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Driving behaviour while self-regulating mobile phone interactions: A human-machine system approach

Oscar Oviedo-Trespalacios[a,b,c,d,*], Md Mazharul Haque[a,b,c], Mark King[a,b], Sebastien Demmel[a,b]

[a] Queensland University of Technology (QUT), Centre for Accident Research and Road Safety – Queensland (CARRS-Q), Queensland, Australia
[b] Queensland University of Technology (QUT), Institute of Health and Biomedical Innovation (IHBI), Faculty of Health, Queensland, Australia
[c] Queensland University of Technology (QUT), School of Civil Engineering and Built Environment, Science and Engineering Faculty, Queensland, Australia
[d] Department of Industrial Engineering, Universidad del Norte, Colombia

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ABSTRACT

Mobile phone distracted driving is a recurrent issue in road safety worldwide. Recent research on driving behaviour of distracted drivers suggests that in certain circumstances drivers seem to assume safer behaviours while using a mobile phone. Despite a high volume of research on this topic, self-regulation by mobile phone distracted drivers is not well understood as many driving simulator experiments are designed to impose an equal level of distraction to participants being tested for their driving performance. The aim of this research was to investigate the relationship between self-regulatory secondary task performance and driving. By a driving simulator experiment in which participants were allowed to perform their secondary tasks whenever they feel appropriate, the driving performance of 35 drivers aged 18–29 years was observed under three phone conditions including non-distraction (no phone use), hands-free interactions and visual-manual interactions in the CARRS-Q advanced driving simulator. Drivers' longitudinal and lateral vehicle control observed across various road traffic conditions were then modelled by Generalized Estimation Equations (GEE) with exchangeable correlation structure accounting for heterogeneity resulting from multiple observations from the same driver. Results show that the extent of engagement in the secondary task influence both longitudinal and lateral control of vehicles. Drivers who engaged in a large number of hands-free interactions are found to select lower driving speed. In contrast, longer visual-manual interactions are found to result in higher driving speed among drivers self-regulating their secondary task. Among the road traffic conditions, drivers distracted by their self-regulated secondary tasks are found to select lower speeds along the s-curve compared to straight and motorway segments. In summary, the applied human-machine system approach suggests that road traffic demands play a vital role in both secondary task management and driving performance.

1. Introduction

Driving requires continuous interactions between human operators and system components such as vehicles and road infrastructure. Mobile phone distraction often interrupts this continuous process of driving and increases the risk of crash and injury. In Australia, a hospital-based study found that drivers who use a mobile phone up to 10 minutes before a crash are nearly four times more likely to have a serious crash (McEvoy et al., 2005). In the U.S., the National Highway Traffic Safety Administration (NHTSA) compiled results from numerous naturalistic studies and concluded that (NHTSA, 2016): (i) mobile phone visual-manual interaction tasks (e.g. texting and browsing) while driving increase the risk of crash and safety-critical events, and (ii) other mobile phone interaction tasks (e.g. phone conversation) seem not to be directly associated with the risk of crashes. Similar findings have been reported in recent systematic reviews (Oviedo-Trespalacios et al., 2016) and meta-analyses (Simmons et al., 2016). Nonetheless, cognitive distraction due to mobile phone use remains a significant concern (Lipovac et al., 2017).

Drivers adapt their driving behaviour, intentionally or unintentionally, while performing mobile phone tasks. Until recently, research suggested that drivers could potentially adapt their driving behaviours in a safer direction in order to compensate for any mobile phone related impairment (Oviedo-Trespalacios et al., 2017a,b,c; Wandtner et al., 2016, Choudhary and Velaga, 2017). Lowering one's driving speed is one of the most documented safe behavioural adaptations among mobile phone distracted drivers in simulator experiments (Oviedo-Trespalacios et al., 2017b, Wandtner et al., 2016), self-

* Corresponding author at: Centre for Accident Research and Road Safety – Queensland (CARRS-Q), Queensland University of Technology (QUT), Brisbane, QLD, Australia.
E-mail addresses: oscar.oviedotrespalacios@qut.edu.au, ooviedot@gmail.com (O. Oviedo-Trespalacios).

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reported questionnaire surveys (Huth and Brusque, 2013, Young and Lenné, 2010), and field observational studies (Fitch et al., 2014, Fitch et al., 2017). Reduced speed can offer safety advantages in terms of crash likelihood or injury severity (see Aarts and Van Schagen (2006) and Choudhary and Velaga (2017)) and, therefore, is often recognised as a risk-minimising driving behaviour. Nonetheless, there is still great uncertainty regarding these sources of self-regulation as frequently reported in the scientific literature. For instance, drivers engaged in mobile phone conversations have been reported to have less lateral lane deviation (Garrison and Williams, 2013, Reimer et al., 2014), but drivers engaged in texting have an increased lane deviation (McKeever et al., 2013, Rudin-Brown et al., 2013). In addition, other studies have reported negligible changes in lateral lane position for either conversations or texting activities (Cao and Liu, 2013, Irwin et al., 2015, Young et al., 2014, Caird et al., 2008). As concluded in a recent comprehensive systematic review of the literature (Oviedo-Trespalacios et al., 2016), research on risk compensatory behavioural adaptations of mobile phone distracted drivers is a largely unexplored phenomenon.

It is important to note that previous research in behavioural adaptation of distracted drivers has confirmed that drivers using a mobile phone modify their driving behaviour as a function of driver characteristics, driving demands, and secondary task demands (Young and Regan, 2013, Oviedo-Trespalacios et al., 2015, Fitch et al., 2017, Choudhary and Velaga, 2017). Personal characteristics such as driving experience, previous experience of multitasking activities, and crash risk perception seem to determine the level of engagement and behavioural changes (Hancox et al., 2013, Oviedo-Trespalacios et al., 2017a,c). Another common result is that the behavioural adaptations of distracted drivers are context-dependent. Drivers using a mobile phone while driving along narrower lanes or roads with high speed limits seem to select a lower driving speed with higher variability and higher lateral acceleration (Liu and Ou et al., 2011). Complex driving situations such as driving along winding roads and driving in heavy traffic are also reported to influence driving speed and lateral lane position variability of mobile phone distracted drivers (Tractinsky et al., 2013, Oviedo-Trespalacios et al., 2017a). Other authors such as Atchley and Chan (2011) have reported that distracted drivers could increase their vigilance even when driving in less stimulating environments. Lastly, differences in the mobile phone task seem to trigger different compensatory strategies, e.g. visual intensive tasks compared with hands-free conversations are typically recognised as more complex and, therefore, drivers might modify their behaviour further (or in diverse ways) depending on the task (Oviedo-Trespalacios et al., 2017c). As a result, in this research special attention is given to the impact of self-regulatory secondary tasks, personal characteristics, and road traffic conditions on mobile phone distracted driving performance.

