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What is the difference in driver's lateral control ability during naturalistic distracted driving and normal driving? A case study on a real highway

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ABSTRACT

Driver distraction is widely recognized as a major contributor to traffic crashes. Although the effect of distraction on simulated driving performance has been studied extensively, comparatively little research based on field tests has been performed on the effects of high driving speeds on lateral driving performance during naturalistic distraction (the driver was unaware of the research topic). In this study, an instrumented vehicle is used to examine the impact of speed and naturalistic visual distraction (rear vehicle's velocity and relative distance estimation) on a driver's ability to keep in the lane. Similar to results from previous studies, visual distraction resulted in an impaired ability to keep in a lane compared to normal driving. Further investigation of steering control parameters showed an increase in steering wheel reversal rates (SRRs at 1.3° and 2.5° levels) and the standard deviation of steering wheel acceleration (SDSWA). The results of this study indicated that the standard deviation of lane positioning (SDLP) and trajectory offset (TO) increased as speed increased. As speed increased, the growth rates of SDLP and TO in the visual distraction task were the same as that in normal driving. Moreover, the SRRs and steering wheel acceleration (SWA) decreased with increased speed. As speed increased, the growth rates of SRRs and SWA during a visual distraction task were the same as that during normal driving. These results suggest that driving speed has a similar effect on driving performance during both distracted driving and normal driving.

1. Introduction

Distracted driving is a common driving behavior that has become a leading cause of traffic accidents. Distracted driving may impair driving performance and the ability to respond to dangerous situations (Horberry et al., 2006). Statistics show that in 2015 in the United States, 3477 people died in traffic accidents caused by distraction (National Highway Traffic Safety Administration, 2017). Distracted driving can lead to lane departure, and data showed that 14.5% of traffic accidents are caused by this sort of lane departure, in which 35% of these traffic accidents led to death (Pohl et al., 2007).

Distraction occurs when a driver's attention is diverted away from driving by a secondary task. While the secondary task may take many types, it is helpful to examine distraction in terms of three major modalities (Zhang and Kaber, 2016): visual distraction (e.g., looking at speedometer), cognitive distraction (e.g., talking to passengers), and manual distraction (e.g., adjusting the radio). Compared with other types of distraction task, visual distraction could more seriously impair the lane-keeping ability (Cuenen et al., 2015). In addition, there are other well-accepted distraction classifications: internal distraction and external distraction (Shaw et al., 2018). Internal distraction is triggered by something or people inside the vehicle (e.g., looking at the mobile phone), external distraction is caused by something or people outside the vehicle (e.g., looking at billboard).

Most of the research on the effect of driving distractions has been conducted using simulators. In several visual distraction experiments, a driver used a mobile phone to perform a dialing task, and it was found that lane deviation at high driving speeds significantly increased and lateral deviation linearly increased as dialing time increased (Caird et al., 2018; Salvucci and Macuga, 2002). Some studies have evaluated a driver's lane-keeping capacity under the influence of secondary tasks using the standard deviation of lane positioning (SDLP). These studies indicated that texting tasks caused the SDLP to increase significantly (Pushpa and Nagendra, 2017; McKeever et al., 2013; Thapa et al., 2015). However, in the case of skilled editors, the effect of editing tasks on lane-keeping capacity was not significant due to less time spent editing (Rumschlag et al., 2015). Based on a fixed driving simulator, Shaw et al. (2018) found that external visual distraction (looking at

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billboards) may increase the variability of driving speed and lateral position.

Many studies that have investigated the effect of visual tasks on lane-keeping ability have shown increases in metrics, such as the steering wheel movements. Some studies proposed that steering wheel reversal rates (SRRs) are a useful metric for detecting the effects of visual and cognitive distractions by using Radial Basis Probabilistic Neural Networks (Son and Park, 2018; Kountouriotis et al., 2016). SRRs measure the number of times the steering wheel changes in the direction of steering wheel movements per minute (SAE J2944, 2015). Some studies have shown that other steering metrics, such as steering wheel acceleration (SWA) and the standard deviation of steering wheel acceleration (SDSWA), have an effect on the vehicle's trajectory, and more frequent steering operations can help improve the lane-keeping ability of the driver (Cooper et al., 2013; Medeiros-Ward et al., 2014). Therefore, it is necessary to compare the effect of visual distraction on driving performance when examining SRRs as well as other steering parameters, such as SWA and SDSWA.

Although many researchers have verified the relative validity of driving simulators, the mean driving speed and standard deviations of speed were significantly different between the simulated road and the real road (Oviedo-Trespalacios et al., 2015; Knapper et al., 2015), and driving speed has a significant effect on driver performance under secondary task (Patten et al., 2004). Therefore, some studies were carried out on the real road and indicated that steering activity was more frequent in the field than in the simulator (Engström et al., 2005). In a contrasting experiment, the upper limit of lateral acceleration on the real road was higher than that in the driving simulator (Reymond et al., 2001). Differences in lateral performance have also been found when using simulators versus on a real road (Santos et al., 2005; Strayer et al., 2015). Moreover, Reimer and Mehler (2011) compared the same high-speed driving protocol in a driving simulator and in a field experiment and found a trend of higher mental workload levels on the real road.

