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ORIGINAL ARTICLE

# Effect of Speed on Driver's Visual Attention: A Study Using a Driving Simulator

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**Abstract**
Road crashes are among the main causes of death worldwide, and driver's attention during driving is the major source of such crashes. Moreover, the likelihood of a car crash increases proportionally to increases in speed. This study investigates the influence of vehicle's speed on the characteristics of a driver's attention during the driving task. It was conducted in a driving simulator in a section of an existing highway of a high crash index. The driver's eyes movements were recorded in the virtual scenario at three different speeds, and the following three movement measures were collected: time of fixation ($F$) (in seconds), number of fixations ($N$), and mean fixation ($F_m$). The mixed design experiment was performed with 12 participants, and the results showed a significant difference in both time of fixation and number of fixations between 70 and 90 km/h, and 70 km/h and 110 km/h. The study enabled the assessment of the relationship between speed and drivers' attention, since speed has a correlation with the severity of crashes. Drivers driving at lower speeds tend to assess their surroundings more attentively.

**Keywords** Driving simulator · Vehicle speed · Eye movement · Fixation duration · Driver's attention

## Introduction

The number of road traffic deaths has steadily risen, and reached 1.35 million in 2016 [1]; however, their rate in relation to the size of the world's population has remained constant. In such increasing global population and simultaneous rapid motorization, this finding suggests road safety efforts may have prevented the situation from worsening.

Driving speed is an important factor in road safety [2], since it not only affects the severity of a crash, but is related to the risk of its occurrence. Considering the dangers of speeding, it is contradictory that drivers do not reduce speed when they see advisory speed plates on a certain stretch of highway. Therefore, speed has drawn research attention in the relationship between crashes and driver's behaviour [3–7].

Several studies have demonstrated the effectiveness of driving simulators as tools in investigations on speed, and driver's eye movement analysis has received increasing attention in traffic safety research. [8–16].

During driving, the driver's fixation point changes with different speeds, and such alterations are mainly perceived from the position, duration, and change of the fixation point. A driver's eye movement can also describe their level of attention while driving. In recent years, research has focused on the driver's fixation point characteristics and eye movement, which have gradually been introduced into the field of transportation.

However, most studies generally address suitability evaluations of road alignment [17–19], traffic control devices and advertising signs [14, 15, 20], assessments of drivers' mental workload [21–26], their visual strategy [27–31], methods for the detection of drivers' fatigue [32, 33], and design of traffic safety facilities [34, 35].

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Studies related to speed aim at the development of predictive models (Yu et al. [36]), or at a specific situation, such as driver's behaviour through tunnels during day and night conditions [37], effect of the tunnel lighting environment on the driving safety [38], assessment of the transition from high- to low-speed areas [18], and validation and prediction models [14, 36].

Analyses of driver's visual behaviour tend to involve small samples, since they are time-consuming experiments and expose participants to some discomfort (e.g. nausea).

Lantieri et al. [18] assessed the gateway components most frequently viewed, and the way gateway design might reduce distraction behaviour (gaze directed at nonrelevant driving targets). The authors recruited fifteen drivers (ten males and five females) from students of the Engineering School of the University of Bologna. Biswas and Prabhakar [39] explored the use of a type of eye gaze movement to detect the cognitive load and instantaneous drivers' perception of road hazards. Data were collected from ten participants.

Xu et al. [33] evaluated driver's fatigue by tracking eye movement behaviours in ten healthy subjects, who performed continuous simulated driving for 1–2 h. Fixation time and the pupil area were recorded by an eye tracking system. Finally, Ehinger et al. [40] applied a data quality test of eye-tracker to 15 recruited participants (nine females and six males) and compared the EyeLink 1000 eye tracker as the reference with the mobile Pupil Labs glasses.

Most research on driver's eye movements has focused on their characteristics and the relationship between visual search mode and driver emotions. However, few studies have investigated the change points of eye movement characteristics related to distraction [25, 41] and speed [18, 37].

This study addresses the use of a driving simulator for analyses of the relationship between driver's attention to the driving task and driving speed, on a simulated 10-km road as a scenario based on a real highway. The driving simulator presented the scenario to the participants, and the speed was controlled to assess its influence on driver attention. Eye movements were recorded during the experiment through an eye tracking system, which determined time of fixation ($F$) (in seconds), number of fixations ($N$), mean fixation ($F_m$), and fixations in regions of interest (ROIs).