Theoretical models such as the human-machine systems framework for mobile phone distracted driving proposed by Oviedo-Trespalacios et al. (2016) (based on the work of Cacciabue (2004) and Degani (1996)) concur that behavioural adaptation is a two-way phenomenon. This means that both driving and mobile phone tasks are closely related in that the mobile phone task is benefited if driving performance decreases and vice versa. This is quite logical given that the mobile phone and vehicle are competing simultaneously for the driver's cognitive and physical resources. While numerous studies have reported that the use of mobile phones impairs driving behaviour such as reaction time (Haque and Washington, 2014), car following (Saifuzzaman et al., 2015a) and braking performance (Haque et al., 2016), the opposite has also been observed, i.e. that driving behaviour impairs performance of mobile phone tasks. For example, Becic et al. (2010) reported that mobile phone conversations while driving have lower conversation quality as measured in terms of speech comprehension, language encoding and language production. In addition, the driving task has also been reported to impair texting performance via an increase in accuracy errors (Alosco et al., 2012) and response times (He et al., 2014). Nonetheless, the relationship between driving performance and secondary task performance has not been studied simultaneously. In order to address this research gap in the literature, this study proposes a novel experiment where the relationship between secondary task performance (texting and talking on a mobile phone) and driving performance is analysed. As a result, an in-depth understanding of the human-machine interactions in mobile phone distracted driving will be achieved.

1.1. Specific aim

The aim of this paper is to investigate the effects of a self-regulated secondary task on the driving performance of mobile phone distracted drivers, while considering driver characteristics, road traffic conditions, and secondary task demands. A driving simulator experiment was designed to investigate driving performance when drivers are allowed to determine their own tempo for engaging in distracted driving. The findings of this research will explore the potential of a human-machine system framework to explain mobile phone distracted driving, and discuss practical implications.

2. Method

This investigation was approved by the Queensland University of Technology Ethics Review Committee (QUT ethics Approval Number 1500001038) and was conducted with explicit consent obtained from each subject.

2.1. Experimental protocol

A driving simulator experiment was designed to investigate the

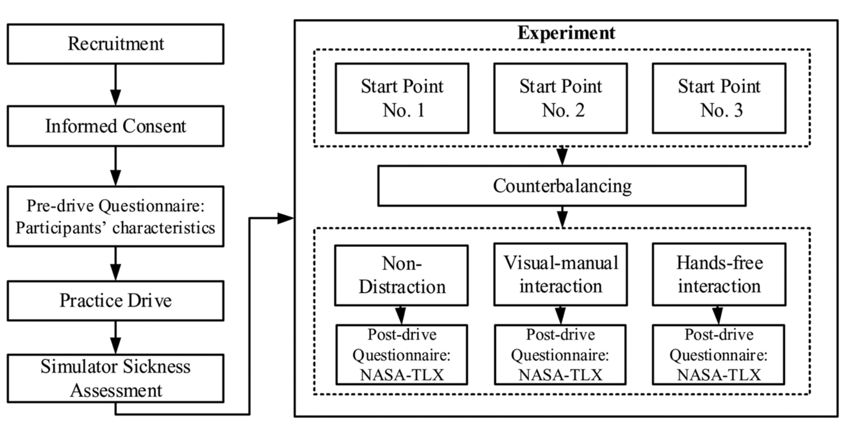

Fig. 1. Experimental protocol.

Table 1
Self-reported mobile phone use history and crash risk perception.

Participant Characteristics	Responses			
Frequency of mobile phone use while driving	Never (1) or Occasionally (2)	Sometimes (3)	Usually (4) or Nearly all the time (5)	M (SD)
Mobile phone conversations	51.4%	48.6%	0.0%	1.77 (0.69)
Mobile phone visual-manual interactions	74.3%	20.0%	5.7%	2.06 (0.84)
Participant Characteristics	**Responses**			
Perceived crash risk of mobile phone use while driving	Unlikely (1) or Very unlikely (2)	Neither likely or unlikely (3)	Likely (4) or Very likely (5)	M (SD)
Mobile phone conversations	51.4%	31.5%	17.1%	2.6 (1.1)
Mobile phone visual-manual interactions	17.1%	31.4%	51.5%	3.6 (1.0)

interaction between self-regulated secondary task and driving performance. The experiment protocol is shown in Fig. 1. Each participant drove through three experimental conditions, including a non-distraction condition (no mobile phone task) drive, a drive while using the mobile phone for hands-free conversation, and a drive while performing a visual-manual interaction task on the mobile phone. Within each driving condition, the simulated route scenario was 10 km long with the following three distinct road traffic conditions found on Australian roads: (1) straight segment in a suburban setting with posted speed of 80 kph, (2) s-curve ($r = 100$ m and -225 m) in a suburban setting with posted speed of 80 kph, and (3) two-lane motorway with posted speed of 110 kph. Three start points were randomly located in separate locations of the simulated road to facilitate data collection in the three phone conditions. Mobile phone conditions and start point order were randomised across participants to avoid learning effects.

Participants took a 10-minute practice drive that also includes driving in the three mobile phone conditions. They were then assessed for motion sickness using the motion sickness assessment questionnaire (MSAQ) (Gianaros et al., 2001). All participants received instructions prior to entering the simulator that they should drive as they usually would in the real world driving and give priority to safe driving. In addition, they were also advised to complete the drive as quick as possible but following the posted speed limit. During the visual-manual and hands-free conditions, participants were asked to use the mobile phone as much as they can in a safe manner. Participants were encouraged to use the mobile phone as realistic as possible given the circumstances. Unlike previous simulator experiments in the literature, participants could stop the mobile phone task wherever and whenever they considered appropriate. This means that participants had the freedom to decide for engaging in mobile phone tasks. Participants used their own phones to conduct the mobile phone tasks. Every drive was approximately 15 minutes long if the speed limit was followed. Participants who completed the experiment were offered $50 vouchers to acknowledge their participation. The total experiment took about 1.5 hours on average.