One issue that has received little study is the effect of visual distraction on lateral driving performance while driving on real roads at high speeds. Many serious traffic accidents on the freeway were related to distraction (Nowakowski et al., 2012). Some naturalistic driving studies have investigated the effect of driving behaviors, such as braking and steering during secondary task activities, on crash risk at high speeds (Wege et al., 2013; Hickman and Hanowski, 2012). Furthermore, Knapper et al. (2015) the effect of speed and phone talking tasks on longitudinal driving performance and showed that driving speed had a significant effect on driving performance. These studies have focused on the relationship between the odds of involvement in a critical safety situation and distracted driving, but they put less consideration on the effect of distraction and speed on lateral performance. In some on real road tests, drivers were asked to perform the "Arrows" task or a dialing task on a mobile phone, which were considered as purely visual tasks. However, drivers had to touch a screen for this type of task (Santos et al., 2005). Their ability to control the steering wheel diminished while touching the screen. Therefore, these types of distraction tasks cannot be considered a purely visual task, as they involve manual tasks and cognitive components (Foley et al., 2013) as well. In addition, in a majority of the previous experiments, the participants knew the purpose of the distraction task and were able to evaluate their driving performance during distracted driving. Therefore, they may have deliberately corrected their driving behavior, which would have affected the results of the experiment.

The general aim of this study is to investigate the effects of naturalistic external visual distraction and speed on driving performance on a real highway. Experiments are conducted in a real environment at high speed in an instrumented vehicle. Some studies have suggested that a visual task that does not require the driver to totally take their eyes off the road, but instead mimics a gaze behavior observed during a non-visual distraction task that can still contribute to similar driving behaviors that non-visual tasks elicit (Kountouriotis et al., 2016). In a number of studies, participants had a complete understanding of the aim of the distracted driving experiments, which would affect the driver's driving behavior and decision-making style. In this study, the participants were not informed of the aim of the experiments, and they were just required to perform the visual task. The visual distraction task used in this study was designed to mimic the gaze behavior found in non-visual tasks.

2. Method

An actual driving experiment was designed for this study. Normal driving and distracted driving on a real road were investigated. All of the participants finished two driving tasks in the same instrumented vehicle.

Before the experiment, the drivers were asked to estimate the relative distance and speed of other vehicles that appeared in the rearview mirror, requiring the driver's line of sight to be off the road while focusing on the target vehicle in the left side rearview mirror. No additional instructions were given to the participants during the test, and the drivers maintained their personal driving styles. While focusing on the target vehicle, drivers could not maintain the lateral position of the subject vehicle; they had to frequently return their sight to the front. This distraction task took place on a real highway environment, and this would cause drivers to focus on the rear vehicle. Therefore, they could not keep their attention on their own vehicle's lane position.

The rearview mirror task is different from the behavior of observing the rearview mirror that occurs during normal driving. This secondary task is not a normal driving task, and it requires more attention from the driver. This task can cause the driver to observe the target car more attentively than usual, and drivers may need more time to observe the rearview mirror. Therefore, drivers cannot keep driving as usual.

2.1. Apparatus

Fig. 1 shows the apparatus. The test vehicle was a multi-purpose vehicle with a time-synchronized data collection system that logged controller area network (CAN) data. The vehicle was equipped with a lane mark recognition system (Mobileye C2-170). This system detects the distance of the test vehicle from the left and right lane markers. The detection frequency was 10 Hz with an accuracy of 5 cm. The measurement accuracy of the steering wheel angle was 1.25°. Millimeter wave radars were used to measure the relative distance and relative speed between the subject vehicle and the target vehicle. The driver's head motion and eye movement, the front, and rear traffic scenes, and

Fig. 1. Instrumented vehicle.

the traffic environment were real-time monitored using multiple-high-speed cameras.

2.2. Participants

Seventeen experienced Chinese drivers (15 males, 2 females), ages 27–48 (mean = 34.7, SD = 7.7), were recruited to participate in the study. Their corrected visual acuity was normal, and their driving experience ranged from 3 to 23 years (mean = 8.4, SD = 5.2). The participants were physically and mentally healthy, and they had not experienced a severe traffic accident within the past three years. All of the participants were non-professional drivers. They were recruited via an advertisement and paid a small sum of money.

All of the drivers were asked to estimate the rear vehicle speed and relative distance, and no more requirements were asked of them. Therefore, the drivers would believe that the purpose of the experiment was to study their ability to estimate speed and distance. Therefore, to improve their estimation ability, they might focus more on this secondary task. Since the drivers did not know the real aim of the experiment was to study the impact of distracted driving on driving performance, the drivers might not deliberately reduce the effect of distraction on their driving performance. This study design was selected to effectively improve the validity of the experimental results.