## Methods

### Participants

12 participants were voluntarily recruited from a university in São Carlos (Brazil) and divided into two groups. The first group consisted of 6 men of 20.3 years (SD = 0.8) mean age, whereas the second consisted of 6 women of 19.8 years (SD = 1.5) mean age. Their driving experience was measured by the time during which they had driven on roads (1.1 year, SD = 0.7) and mean time of their driver's license (1.5 years, SD = 0.8). The participation criterion was to have driver's license.

### Apparatus

The study involved a driving simulator and eye tracking system of the São Carlos School of Engineering (EESC) at the University of São Paulo.

#### Driving Simulator

The experiment was performed in a fixed-based driving simulator specifically designed for research on road safety (Fig. 1). The simulator consisted of a cockpit with a car seat, a Logitech G27 steering wheel that provided the steering force feedback, a throttle, an interlocked brake, and clutch pedals similar to the setup of a real car. The sound was provided by two sound boxes that transmitted the main vehicle's mechanical system sounds and the surrounding sounds from prerecorded sounds.

The projection system was comprised of a DepthQ projector of 1080p resolution and 60 Hz refresh rate, and a projection screen positioned in front of the driver, which

**(a)** Scenario with signalization **(b)** Scenario with traffic

**Fig. 1** EESC driving simulator

provided a field of view of 120-degree horizontal freedom and 50-degree vertical freedom. The simulator showed a dynamic image of the driving scene according to the drivers' input. The rear view and left and right mirrors were integrated into the projected image.

ROD Scenario Editor® software designed the 3D-dimensional virtual highway in Brazil, and the scenario of the experiment was exhibited at 60 frames per second and integrated into the system by VI-Grade Virtual Test Drive® and VI-CarRealTime®. During the experiment, the data were recorded at a 60 Hz sampling rate.

### Eye Tracking System

The study employed the Smart Eye system, which consists of three infrared cameras that record the driver's face and one camera that stores the driver's view. Since the positions of the infrared cameras were previously known, both head position and eye movement were estimated.

The system was calibrated for accurately and precisely determining the reflection of the cornea. The data were recorded at a 60 Hz rate; the system processed the images received in real time and indicated the point that held the driver's attention by detecting the position of their pupils. Regions of interest (ROIs) were delimited during the recording of the experimental data for further processing and determination of fixation times. Differently from methods that include electrodes and contact lenses with inductive sensors, this eye tracking technique is non-invasive.

Figure 2 illustrates the eye tracking system and position of four cameras in the driving simulator, and Fig. 3

**(a)** Eye tracking system

**(b)** Front cameras of the eye tracking system

**(c)** Infrared Camera

**Fig. 2** Eye tracking system and details of infrared cameras

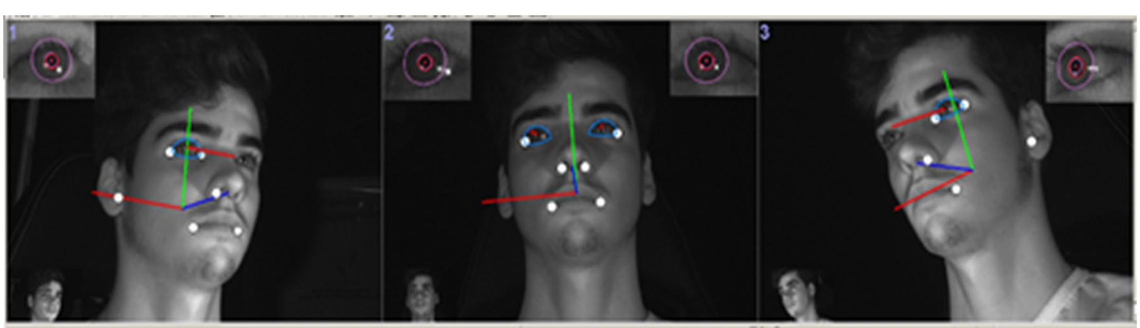


**Fig. 3** Data recording of eye movements during experiment

shows the eye tracking system recording a participant in the experiment.