The study included pre-drive and post-drive questionnaires. The pre-drive questionnaire included general demographic information (*age, gender, and driving history*) and mobile phone use history (*frequency of mobile phone use while driving and perceived crash risk of mobile phone use while driving*). Single item measures were mainly used in the pre-drive questionnaire to prevent redundancy (Rossiter, 2002), and mitigate exhaustion among participants (Türkay, 2016). The post-drive questionnaires included the NASA-TLX questionnaire (Hart and Staveland, 1988), which is widely applied as a reliable measure of subjective workload.

2.2. Recruitment and participants' demographic information

Thirty-five drivers aged 18–29 years (62% male) were recruited through email, using newsgroups and social networks. All participants were required to have a valid driver's license in Australia, and to regularly drive for a total of at least 1 hour every week. The average age of participants was 22.9 years (SD 4.0). Mean ages for males and females were respectively 22.23 (SD 4.06) and 24.23 (SD 3.81) years. The average driving experience of drivers in this study was about 3.48 years.

2.2.1. Participants' responses to pre-drive questionnaire items

Self-reported use of mobile phones while driving and crash risk perception of the participants of this study are presented in Table 1. About 74% of participants reported that they never or occasionally engage in visual-manual tasks, while about 51% reported that they never or occasionally engage in conversations. It is important to note that this research was conducted in Queensland (Australia) where handheld mobile phone use while driving is prohibited. About half of the drivers reported that it is likely or very likely that a crash could occur due to using a mobile phone for visual-manual interactions while driving. In contrast, only 17% drivers reported that it is likely or very likely that a crash could occur due to using a mobile phone for conversations. The difference in risk perception may have resulted from their own experience of using mobile phones or from the large number of campaigns that have been conducted to prevent texting while driving in Australia.

2.3. Equipment

The experiment was conducted in the CARRS-Q advanced driving simulator (see Fig. 2), which is a high-fidelity driving simulator consisting of a complete car with working controls and instruments surrounded by three front-view projectors providing 180-degree high resolution field view to drivers. Wing mirrors and the rear-view mirror are substituted by LCD monitors to simulate rear view mirror images. Road images and interactive traffic are generated at life size onto front-view projectors, wing mirrors and the rear-view mirror at 30 Hz to

Fig. 2. CARRS-Q advanced driving simulator.

provide a photorealistic virtual environment. The car used in this experiment was a complete Holden Commodore vehicle with automatic transmission. The full-bodied car rests on a 6 °-of-freedom motion base that can move in three dimensions to accurately reproduce motion cues for sustained acceleration, braking manoeuvres, cornering and interaction with varying road surfaces. The simulator is also capable of producing realistic forces through the steering wheel to provide a realistic driving experience, particularly when negotiating horizontal curves. The simulator uses SCANeR™ studio software with eight computers linking vehicle dynamics with the virtual road traffic environment. The audio system of the car is linked with the simulator software so that it can accurately simulate surround environment sounds for engine noise, external road noise and sounds for other traffic interactions, thus further increasing the realism of driving experience. Driving performance data such as position, speed, acceleration and braking were recorded every 0.05 s. Further information on the driving simulator can be found in https://research.qut.edu.au/carrsq/.

2.4. Mobile phone tasks

During the mobile phone conditions, participants were engaged in two types of secondary tasks: hands-free conversation and visual-manual interaction task.

The hands-free interaction involved a continuing communication with the Research Officer (RO). The conversation required participants to repeat back four randomly generated alphabetical and numerical characters (e.g., H4ID, WKD5, 1T3S, etc.) read by the RO over the phone. Participants were instructed to start driving once the first group of the characters were mentioned by the research officer. Participants were also instructed to say the word "Repeat" if they do not recall the characters. Participants were allowed to self-pace the task, take time whenever they feel necessary, and request RO to repeat the characters. The RO was located in a different room so she was not aware of the simulator route progress. In addition, the RO was trained to read out the four digits in similar manner throughout the drive.

The visual-manual interaction task involved participants reading out loud a series of randomly generated characters like the previous one. These characters were sent through an email before the experimental drive so that participants could read them on their phone. Participants were instructed to start driving once they read the first group of the characters aloud. The research officer did not mention anything else during the experiment. Participants were free to self-regulate where and when to engage in the reading task.

The interactions of participants with mobile phone were recorded using time stamps and then merged with the driving simulator data.

2.5. Driving and secondary task performance measurement

Driving performance was measured in terms of longitudinal and lateral control of the driven vehicle. In specific, longitudinal performance was measured based on driving speed, which includes deviation of driving speed from the speed limit [speed limit – driving speed] and standard deviation of driving speed along the segment. Lateral control was measured as a function of standard deviation of the lateral lane position (none of the participants had lane departures).

Secondary task performance was measured using five variables: number of mobile phone interactions per second of driving, average duration of mobile phone interactions, standard deviation of duration of mobile phone interactions, average time to engage in a mobile phone interaction, and standard deviation of the time to engage in a mobile phone interaction. Fig. 3 illustrates how these variables were calculated from the secondary task performance of drivers. The main assumption is that drivers can modify their secondary task performance in two ways: (1) modifying the time period that is used to complete a task (time completing an interaction) and, (2) modifying the time period that is used to engage in the next task (time to engage in the next interaction). In case of visual-manual tasks while driving, the time to engage was calculated as the time between interactions or time taken to engage in the next interaction after completing one (see the upper part of Fig. 3). In the case of the hands-free interactions while driving, the time to engage was calculated as the time taken by the participant to respond after the research officer finished reading the four digits (see the lower part of Fig. 3).

2.6. Data treatment and analysis

Three stages of data analysis were conducted in this study.