Before the experiment, we informed all drivers of the potential risks that could arise during the duration of the experiment. Although we bought insurance for all of the participants, the drivers would have to bear the corresponding legal liabilities in case of a traffic accident. All participants, after understanding the potential risks of the experiment and other details, signed an informed consent form and participated in the experiment. The Chang'an University research committee approved of the experimental protocol in advance.

2.3. Driving route

The driving route was G3001 freeway section from Sanqiao to Xinzhu, China. The route was a two-way six-lane road with a speed limit of 100 km/h. The test road was about 38 km and the driveway width was 3.75 m, which is same to most EU countries (Wegman and slop, 1998), though slightly wider than the American freeway (3.7 m) (Federal Highway Administration, 2016). Vehicles in the inner lane generally move with a faster velocity than vehicles in the middle and curb lane. The test was carried out during nonpeak hours to minimize the traffic congestion problem. All of the tests were conducted in clear weather conditions to avoid negative weather effects on driver performance.

2.4. Rearview mirror task

The experiment investigated the effect of a visual distraction task on a driver's lane-keeping ability. Participants were asked to drive along the test road in the middle lane and estimate the speed and relative distance of a vehicle behind them in the inner lane. Within the entire experiment, a staff member was seated in the back seat of the car to ensure the equipment ran normally and recorded the experimental data. Another staff member with more than 20 years of driving experience was seated in the front passenger seat to maintain driving safety. Before the start of the experiment, the driver had a preparation phase that consisted of practice driving on a test road. The participants informed the staff when they were used to the experimental vehicle and road, and then the experiment began.

After the preparation phase, the staff would not give any information to the drivers except any potential risks and equipment problem. According to the rear traffic scene monitor, staff can find rear vehicles in advance and remind the driver of any rear vehicles. When a vehicle appeared in the rearview mirror, if driver found the situation to be safe, the driver would make a judgment of the relative distance and speed of the target vehicle and informed the staff of an estimated value. The schematic diagram of the Rearview Mirror Test is shown in Fig. 2.

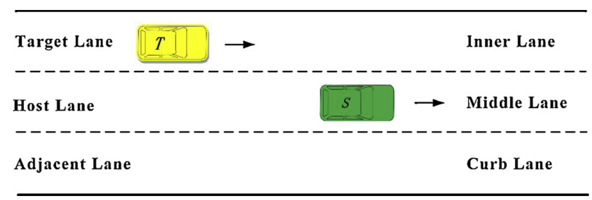

Fig. 2. Rearview Mirror Test. T = Target vehicle, S = Subject vehicle.

2.5. Experimental design and procedure

The driver was asked to observe the rear vehicle in the inner lane using the left side rearview mirror. Then, the driver was required to estimate the speed of the rear vehicle and the distance quickly and repeatedly while the rear vehicle was approaching the subject vehicle. The driver then immediately orally reported the information to the experimental staff. The rearview mirror tasks were carried out in cruise control mode at subject vehicle speeds of 60, 70, 80, and 90 km/h. The target vehicles were free driving on the freeway, and the speed and the relative distance between the subject vehicle and target vehicle were constantly changing.

The experiment was divided into two phases. For the first phase, subjects drove from Sanqiao to the Xinzhu. After a 30-minute break in Xinzhu, the second stage would be carried out, where subjects needed to drive from Xinzhu to Sanqiao. Each stage would take about 40 min.

The surrounding vehicle could have an impact on subject vehicle safety. In order to ensure safety, the staff would arrange the driving speed according to the driving environment. If there were any potential risks, the staff will choose a lower speed or stop the rearview mirror task. On the same safe driving environment condition, the staff would randomly arrange the driving speed.

2.6. Human subjects' protection

A staff with more than 20 years of driving experience would focus on the driving environment during the experiment. If there were any potential risks, the staff would remind the driver. The test vehicle was equipped with millimeter-wave radar, under the cruise control mode, the vehicle will automatically quit the cruise mode and slow down when the subject vehicle was too close to the front vehicle. Furthermore, we bought insurance for all drivers.

2.7. Data selection

Surveillance video of the traffic scenarios and driving behavior were played back, and the driver's motions were used to determine the time used during the distraction process. The beginning time was defined to be the moment that the driver's sight turned from the front to the rearview mirror, and the ending time was defined to be the moment that the driver's sight turned from the rearview mirror to the front.