## Experimental Design

The rural road simulated was a 10-km stretch from a Brazilian highway that connects São Paulo and Curitiba and is the major connection among Brazil and other South American countries. The stretch is located in a mountainous region, and its geometric design is winding, with a curve radius lower than the minimum value set by the Brazilian standards of geometric design [22]. The experimental route consisted of 20 curves, some of radii smaller than 150 m, with three lanes and 10.5 m section width.

A mixed design was implemented. The within factor was speed, with *70* km/h, 90 km/h and 110 km/h levels, and its combination produced six (3!) treatments previously randomized towards minimizing the effects of route familiarity. Twelve participants were divided into two groups, composed of six men and six women each, and submitted to six sequences (Table 1).

The right, left and rear view mirrors, as well as the speedometer represented regions of interest (ROIs) generated according to previous studies [42, 43]—Fig. 4 shows the regions assessed. The dependent variables were time of fixation ($F$) in seconds in the ROIs, number of fixations ($N$), and mean fixation ($F_m$) measured in seconds per fixation. They were defined for assessments of the allocation of the participants' attention to the ROIs.

## Experimental Procedure

In the preparation stage, each participant answered a questionnaire on drivers' characterization and were instructed on the controls of the simulator, namely steering wheel, accelerator, automatic gear, and brake. Next, they underwent a 10-min session in a training scenario [44, 45] to be familiarized with the operation methods of the simulator and the response of the pedals and steering wheel, and also to test their possible experiencing symptoms of motion sickness, including eye strain, nausea, headache, and dizziness.

**Table 1** Randomized order of speeds

| Sequence | 1st speed [km/h] | 2nd speed [km/h] | 3rd speed [km/h] |
|---|---|---|---|
| 1st | 70 | 90 | 110 |
| 2nd | 90 | 70 | 110 |
| 3rd | 70 | 110 | 90 |
| 4th | 90 | 110 | 70 |
| 5th | 110 | 70 | 90 |
| 6th | 110 | 90 | 70 |


**Fig. 4** Regions of interest (ROIs)

SmartEye® was calibrated to capture the traces of the participant's gaze during the experiment. The participants were instructed to drive in the middle lane and the way they would drive in a real situation. At the beginning of each of the three courses, they were asked on any feeling of discomfort; in case of a negative answer, they were informed on the speed to be maintained (see Fig. 5). All sessions were conducted in the same scenario.

After the data collection stage, the participants answered an adapted simulation assessment questionnaire developed by Witmer and Singer [46] on their experience in the simulator. Each participant drove for less than 25 min. The experimental procedure lasted approximately 60 min. Figure 5 displays the stages of the experimental procedure.

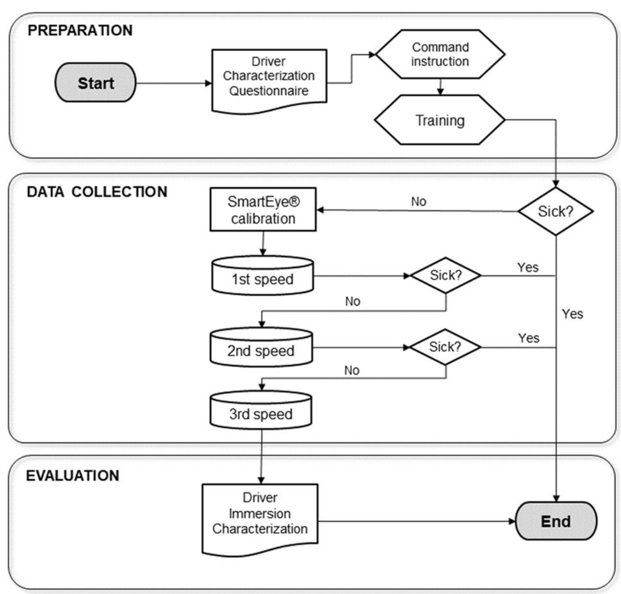



**Fig. 5** Flowchart of the experimental procedure

## Data Analysis

The participants provided personal information, such as age, sex, education, records of past involvement in some type of crash, number of years holding a driver's license, and total mileage driven per month. Eye tracking data were recorded for each participant. Eye blinks and other missing data were removed from such data.