First, driving performance data (deviation of driving speed from the speed limit, standard deviation of the driving speed, and variability of the lateral lane position) were tabulated across road traffic conditions (straight lane, motorway, and s-curve) and mobile phone tasks (non-distraction, hands-free interaction, and visual-manual interaction). Speed deviation measured as the deviation from the speed limit (Speed Limit – Driving Speed) allows comparison of driving performance across various road traffic conditions. A positive value of speed deviation from the speed limit means a lower speed which suggests an increase in safety. Differences in driving behaviour across the three mobile phone conditions were assessed using repeated measures ANOVA and post hoc tests (Bonferroni). An additional analysis at this stage compared the subjective workload due to mobile phone use while driving across experimental conditions. This was intended as a manipulation check of the mobile phone tasks used in this study, given that previous research has consistently showed that visual-manual mobile phone interactions have increased workload compared with other mobile phone tasks such as hands-free conversations or non-distraction driving (Oviedo-Trespalacios et al., 2016).

Second, secondary task performance variables (*number of mobile phone interactions, average duration mobile phone interactions, etc.*) were

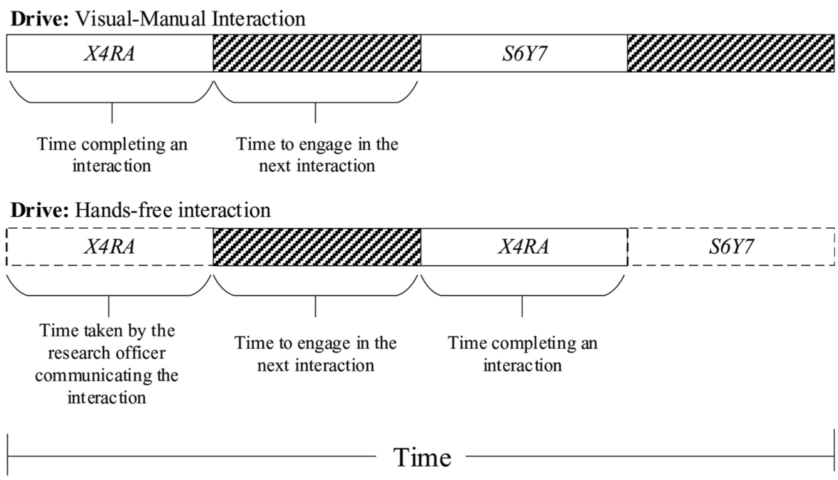

Fig. 3. Variables utilised to describe secondary task performance.

Table 2
Driving performance across experiment conditions.

Variables	Tasks			Repeated measures ANOVA *p*-value
	Non-distraction M (SD)	Hands-free interaction M (SD)	Visual-manual interaction M (SD)	
Deviation of driving speed from the speed limit (kph)	2.49 (6.00)	2.30 (6.66)	2.84 (8.53)	0.88
Standard deviation of the driving speed (kph)	4.26 (2.88)	4.62 (2.96)	5.00 (3.40)	< 0.001***
Standard deviation of the lateral lane position (metres)	0.36 (0.21)	0.34 (0.20)	0.42 (0.20)	0.003**

Note: ** $p < 0.01$; *** $p < 0.001$.

tabulated across road traffic conditions (*straight lane, motorway, and s-curve*). Analyses were performed separately for *hands-free interaction and visual-manual interaction* given the fundamental differences in the task execution and complexity, with hands-free interactions having an external input compared to visual-manual interactions. Repeated measures ANOVA and post hoc tests (Bonferroni) were used to determine changes in secondary task performance across road traffic conditions.

Third, Generalized linear mixed models (GLMMs) were developed to model driving performance of drivers self-regulating their driving task. In particular, driving performance (e.g., *deviation of driving speed from the speed limit, standard deviation of the driving speed, and variability of the lateral lane position*) is modelled as a function of driver characteristics (e.g., *age, gender, time with a valid driving license, and frequency of mobile phone use while driving, and perceived crash risk of mobile phone use while driving*), driving demands (e.g. *straight segment, motorway, and s-curve*), mobile phone task types (e.g., *hands-free or visual-manual interaction*) and secondary task performance (e.g., *number of mobile phone interactions per* 10 s *of driving, duration of the mobile phone interactions, standard deviation of the average duration of the mobile phone interactions, time to engage in a mobile phone interaction, and standard deviation of the average time to engage in a mobile phone interaction*). The mathematical formulation of driving performance model is as follows.

Let's say, μ_{ij} represents the deviation of driving speed from the speed limit or any other driving performance metric (e.g. variability in lateral lane position) for participant *i* along road segment *j*. The GLMM for deviation of driving speed from the speed limit can be expressed as follows:

$$g(\mu_{ij}) = \alpha + \mathbf{X'}_i\boldsymbol{\beta} + \mathbf{Y'}_i\boldsymbol{\gamma} + \mathbf{Z'}_j\boldsymbol{\lambda} \tag{1}$$

where g is the link function with Gaussian link, $\mathbf{X}_i$ is a vector of attributes for driver characteristics, $\mathbf{Y}_i$ is a vector of variables related to mobile phone task performance, and $\mathbf{Z}_j$ is a vector of variables describing the road traffic condition. $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, γ and $\boldsymbol{\lambda}$ are vectors of the estimable parameters. Parameters (such asβ) in the GLMM are estimated as follows (Wang and Abdel-Aty (2006)):

$$S(\beta) = \sum_{i=1}^{k} \frac{\partial \mu'_i}{\partial \beta} V_i^{-1}(SA_i - \mu_i(\beta)) = 0 \tag{2}$$

where V_i is an estimator of the covariance matrix of SA_i specified as $V_i = \varphi A_i^{1/2} R_i(\rho) A_i^{1/2}$. In the covariance matrix, A_i is an $n_i \times n_i$ diagonal matrix with $v(\mu_{ij})$ as the *j*th diagonal element. V_i can be different from one driver to another, but it is common to specify the same form for all drivers. $R_i(\rho)$ is an $n_i \times n_i$ working correlation matrix specified by the vector parameter ρ. An exchangeable working correlation that makes constant correlations between any two observations within a driver is specified as:

$$Corr(SA_{ij}, SA_{il}) \begin{cases} 1 & j = l \\ \rho & j \neq l \end{cases} e.\ g.\ R_{4x4} = \begin{bmatrix} 1 & \rho & \rho & \rho \\ \rho & 1 & \rho & \rho \\ \rho & \rho & 1 & \rho \\ \rho & \rho & \rho & 1 \end{bmatrix} \tag{3}$$

Detailed expressions for estimating ρ's are available in Liang and Zeger (1986), and the suitability of this approach for modelling driving performance of distracted drivers has been tested before by Oviedo-Trespalacios et al. (2017a). The above specification accounts for correlations resulting from multiple observations from the same driver as the case of experimental data of this study. The parsimonious model was obtained by backward stepwise elimination technique with a 5% level of significance and assessed using the Akaike information Criterion (AIC) and Schwarz's Bayesian Criterion (SBC). All analyses were conducted in SPSS 18.0 (SPSS, 2005).