An example distraction process is shown in Fig. 3a-e. The driver's sight and head position prior to the task are shown in Fig. 3(a). The moment his sight is transferred to the left side rearview mirror is shown in Fig. 3(b). The driver's sight stayed on the left side rearview mirror, as shown in Fig. 3(c). The end moment when the driver's sight began to move back to the front is shown in Fig. 3(d). After this end moment, the moment the driver's sight completely returned to the front is shown in Fig. 3(e). The frequency of the video was 24 frames/s. From Fig. 3(b)–(d), the entire distraction duration was 2 s and 3 frames, namely 2.125 s. The distraction duration is eyes off forward roadway duration.

Fig. 3. Drivers' distraction segments.

2.8. Data analysis

We evaluated several driving performance metrics during naturalistic distracted driving and normal driving at 60, 70, 80, and 90 km/h. Ostlund et al. (2005) demonstrated that the SDLP increased with driving duration. In order to examine the effects of the task itself on driving performance metrics, we investigated the relationship between driving performance metrics and distraction duration at each speed. We statistically found that all metrics increased linearly with task duration at the different levels of speed. Due to the linearity, mean trajectory offset per second, mean SDLP per second, mean steering wheel acceleration per second, mean standard deviation of steering wheel angle per second, and mean steering wheel reversal rates per minute were used for both normal and naturalistic distracted driving, which can eliminate the influence of task duration,

Linear regression was used to analyze the differential effects of speed between distracted driving and normal driving (Gujarati, 1970) when the speed has a statistically significant effect on driving metrics. To eliminate the influence of different units between speed and metrics, the standardized coefficient was used.

We conducted Repeated Measures ANOVAs on each metrics. When the Mauchly's sphericity assumption was violated (Mauchly, 1940), Huynh-Feldt correction was used (Huynh and Feldt, 1980).

3. Results

1200 distracted driving segments were recorded. A statistical analysis of the distracted driving segments was conducted, and the minimum distraction duration was 0.18 s, the maximum duration was 8.27 s, and the mean was 2.11 s, with a standard deviation of 1.05 s. This result was longer than normal gaze behavior (0.451 ms) (Shahar et al., 2012). There were 205 segments that had a range of 0–1 s distraction duration, 478 segments that had a range of 1–2 s, 301 segments that had a range of 2–3 s, 151 segments that had a range of 3–4 s, and 65 segments longer than 4 s. The distraction duration distribution is shown in Fig. 4. The total number of the segments was 300 for the 60 km/h subject vehicle speed, 300 for 70 km/h, 300 for 80 km/h, and 300 for 90 km/h speed.

In order to examine the effect of distracted driving, 1200 normal driving segments were collected. To eliminate the influence of task duration, a fixed 2 s time window was selected.

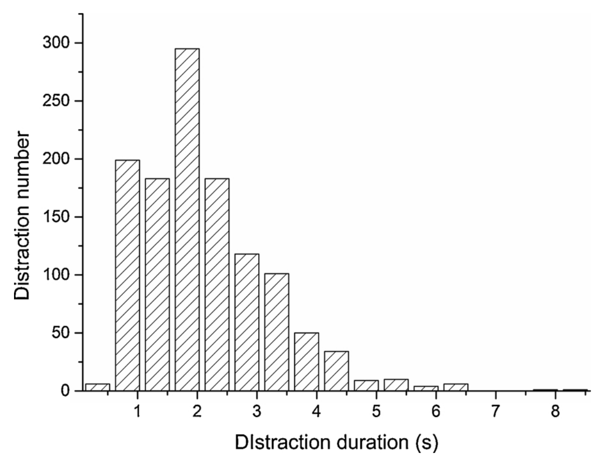

Fig. 4. Distraction duration distribution.

3.1. Distraction duration

The distracted driving duration data were analyzed using correlation analysis and one-way analysis of variance (ANOVA) with four speed levels (60, 70, 80, and 90 km/h). Mean distraction duration and the standard error of the means are shown in Fig. 5.

The results revealed the distraction duration was significantly

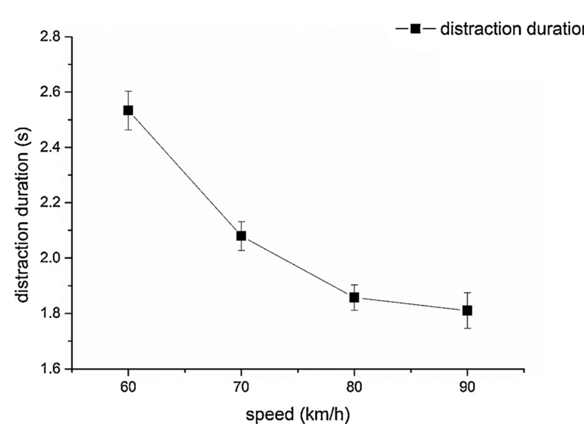

Fig. 5. The main effect of speed on distraction duration.

