position (*SDLP*), respectively. Bars indicate the standard error.

Cognitive tests carried out before and after the driving task revealed a significant increase in PRTs for drivers that used the A-DDW device. While the distracted drivers in Group 1 exhibited a significant reduction in their auditory performances only, Group 2 drivers experienced a significant deterioration in PRT values for both visual and auditory stimuli on completion of the driving session. It is worth noting that while visual information is the most important type for drivers (Sivak, 1996), the noise level also impacts the driving task (Denjean *et al.*, 2012), and auditory reactiveness is inversely proportional to the cognitive workload while driving (Reimer & Mehler, 2011). These results concur with those obtained by Chen *et al.* (2005) regarding the increase in driver perception and reaction times while they are engaged in a series of mental processing tasks. In this study, we measured the difference before and after the driving session, and drivers who were exposed to distraction and interaction with the A-DDW device experienced a significant deterioration in their cognitive performances. Milosevic (1997) observed that a driver's mental workload leads to excessive fatigue which in turn leads to an increase in visual and auditory PRT values. Since simulated driving is much more demanding than real driving (Philip *et al.*, 2005), it cannot be excluded that the observed differences were attributable to the simulation effect, while in real driving conditions the same cognitive deterioration can be observed after a prolonged exposure to the A-DDW interaction (Engström *et al.*, 2005).

4. CONCLUSIONS

Carmakers and automotive companies are introducing new driver monitoring systems which use communication apparatuses to draw attention to and contrast the unsafe behavioural habits of distracted drivers, thus helping to reduce the number of road crashes. However, their effectiveness on driver performance has yet to be established.

In this study, the effectiveness of an auditory driver distraction warning (A-DDW) device was tested under motorway driving conditions by measuring longitudinal and lateral behaviour indicators when drivers are deliberately distracted for a sustained period of time with the device repeatedly reminding them to concentrate on their primary task. The longitudinal and transversal behaviour patterns of forty-two volunteers spanning a wide spectrum of ages and levels of driving experience were monitored.

Based on statistical data modelling, the main outcomes of this investigation were as follows:

1. in cars equipped with an A-DDW device and travelling along motorways, drivers experience a marginal improvement in their lateral control when distracted with respect to those who are not supported by such a device;
2. distracted male drivers interacting with an A-DDW device react differently to female drivers; while males tend to travel at higher speeds, females reduce their speed to levels lower than those of distracted and non-distracted drivers;
3. distracted drivers interacting with an A-DDW operate with a higher mental workload;
4. stable and free-flow traffic conditions impact the lateral position in the lane of distracted drivers irrespective of the presence of an A-DDW device;
5. the individual personality traits of drivers affect speed and to a lesser extent their position within the lane, while longitudinal and lateral control indicators are mostly influenced by the level of distraction and the countermeasures used to contrast same.

The hypothesis being tested is only partially confirmed in terms of average speed, since female drivers supported by the A-DDW device behave differently from males, a finding which merits further investigation, since we have adopted an unbalanced composition of males and females. However, the hypothesis is confirmed for lateral control. We observed that distracted drivers interacting with the A-DDW device reduce their lateral weaving movement within the lane more than that of simply distracted drivers. Hazardous interactions with fixed installations (e.g., safety barriers, vertical signals) and surrounding vehicles are reduced with the presence of an A-DDW device onboard. In conclusion, the use of an A-DDW device only partially contrasts driving impairments caused by deliberate distraction.

The results of this study should be considered by those who are developing anti-distraction systems of the type investigated here. Although their use should serve to discourage anyone from engaging in secondary activities that divert attention from the (primary) driving task, the possibility that drivers will persist in such safety-threatening behaviour must, nevertheless, receive serious consideration. In addition, this study emphasises the need to explore the safety implications when drivers adopt improper driving behaviour despite the influence of technological countermeasures that promote better driving practises but which do not override their actions.

However, the results obtained must also be viewed in the light of five shortcomings. First, we used only one A-DDW device which uses an acoustic message to alert the driver. A different warning interface design, e.g., with visual or haptic warnings of different intensity, duration and/or repetition, could have a different impact on driver behaviour. Similarly, the timing and reliability of warnings determine their effectiveness. If drivers receive false warnings, they may begin to ignore the information and fail to respond quickly and appropriately. Therefore, visual and haptic modes should also be tested in the short and long term to see which of them are the most effective in terms of driving performance, subjective acceptance and usability. Second, the nature of the secondary task (i.e., doing math while driving) may imply external validity issues since such a scenario does not occur in real driving. Third, due to the differences in driving behaviour between males and females highlighted here and also reported in the literature, especially in terms of speed (Reed and Robbins, 2008; Li *et. al.*, 2015), gender must also be considered among the experimental factors. For this reason, balanced groups consisting of equal numbers of males and females should be adopted in the future. Fourth, the extension of this observation to other road types and environmental contexts should be the subject of future investigations. Finally, this study was conducted on a fixed-base driving simulator with drivers encouraged to perform a secondary task while driving; future studies should be conducted in a more ecological way with real vehicles running on testing tracks and with the secondary task also performed on a voluntary basis. The issue of how to directly measure crash risk should also be addressed in addition to driving performance measurements.

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