Table 3
Self-regulated secondary task performance across road traffic conditions.

Tasks	Variables	Road Traffic Conditions			Repeated measures ANOVA *p*-value
		Straight road *M* (*SD*)	Motorway *M* (*SD*)	S-curve *M* (*SD*)	
Hands-free interaction	Number of mobile phone interactions per second driving	0.19 (0.04)	0.21 (0.04)	0.19 (0.04)	0.02*
	Duration of the mobile phone interactions (sec)	1.4 (0.3)	1.4 (0.25)	1.39 (0.19)	0.97
	Standard deviation of the duration of mobile phone interactions (sec)	0.48 (0.16)	0.45 (0.21)	0.37 (0.17)	0.02*
	Time to engage in a mobile phone interaction (sec)	1.28 (0.68)	1.05 (0.54)	1.21 (0.56)	0.26
	Standard deviation of the time to engage in a mobile phone interaction (sec)	0.96 (0.78)	0.83 (0.63)	0.85 (0.7)	0.72
Visual-manual interaction	Number of mobile phone interactions per second driving	0.26 (0.10)	0.29 (0.17)	0.18 (0.11)	0.02*
	Duration of the mobile phone interactions (sec)	1.01 (0.23)	1.1 (0.4)	1.12 (0.41)	0.89
	Standard deviation of the duration of mobile phone interactions (sec)	0.34 (0.17)	0.47 (0.29)	0.46 (0.24)	0.02*
	Time to engage in a mobile phone interaction (sec)	2.43 (1.22)	6.93 (11.71)	4.33 (4.48)	0.48
	Standard deviation of the time to engage in a mobile phone interaction (sec)	2.51 (1.39)	1.45 (1.38)	3.98 (5.25)	0.002**

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

3. Results

3.1. Driving performance

Driving performance as measured by deviation of driving speed from the speed limit (*kph*), standard deviation of the driving speed, and variability of the lateral lane position were compared across phone conditions and presented in Table 2. Repeated measures ANOVA identified statistically significant effects of self-regulated mobile phone tasks on standard deviation of the driving speed ($F_{2,134.6} = 33.58$, *p-value* < 0.001) and lateral lane position ($F_{2,161.1} = 23.54$, *p-value* 0.003). Post-hoc tests confirmed that the drivers in the non-distraction condition have lower deviation of driving speed compared to self-regulated hands-free (*p-value* < 0.001; $\Delta_{\text{Non-distraction-Hands-free}} = -2.43$) and visual-manual (*p-value* = 0.001; $\Delta_{\text{Non-distraction-Visual-manual}} = -2.52$) tasks. In addition, post-hoc tests confirmed that the drivers in the self-regulated visual-manual interaction task have larger lateral lane position variability compared to hands-free (*p-value* < 0.001; $\Delta_{\text{Visual-manual-Hands-free}} = 0.12$) and non-distraction (*p-value* = 0.001; $\Delta_{\text{Visual-manual-Non-distraction}} = 0.09$) conditions.

3.1.1. Self-reported workload (post-drive questionnaire)

The NASA-TLX was completed by the participants at the end of each experimental drive to study the impact of mobile phone tasks on mental workload. The average values of workload in non-distraction, hands-free and visual-manual conditions were respectively 33.9 (*SD* = 18.17), 49.9 (*SD* = 18.16), and 60.7 (*SD* = 14.41). A repeated measures ANOVA identified that the interaction between experimental conditions and NASA-TLX workload scores was statistically significant ($F_{2,66.4} = 24.68$, *p-value* < 0.001). Post-hoc tests confirmed that there were significant differences between each pair of conditions: non-distraction vs. hands-free interaction task (*p-value* = 0.001; $\Delta_{\text{Non-distraction-Hands-free}} = -16.67$), non-distraction vs. visual-manual interaction task (*p-value* < 0.001; $\Delta_{\text{Non-distraction- Visual-manual}} = -27.53$), and hands-free interaction task vs. visual-manual interaction task (*p-value* = 0.02; $\Delta_{\text{Hands-free- Visual-manual}} = -10.85$). The visual-manual task appears to have the highest workload scores among the phone conditions.

3.2. Self-regulated secondary task performance

Secondary task performance across road traffic conditions were assessed by repeated measures ANOVA and presented in Table 3.

The *rate of mobile phone interactions per second driving* were significantly different across road traffic conditions both in hand-free ($F_{2,67.21} = 4.26$, *p-value = 0.02*) and visual-manual ($F_{2,55.73} = 4.25$, *p-value = 0.02*) conditions. In the hands-free condition, the *number of mobile phone interactions per second driving* along S-curve was significantly lower than motorway (*p-value* = 0.031; $\Delta_{\text{Motorway-S-curve}} = 0.025$). The difference in rate of mobile phone interactions per second driving between S-curve and straight segment was not statistically significant. In the visual-manual interaction task, the *rate of mobile phone interactions per second driving* along S-curve was significantly lower compared to straight segment (*p-value* = 0.006; $\Delta_{\text{Straight-S-curve}} = 0.08$) and motorway (*p-value* = 0.007; $\Delta_{\text{Motorway-S-curve}} = 0.11$).