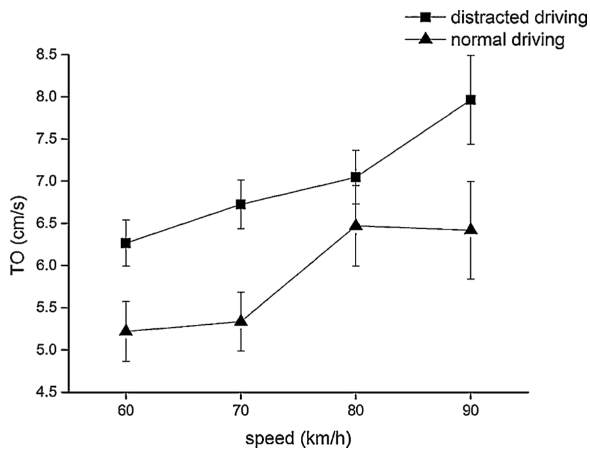

Fig. 6. The interaction between Task and Speed in TO.

negatively correlated with driving speed (r = -0.253, n = 1200, p < 0.001), and the ANOVA result showed a significant effect of driving speed on the mean distraction duration, F(3, 1197) = 25.060, p < 0.001. Post Hoc Comparisons indicated that distraction duration was shorter under the 70 km/h condition compared to 60 km/h (p < 0.001) and shorter at 80 km/h compared to 70 km/h (p < 0.009). However, no statistically significant difference was found in the mean distraction duration between 80 km/h and 90 km/h (p = 0.992).

3.2. Trajectory offset (TO)

Trajectory offset is the change of the lateral position of the vehicle at the start of the task and at the end of the task. Based on SAE J2944standards (2015), the lateral lane position was calculated with respect to the lane center, and vehicle position was measured relative to the center of the vehicle front axle. To eliminate the influence of distraction duration during the test, a trajectory offset per second was used.

A 2 (Task) × 4 (Speed) Repeated Measures ANOVA was conducted on the TO, as shown in Fig. 6. Mauchly's assumption of sphericity was violated for the interaction between task and speed (p = 0.01). Therefore, a Huynh-Feldt correction was made. This analysis showed a significant main effect of distracted task (F(1,299) = 16.565, p < 0.001) and a significant main effect of speed (F(3,897) = 3.147, p = 0.028). The interaction between speed and task did not reach significance (F(3,897) = 0.067, p = 0.971). The TO changed significantly with speed and displayed a linear curve (F(1,299) = 7.990, p = 0.005). The main effect of the task was driven by higher TO in the visual distraction (mean = 6.953, SEM = 0.241) was compared to normal driving (mean = 5.554, SEM = 0.255).

Linear regression was used to analyze the differential effect of speed on the TO in the distracted driving and normal driving scenarios. The result revealed that there was no significant difference between the coefficient of the speed during distracted driving and normal driving, the standardized coefficient of the speed during distracted driving was 0.092, which was slightly higher than that during normal driving (0.086).

3.3. SDLP

According to the SAE J2944standards (2015), SDLP was calculated with respect to the center of the lane, and unbiased estimator was used. The vehicle position was measured relative to the center of the vehicle front axle.

A correlation test was carried out on the distraction duration, speed, and SDLP for all of the distracted driving segments. The distraction duration and SDLP were correlated at a statistically significant r of 0.454 (n = 1200, p < 0.001). The speed and SDLP were at a statistically significant r of −0.067 (n = 1200, p = 0.023).

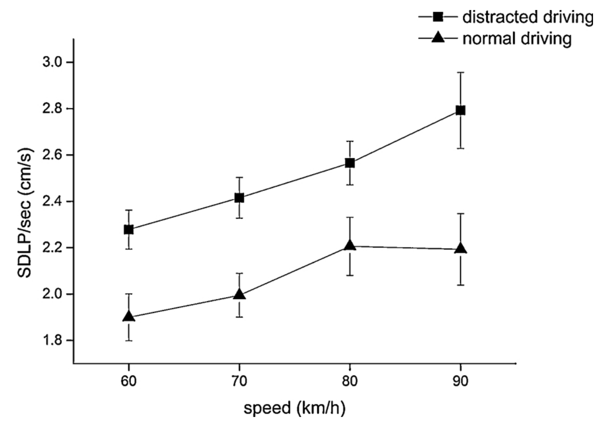

Fig. 7. The interaction between Task and Speed in SDLP.

In contrast, the SDLP varied by speed group and task, but not by distraction duration, the SDLP per second was used. As shown in Fig. 7, a 2 (Task) × 4 (Speed) Repeated Measures ANOVA was conducted on the SDLP. Mauchly's sphericity assumption was violated for the speed (p = 0.005) and the interaction between task and speed (p = 0.001). Therefore, a Huynh-Feldt correction was used. This analysis revealed a significant main effect of distracted task (F(1,299) = 21.835, p < 0.001) and a significant main effect of speed (F(3,897) = 2.801, p = 0.039). The interaction between speed and task did not reach significance (F(3,897) = 0.207, p = 0.892). The SDLP changed significantly with speed and displayed a linear curve (F(1,299) = 7.129, p = 0.008). The main effect of the task was driven by higher SRRs in visual distraction (mean = 2.449, SEM = 0.070) as compared to normal driving (mean = 1.997, SEM = 0.067).

Linear regression was used to analyze the different effects of speed on the SDLP for distracted driving and normal driving across all of the segments. The result revealed that there was no significant difference between the coefficient of the speed during distracted driving and normal driving, the standardized coefficient for speed during distracted was 0.098, which was higher than that during normal driving (0.074).

3.4. Steering wheel acceleration (SWA)

Steering wheel acceleration means the angular acceleration of the steering wheel, which can show steering smoothness and instability (Cloete and Wallis, 2011).

As shown in Fig. 8, a 2 (Task) × 4 (Speed) Repeated Measures ANOVA was conducted on SWA. This analysis showed no significant

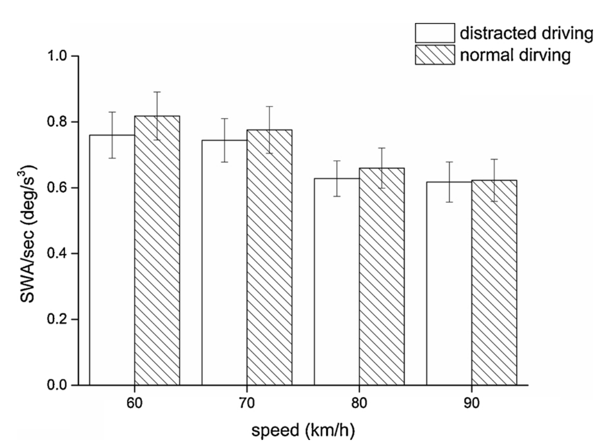

Fig. 8. The interaction between Task and Speed in SWA.

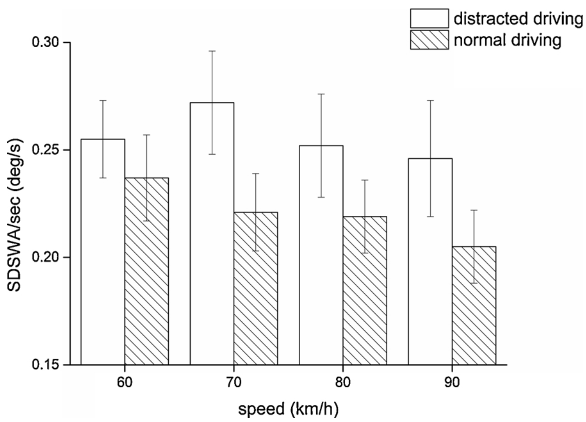

Fig. 9. The interaction between Task and Speed in SDSWA.

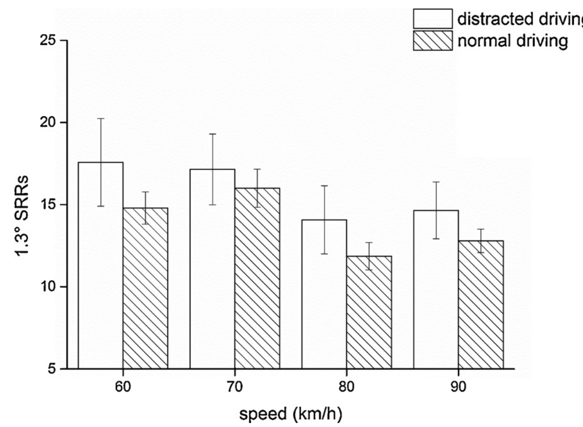

Fig. 10. The interaction between Task and Speed in 1.3 °SRRs.

main effect of distraction task ($F(1,299) = 0.619$, $p = 0.432$), a significant main effect of speed ($F(3,897) = 2.745$, $p = 0.042$), and no interaction between speed and Task did not reach significance ($F(3,897) = 0.068$, $p = 0.977$). The SWA changes with speed significantly obey the linear curve ($F(1,299) = 6.913$, $p = 0.009$). The main effect of task was driven by higher SWA during visual distraction (mean = 0.719, SEM = 0.035) compared to normal driving (mean = 0.687, SEM = 0.031).

Linear regression was used SWA to analyze the different effect of speed on SWA while the distracted driving and normal driving across all the segments. The result revealed that there was no significant difference between the coefficient of the speed during distracted driving and normal driving, the standardized coefficient for speed during distracted was -0.081 which was slightly higher than that during normal driving (-0.091).

3.5. *Standard deviation of steering wheel angle (SDSWA)*

Steering wheel angle means the angular position of a steering wheel (SAE J2944, 2015).