Self-regulated secondary task performance in terms of *standard deviation of the duration of mobile phone interactions* (see Table 2) were also significantly different across road traffic conditions both in visual-manual ($F_{2,61.9} = 4.22$, *p-value = 0.02*) and hands-free ($F_{2,49.4} = 4.35$, *p-value = 0.02*) phone condition conditions. In the hands-free condition, post-hoc test confirmed that the variability of the mobile phone interactions was higher in the straight segment than s-curve (*p-value* = 0.02; $\Delta_{\text{Straight-S-curve}} = 0.12$). In the visual-manual task, post-hoc test confirmed that the variability of the mobile phone interactions was lower in the straight segment compared to the s-curve (*p-value* = 0.03; $\Delta_{\text{Straight-S-curve}} = -0.13$.).

Time to engage in a secondary task—measured as the time difference between two consecutive involvements in the same secondary task—was compared across road traffic conditions for each secondary task. Among all interactions between *time to engage* in each secondary task type and road traffic conditions, the standard deviation of time to engage in visual-manual task was found to be significantly different across road traffic conditions ($F_{2,46.7} = 7.28$, *p-value* = 0.002). Post-hoc tests showed lower variability in the time to engage in a secondary task while driving in the motorway compared to s-curve (*p-value* = 0.02; $\Delta_{\text{Motorway-S-curve}} = -2.79$) and straight segment (*p-value* = 0.01; $\Delta_{\text{Motorway-Straight}} = -1.06$).

3.3. The relationship between self-regulated secondary task and driving

This section presents the GLMM model results for the relationship between self-regulated secondary task performance and driving performance for hands-free and visual-manual interactions.

3.3.1. Impact of self-regulated hands-free interactions on driving performance

Table 4 and 5 presents the results of GLMM estimates of driving performance in self-regulated hands-free interactions. Separate GLMM was estimated for *speed deviation from the speed limit (kph)*, *standard*

Table 4
GLMMs predicting driving performance during self-regulated hands-free mobile phone interactions.

Parameter	Coefficient	*SE*	*t*	*p*	95% *CI*
Dependent variable: deviation of driving speed from the speed limit (kph)[a]					
Intercept	−7.31	2.93	−2.49	0.014*	[−13.13, −1.47]
Road traffic condition					
Motorway	*ns.*	*ns.*	*ns.*	*ns.*	*ns.*
S-curve	5.38	1.05	5.11	< 0.001***	[3.28, 7.48]
Straight segment	— °	— °	— °	— °	— °
Hands-free interactions per 10 seconds of driving	4.12	1.46	2.81	0.006**	[1.21, 7.02]
Dependent variable: standard deviation of the driving speed (kph)[b]					
Intercept	4.34	0.57	7.55	< 0.001***	[3.2, 5.48]
Road traffic condition					
Motorway	−3.61	0.51	−6.96	< 0.001***	[−4.64, −2.58]
S-curve	*ns.*	*ns.*	*ns.*	*ns.*	*ns.*
Straight segment	— °	— °	— °	— °	— °
Perceived crash risk: mobile phone conversations	0.55	0.16	3.48	< 0.001***	[0.23, 0.88]
Dependent variable: standard deviation of the lateral lane position (metres)[c]					
Intercept	0.21	0.02	9	< 0.001***	[0.17, 0.26]
Road traffic condition					
Motorway	−0.06	0.02	−2.37	0.01*	[−0.11, −0.01]
S-curve	0.31	0.02	12.35	< 0.001***	[0.26, 0.36]
Straight segment	— °	— °	— °	— °	— °
Gender					
Male	0.06	0.02	2.44	0.01*	[0.01, 0.1]
Female	— °	— °	— °	— °	— °

Note: ° Reference category; *ns*. Non-significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

[a] **Deviation of vehicle speed from the speed limit model:** Bayesian Information Criterions (BIC) = 656.844; Akaike's Information Criterion (AIC) = 651.61; ρ = 0.48.

[b] **Standard deviation of the driving speed model:** Bayesian Information Criterions (BIC) = 469.216; Akaike's Information Criterion (AIC) = 474.44; ρ = -0.40.

[c] **Standard deviation of the lateral lane position model:** Bayesian Information Criterions (BIC) = -132.08; Akaike's Information Criterion (AIC) = -137.32; ρ = 0.10.

Table 5
GLMMs predicting driving performance during self-regulated visual-manual mobile phone interactions.

Parameter	Coefficient	*SE*	*t*	*p*	95% *CI*
Dependent variable: deviation of driving speed from the speed limit (kph)[a]					
Intercept	12.32	2.76	4.45	< 0.001***	[6.78, 17.85]
Road traffic condition					
Motorway	ns.	ns.	ns.	ns.	ns.
S-curve	8.36	1.31	6.38	< 0.001***	[5.73, 10.98]
Straight segment	— °	— °	— °	— °	— °
Duration of the mobile phone interactions	−4.55	1.18	−3.85	< 0.001***	[-6.89, −2.2]
Previous experience with mobile phone visual-manual interactions	−3.27	1.04	−3.13	< 0.001***	[−5.39, -1.16]
Dependent variable: standard deviation of the driving speed (kph)[b]					
Intercept	6.09	0.53	11.36	< 0.001***	[5.03, 7.16]
Road traffic condition					
Motorway	−2.9	0.75	−3.82	< 0.001***	[−4.41, −1.4]
S-curve	ns.	ns.	ns.	ns.	ns.
Straight segment	— °	— °	— °	— °	— °
Dependent variable: standard deviation of the lateral lane position (metres)[c]					
Intercept	0.28	0.03	7.9	< 0.001***	[0.19, 0.35]
Road traffic condition					
Motorway	ns.	ns.	ns.	ns.	ns.
S-curve	0.29	0.02	11.2	< 0.001***	[0.24, 0.35]
Straight segment	— °	— °	— °	— °	— °
Visual-manual interactions per 10 seconds of driving	0.023	0.01	2.24	0.02*	[0.002, 0.04]

Note: ° Reference category; *ns*. Non-significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

[a] **Deviation of vehicle speed from the speed limit model:** Bayesian Information Criterions (BIC) = 630.72; Akaike's Information Criterion (AIC) = 625.68; ρ = 0.39.

[b] **Standard deviation of the driving speed model:** Bayesian Information Criterions (BIC) = 545.04; Akaike's Information Criterion (AIC) = 539.79; ρ = -0.03.