As shown in Fig. 9, a 2 (Task) × 4 (Speed) Repeated Measures ANOVA was conducted on SDSWA, Mauchly's sphericity assumption was violated for the interaction between task and speed ($p = 0.001$), so a Huynh-Feldt correction was used. This analysis revealed a significant main effect of distracted task ($F(1,299) = 5.470$, $p = 0.020$), and no significant main effect of speed ($F(3,897) = 0.452$, $p = 0.716$). The interaction between speed and task did not reach significance ($F(3,897) = 0.246$, $p = 0.864$). The main effect of task is seen in the higher SDSWA in visual distraction (mean = 0.256, SEM = 0.013) as compared to normal driving (mean = 0.220, SEM = 0.009).

3.6. *Steering reversal rates (SRRs)*

Steering wheel Reversal Rates means the number of steering reversals per minute, steering reversal was measured by using two minimum amplitude thresholds (1.3° and 2.5°) to identify (SAE J2944, 2015). Due to the duration of each segment was short, all the segment at each speed under each task was divided into 14 groups, each group has the same duration.

3.6.1. *Reversal rates greater or equal to 1.3°*

A 2 (Task) × 4 (Speed) Repeated Measures ANOVA was conducted on 1.3 °SRRs. This analysis showed a significant main effect of speed ($F(3,39) = 3.826$, $p = 0.017$), but no significant main effect of Task ($F(1,13) = 1.077$, $p = 0.318$). The interaction between speed and task did not reach significance ($F(3,39) = 0.169$, $p = 0.916$). The SRRs changed significantly with speed and displayed a linear curve ($F(1,13) = 18.600$, $p = 0.001$).

The main effect of the task is seen in the higher SRRs during visual distraction (mean = 15.857, SEM = 1.703) as compared to normal driving (mean = 13.857, SEM = 0.660). The main effects of speed and task are shown in Fig. 10.

A linear regression analyzed the differential effect of speed on the SRRs during distracted driving and normal driving across all the groups. The result revealed that there was no significant difference between the coefficient of the speed during distracted driving and normal driving, the standardized coefficient for speed during distracted was -0.166, which was lower than that during normal driving (-0.303).

3.6.2. *Reversal rates greater or equal to 2.5°*

A 2 (Task) × 4 (Speed) Repeated Measures ANOVA was conducted on the 2.5 °SRRs. This analysis showed a statistically significant main effect of speed ($F(3,39) = 5.399$, $p = 0.003$), and a statistically significant main effect of Task ($F(1,13) = 5.047$, $p = 0.043$). The interaction between speed and task did not reach statistical significance ($F(3,39) = 0.066$, $p = 0.978$). The SRRs significantly changed with speed and displayed a linear curve ($F(1,13) = 18.600$, $p = 0.001$).

The main effect of the task is seen in the higher by SRRs during visual distraction (mean = 3.607, SEM = 0.472) as compared to normal driving (mean = 2.321, SEM = 0.225). The main effect of speed and task are shown in Fig. 11.

Linear regression was used to analyze the differential effect of speed on the SRRs during distracted driving and normal driving across all of the groups. The result revealed that there was no significant difference between the coefficient of the speed during distracted driving and normal driving, the standardized coefficient for speed during distracted driving was -0.281, which was lower than that during normal driving (−0.365).

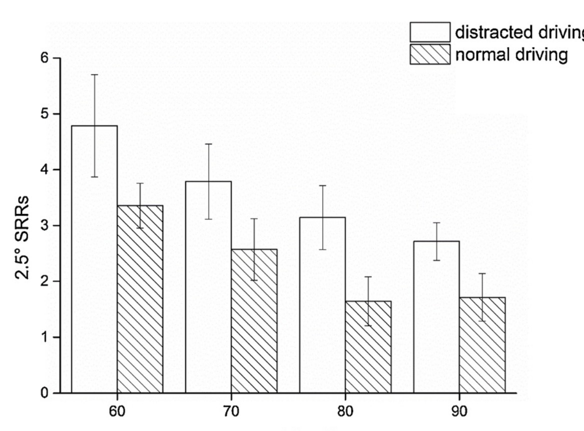

Fig. 11. The interaction between Task and Speed in 2.5 °SRRs.

Table 1
Results of analyses for several metrics of driving performance.

Independent variable	Distraction duration	TO	SDLP	SWA	SDSWA	SRRs (1.3°)	SRRs (2.5°)
Speed	–	+	+	–	NS	–	–
Distraction task	/	*	*	NS	*	NS	*

– Significant at 0.05 and negative correlation.
+ Significant at 0.05 and positive correlation.
*Significant at 0.05.
NS Not significant at 0.05.
/Not test.

3.7. Result summary

The results of these analyses are summarized in Table 1. It can be concluded that distraction duration, SWA, and SRRs (at both levels) will decrease with increasing speed. On the contrary, TO and SDLP will increase. Distraction task has a significant effect on TO, SDLO, SDSWA, and SRRs (2.5°).

4. Discussion

The aim of this research was to investigate the relationship between high speed and a driver's lateral driving performance during naturalistic visually distracted driving and normal driving on a real road.