[c] **Standard deviation of the lateral lane position model:** Bayesian Information Criterions (BIC) = -98.63; Akaike's Information Criterion (AIC) = -103.86; ρ = 0.41.

deviation of driving speed (kph), and *variability in lateral lane position (metres)*.

Road traffic condition was found to be a significant predictor in all three driving performance models. Results indicate that drivers engaged in self-regulated hands-free interactions select about 5.38 kph lower driving speed (than the speed limit) and have about 0.31 m more lateral variability along S-curve compared to the straight segment. On the other hand, the speed variability among drivers engaged in hands-free interactions is about 3.61 kph lower along motorway compared to the straight segment.

Among secondary task performance variables, the number of mobile phone interactions was a significant predictor of deviation of driving speed from the speed limit. Results indicate that the deviation of driving speed from the speed limit is higher among drivers who engage in a higher number of hands-free interactions per second driving, with every additional interaction per 10 s of driving resulting in about 4.12 kph less speed.

Personal characteristic variables like risk perception and gender are also found to influence the driving performance of drivers distracted by self-regulated hands-free interactions. Drivers who reported perceiving higher crash risk due to mobile phone conversations while driving showed more variability in driving speed. The lateral variability in lane position under self-regulated hands-free distraction is about 0.06 m higher among male drivers compared to female drivers.

3.3.2. Impact of self-regulated visual-manual interactions on driving performance

Table 5 presents the GLMM estimates of driving performance during self-regulated visual-manual interactions.

Road traffic condition was found to be a significant predictor in all three driving performance models. Results indicate that drivers engaged in self-regulated visual-manual interactions select about 8.36 kph lower driving speed and have about 0.29 m more lateral variability along S-curve compared to other road traffic conditions. The speed variability among drivers engaged in self-regulated visual-manual interactions is about 2.9 kph lower along motorway compared to S-curve or straight segment.

Among self-regulated secondary task performance variables, the duration of the visual-manual interaction task is found to influence the deviation of driving speed from the speed limit, with every second increase in the duration of visual-manual interaction increase the driving speed by 4.55 kph. The lateral variability among drivers distracted by self-regulated visual-manual task increases with the increase in the number of visual-manual interactions per 10 s of driving.

Among personal characteristic variables, drivers who self-reported having more experience of visual-manual interactions while driving are found to drive with a higher driving speed, with every addition unit in 5-point scale of the questionnaire item associated with about 3.27 kph higher driving speed.

4. Discussion and conclusion

This experimental study showed evidence of changes in self-regulated secondary task performance and their relationship to driving behaviour. The effects of self-regulated mobile phone tasks on driving performance were observed using a driving simulator experiment. The findings from this research provide empirical evidence of mobile phone self-regulation, which is currently a significant gap in the scientific literature (Young and Regan, 2013).

Drivers were observed not to modify their driving speed in the presence of self-regulated distraction. Most of the studies in mobile phone distraction have observed speed changes in presence of other vehicles, in particular the presence of heavy traffic (Fitch et al., 2015, Fitch et al., 2017). When comparing our results with those of other simulator experiments that found lower driving speeds in distracted conditions (Oviedo-Trespalacios et al., 2017b, Choudhary and Velaga, 2017), it is important to consider that in these other studies drivers were usually constrained to remain engaged in the secondary task regardless of their preference for self-regulation. In this experiment, drivers self-regulated their engagement with mobile phone interactions, and this could explain the lack of speed change, i.e. they used the phone at points on the journey where they believed it was possible to do so without moderating their speed. In addition, visual-manual interactions resulted in larger variability of the lateral lane position. This could be interpreted as an impairment or overcorrection by the driver using the mobile phone. Previous research found similar patterns in lateral lane position deviation among drivers (Caird et al., 2014, Oviedo-Trespalacios et al., 2016). More research is necessary to understand the safety implications of these findings.

Road traffic conditions appears to play a vital role in self-regulation of secondary task and associated driving performance. Road traffic conditions were found to influence each driving performance variable both in hands-free and visual-manual phone conditions. As expected, while driving along the s-curve (posted speed 80kph), drivers reduced their speed to 71.64 kph for visual-manual tasks and 74.56 kph for hands-free tasks. Previous research has reported that drivers consider curves as riskier road traffic conditions (Charlton et al., 2014), which suggest that drivers could be adapting their behaviour to an increased perceived risk. The Task-Capability Interface (TCI) model (Fuller et al., 2008) of driver behaviour assumes that speed selection behaviour is a consequence of the driver, the vehicle, and the surrounding road traffic environment. Therefore, it could be hypothesised that road curves increase workload as they compete for the driver's cognitive (e.g. planning), physical (e.g. steering wheel), and visual (e.g. road monitoring) attention resources. It is also interesting that drivers engaged in visual-manual tasks showed larger variability in the time to engage in an interaction. This could suggest that the increased demands result in drivers reflecting more in their level of engagement, resulting in frequent changes in the length of the time to engage. The intention of drivers to engage in a visual-intensive secondary task has been shown to change based on the road traffic complexity (Hancox et al., 2013). The level of agency among distracted drivers to self-regulate mobile phone tasks should be considered in future research.

Secondary task performance of self-regulated mobile phone interactions varied according to the road traffic conditions. This was observed during hands-free and visual-manual interactions in complex road sections such as s-curves, where drivers reduced the amount of interactions compared to simpler road sections such as straight segments. Driving along curve segments is more demanding because drivers need to negotiate speed and steering wheel control. These results further confirm that environmental complexity is associated with apparent safer behaviours among drivers using the mobile phone while driving. Authors such as Xiong et al. (2014), Tivesten and Dozza (2015), and Kidd et al. (2016) have reported that drivers avoid using a mobile phone in demanding driving environments (e.g. roundabouts, curves, etc.). Nevertheless, although these results suggested that drivers consider driving demands, there is no guarantee that their judgement is sufficient to reduce risk. Research has shown that personal characteristics such as age and experience have a significant role in explaining drivers' risk perception of road design elements (Kanellaidis et al., 2000).