The research was conducted using 17 Chinese drivers during normal highway driving conditions (low traffic and simple road geometry). All of the tests were carried on a straight road. The lateral driving performance metrics examined for the purposes of this study were: SDLP, TO, SWA, SDSWA, and SRRs (investigated at 1.3° and 2.5°). In order to control for the driving duration, mean SDLP per second, mean TO per second, mean SWA per second, mean SDSWA per second and mean SRRs per minute were used as metrics. The main independent variables were the different driving speeds: 60, 70, 80, and 90 km/h. The two driving conditions were a visual distraction task and normal driving. In addition, the effect of driving speed on distracted driving duration was investigated. The main effects of driving conditions and speed and the interaction effects between the variables were analyzed using design Repeated Measures ANOVA tests, Mauchly's sphericity assumption, a Huynh-Feldt correction, and Bonferroni's post hoc tests at a 0.05 significance level.

In line with previous studies (Thapa et al., 2015; Salvucci and Macuga, 2002), during visually distracted driving, the TO and SDLP were higher than those during normal driving. In the rearview mirror task, the participant's gaze concentration was directed towards the rear vehicle in the driver's left outside mirror, which is similar to the gaze behavior observed during visually distracted driving. Furthermore, drivers had higher levels of the SDSWA and SRRs at the 2.5° level as compared to normal driving. These parameters can be used to indicate lateral driving performance. Therefore, driving comfort and the ability to stay in a lane were impaired during visually distracted driving. However, the present study results suggested some parameters, such as the SWA and SRRs at the 1.3° level, did not have a statistically significant difference from visually distracted driving. In comparison, previous researchers (Kountouriotis et al., 2016) have suggested that only 10 °SRR levels can be used to detect distracted driving. This study confirmed that different gap levels show different types of distraction.

The results of this study showed a statistically significant effect from high speeds (at four levels) on the TO, SDLP, SRRs (at both the 1.3° and 2.5° levels), and the SWA. This result is consistent with a previous study result conducted by Knapper et al. (2015) that examined the main effects of driving speed and cognitive distraction tasks on longitudinal driving performance, such as the mean speed and standard deviation of speed, on a real road. This study investigated the effect of visually distracted driving. In addition, the effect of different speeds on visually distracted driving and normal driving were also investigated. The study results showed that in both in the visual distraction task and with no visual task, the higher speed contributed to a higher TO and SDLP and lower SRRs and SWA. This means that as the speed of the car increases, the reduction of the SRRs and SWA can still cause a higher TO and SDLP, which is inconsistent with previous studies that pointed out that decreases in steering metrics are directly attributed to the lowered SDLP and TO (Cooper et al., 2013; Medeiros-Ward et al., 2014). There are three reasons that may explain this difference. First, in these previous studies, they neglected the effect of driving duration on SDLP. However, in this experiment, we controlled for that by using the rates of SDLP and TO. Second, the previous studies did not consider the influence of driving speed on the driving performance during distracted driving. Due to the characteristics of lane departure on real roads, this characteristic would be aggravated by high speed driving. This may explain why, although the steering metrics were reduced, the SDLP and TO were higher. Alternately, the lateral speed and acceleration of a vehicle are more sensitive to steering metrics with an increase in driving speed wheel operation. This means that when the vehicle speed increases, frequent steering operations would reduce the safety of the vehicle and the comfort of the passenger. In actual driving, when the driver increases driving speed, to ensure driving performance, they may reduce steering behavior. Similarly, the same phenomenon might occur in distracted driving, which would mean that drivers have the ability to perceive speed and stability during visually distracted driving. According to these findings, in the professional driver program, the driver needs to be informed that the frequency and duration of observations of the surrounding environment (billboard, surrounding scenery, etc.) should be reduced during the high-speed driving, which could decrease the distraction duration, and improve the driving stability and comfort.

An interesting finding of this study was a similar effect from speed on driving stability and comfort during distracted driving as compared to normal driving. The standardized coefficient of speed to SDLP, TO, SWA and SRRs (at both levels) during distracted driving was the same as the standardized coefficient of speed during normal driving. This may mean that driving stability and comfort are impaired during both distracted driving and normal driving at high speeds.

Furthermore, the results indicated that the distraction duration decreased as speed increased, that is, drivers reduced the mean duration that their eyes were off the forward roadway at higher speeds. In a given driving domain, such as urban or highway driving with a fixed speed limit, the crash risk increases as speed increases (Aarts and Van Schagen, 2006). To reduce the risk, it is plausible that the driver will return the line of sight to the front roadway more frequently and reduce the duration to perform the distraction task. It infers that drivers increased their self-regulation at higher speeds. This result is similar to a previous study result conducted by Young (2014) that drivers self-regulate their driving behavior to keep safe driving while performing secondary tasks.

Declarations of interest

None.

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