The relationship between self-regulated secondary task performance and driving performance was confirmed in this study. The amount of interactions that drivers performed on the mobile phone while driving was associated with driving performance. A larger amount of hands-free interactions was associated with lower driving speed. This confirms that drivers engaged in hands-free tasks, which are purely cognitive, modify their driving speed as the main source of self-regulation (Caird et al., 2008). On the other hand, the duration of the visual-manual interactions was associated with higher driving speed. This suggests that the act of looking at the mobile phone interferes with speed management performance by reducing environmental cues presented to the driver or through reduced speedometer inspection, as suggested by Oviedo-Trespalacios et al. (2016). Additionally, a larger amount of visual-manual interactions was associated with higher variability in lateral lane position. Holding a phone may reduce the driver's capacity to control the steering wheel, or visual impairment may reduce the driver's capacity to correct vehicle position in a timely manner. Together, these findings confirm that depending on the mobile phone task, the level of engagement in mobile phone interactions determines the extent of driving performance changes. This is supported by early evidence suggesting that the performance of a mobile phone task can be modified while driving (see Alosco et al. (2012) and Becic et al. (2010)).

Personal characteristics variables appeared to predict driving performance under the influence of a self-regulated secondary task. During hands-free interactions, perceived crash risk and gender were significant predictors of standard deviation of driving speed and standard deviation of lateral lane position, respectively. Personal characteristics variables appeared to predict driving performance under the influence of a self-regulated secondary task. For hands-free interactions, perceived crash risk and gender were significant predictors of standard deviation of driving speed and standard deviation of lateral lane position, respectively. This suggests that drivers were adapting their speed on the basis of perceived crash risk of road traffic conditions. An increased variability suggests that drivers were overcorrecting their speed to cope with the increased risk. Males have larger standard deviation in lateral lane position compared to females. Gender differences in grip force while controlling the steering wheel has been reported previously. For example, Eksioglu and Kızılaslan (2008) showed that males have large grip force variability than females. Nevertheless, it is unclear why these relationships were only observed for the hands-free interactions.

Drivers who self-reported having more experience in mobile phone visual-manual interactions drove faster in the experimental drive while performing visual-manual tasks. This result is consistent with previous observations which suggest that drivers with less experience of a secondary task seem to be more cautious (Oviedo-Trespalacios et al., 2017b). In addition, visual-manual interactions could undermine drivers' capacity to monitor speed accurately (Oviedo-Trespalacios et al., 2016). It is important to note that hand-held phone use is unlawful in Australia, which might explain why secondary task experience does not predict performance in the hands-free interaction condition.

Finally, the results in this study confirmed the suitability of the human-machine system model framework—which proposes that in-vehicle tasks result in a two-way interaction between driving performance and mobile phone task performance (Oviedo-Trespalacios et al., 2016)—in explaining self-regulation of distracted drivers. This could potentially have enormous benefits for road safety research and practice. As argued by Young and Regan (2009), little attention has been given to the mechanisms by which moderating factors are associated with mobile phone distracted driving. This information could support development of countermeasures such as in-vehicle monitoring systems and understanding high-risk driving populations. Future research is needed to investigate whether this pattern could be used to safely integrate mobile phone interactions into driving.

4.1. Limitations and future research

The findings of the current research, however, should be interpreted in light of the limitations of the methodology implemented.

First, the use of a driving simulator in this study is an important limitation as simulators are often criticised for their ability in creating a realistic driving experience. The experiments in this study were conducted using a high-fidelity simulator with a motion platform with six degrees of freedom that can move and twist in three dimensions. Findings from studies completed in this simulator have been successful explaining real world driving data (Saifuzzaman et al., 2015b). Nevertheless, even the most sophisticated driving simulators do not provide all the visual, vestibular, and proprioceptive interactions that occur when driving in certain speed, which is particularly important for driver behaviour research. Although other researchers (e.g. Charlton (2009) and Meuleners and Fraser (2015)) have demonstrated the relative validity of driving simulators compared to real world driving, further research is necessary to generalise the findings of this experiment. Field and naturalistic studies could enhance the understanding of self-regulated mobile phone distracted driving.

Second, the small sample size, unequal gender distribution, and relatively young group of participants may limit the degree to which the findings of this study can be generalized to the overall driver population. In addition, participation in this study was voluntary. This could have produced selection bias, meaning that perhaps the 'safest' drivers might have been interested in participating in this research, while the 'riskiest' drivers were not. Given the importance of drivers' characteristics found in this study, future research should seek to recruit a larger sample with a better mix of participants to better understand the interactions between self-regulated secondary task performance and driving performance.

Third, road and traffic features included in this study are limited and rather simple. There are other ecological variables that could influence mobile phone task and driving performance, e.g. traffic and weather. Therefore, caution should be taken in utilising the results of this study given that the virtual environment/animation may lack the richness of real road traffic conditions. Despite these limitations, this research offers a starting point to be used in distracted driving research regarding self-regulation or behavioural adaptation. In future studies, more naturalistic designs and diverse road traffic conditions are necessary to rigorously determine the effect of self-regulated mobile phone distracted driving.

Fourth, artificial conversation dialogues and reading activities were used in this research mainly to ensure a consistent level of cognitive distraction among participants. The artificiality of the mobile phone tasks could limit generalization of the observed behaviours. For example, research has shown that contentious conversation increases workload compared with emotionless conversations (Lansdown and Stephens, 2013). The results of this study, which only examined the effects of hands-free and visual-manual interactions, should be confirmed or compared with other mobile phone tasks. It should also be noted that mobile phone interactions in real driving require other support tasks (e.g. reaching for the phone, dialling, answering, monitoring the battery, etc.) which could be studied for a complete understanding of mobile phone distracted driving.

4.2. Conclusion

This research investigated the effects of the self-regulated mobile phone tasks on driving performance and found that the level of performance of self-regulated secondary tasks is closely related to the extent of the changes in driving behaviour. In other words, drivers are observed to reduce their level of engagement in secondary tasks to benefit driving performance. Therefore, the two-way interaction between mobile phone and driving performance is a self-regulatory mechanism with potential of minimising crash risk. Previous research, where self-regulation behaviours of distracted drivers were not considered, has potentially inflated estimates of driving impairment because of imposed mobile phone distraction. In addition, it is important to highlight that the self-regulation of mobile phone tasks is heavily influenced by human factors such as crash risk perception, experience with a secondary task, and gender. Future research is necessary to test the two-way interaction of distracted driving using naturalistic driving data.

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