The dependent variables were time of fixation ($F$), defined by the sum of all time intervals of fixation on the speedometer during each course and expressed in seconds, number of fixations ($N$), which is the total number of fixations in the speedometer region, and mean fixation ($F_m$), determined dividing time of fixation by number of fixations. The independent variables were Speed and Gender.

Two types of statistical analyses, namely parametric and nonparametric, were performed. One-way repeated measures ANOVAs investigated possible significant differences in the drivers' attention in the scenario at the three different speeds, and Bonferroni's post hoc test identified the differences among the three speeds. Friedman test, ANOVA nonparametric version, and Mann–Whitney test were also applied due to the small sample size of the experiment. The results from both parametric and nonparametric tests were compared. All analyses were carried out with Statistical Package for the Social Sciences (SPSS).

## Results

The results were divided into five sections. The first reports on an exploratory analysis of the dependent variables; the second and third are related to parametrical and non-parametrical analyses, respectively; the fourth is devoted to a brief comparison of the above-mentioned analyses; finally, the fifth section addresses the validation of the experiment.

### Exploratory Analysis

The data on subjects'eye movements acquired during the driving processes at different speeds (70 km/h, 90 km/h and 110 km/h) were analyzed. The mean duration of the course at 70 km/h was 8′53″, with 67.61 km/h mean speed; at 90 km/h, it was 7′12″, with 83.39 km/h mean speed, and at 110 km/h, it was 6′26″, with 93.52 km/h mean speed. The mean speed of the courses was lower than the requested speed, due to the winding stretch.

Normality was checked by Shapiro–Wilk test, which showed most dependent variables, except time of fixation ($F$) and number of fixations ($N$) at 110 km/h followed a normal distribution ($p > 0.05$).

ROIs analysis assessed driver's fixation. Table 2 shows the means and standard deviations of time of fixations in the ROIs, of which the speedometer was the one of longer driver's time of fixation; all mirrors were gazed for less time.

Table 3 shows a summary of the dependent variables by gender and speed. Their means were higher for male drivers than for female drivers, and the highest values of time of fixations ($F$) and number of fixations ($N$) were obtained at 70 km/h.

Regarding gender, the boxplots show the time of fixations ($F$) was generally higher for men than for women (Fig. 6a)—the same tendency was observed for number of fixation ($N$) (Fig. 6b). Mean fixation ($F_m$) provided similar values for men and women (Fig. 6c), therefore, the graphical analysis of the dependent variables suggests men gazed on the speedometer over a higher time interval and more frequently than women. However, the mean fixation, i.e., the mean time

**Table 2** Means and standard deviations of time of fixation ($F$) (in seconds) in ROIs (standard deviations in brackets)

| | 70 km/h | | 90 km/h | | 110 km/h | |
|---|---|---|---|---|---|---|
| ROIs | Male | Female | Male | Female | Male | Female |
| Right mirror | 1.0 (0.7) | 0.2 (0.2) | 1.0 (2.0) | 0.0 (0.0) | 0.0 (0.0) | 0.1 (0.2) |
| Left mirror | 0.1 (0.2) | 0.1 (0.2) | 0.1 (0.2) | 0.0 (0.0) | 0.1 (0.2) | 0.1 (0.2) |
| Rear view mirror | 0.7 (0.9) | 0.2 (0.4) | 1.1 (2.0) | 0.0 (0.0) | 0.2 (0.4) | 0.0 (0.0) |
| Speedometer | 36.7 (18.8) | 18.6 (11.5) | 17.9 (8.5) | 10.8 (8.3) | 14.5 (11.6) | 2.6 (1.2) |

**Table 3** Means of dependent variables by gender

| | 70 km/h | | 90 km/h | | 110 km/h | |
|---|---|---|---|---|---|---|
| | Male | Female | Male | Female | Male | Female |
| Time of fixations ($F$) | 38.5 | 19.1 | 20.1 | 10.8 | 14.8 | 2.8 |
| Number of fixations ($N$) | 63 | 35 | 32 | 19 | 25 | 5 |
| Mean fixation ($F_m$)[a] | 0.61 | 0.55 | 0.63 | 0.56 | 0.59 | 0.53 |

[a] $F_m = \left(\frac{F}{N}\right)$

(a)

(b)

(c)

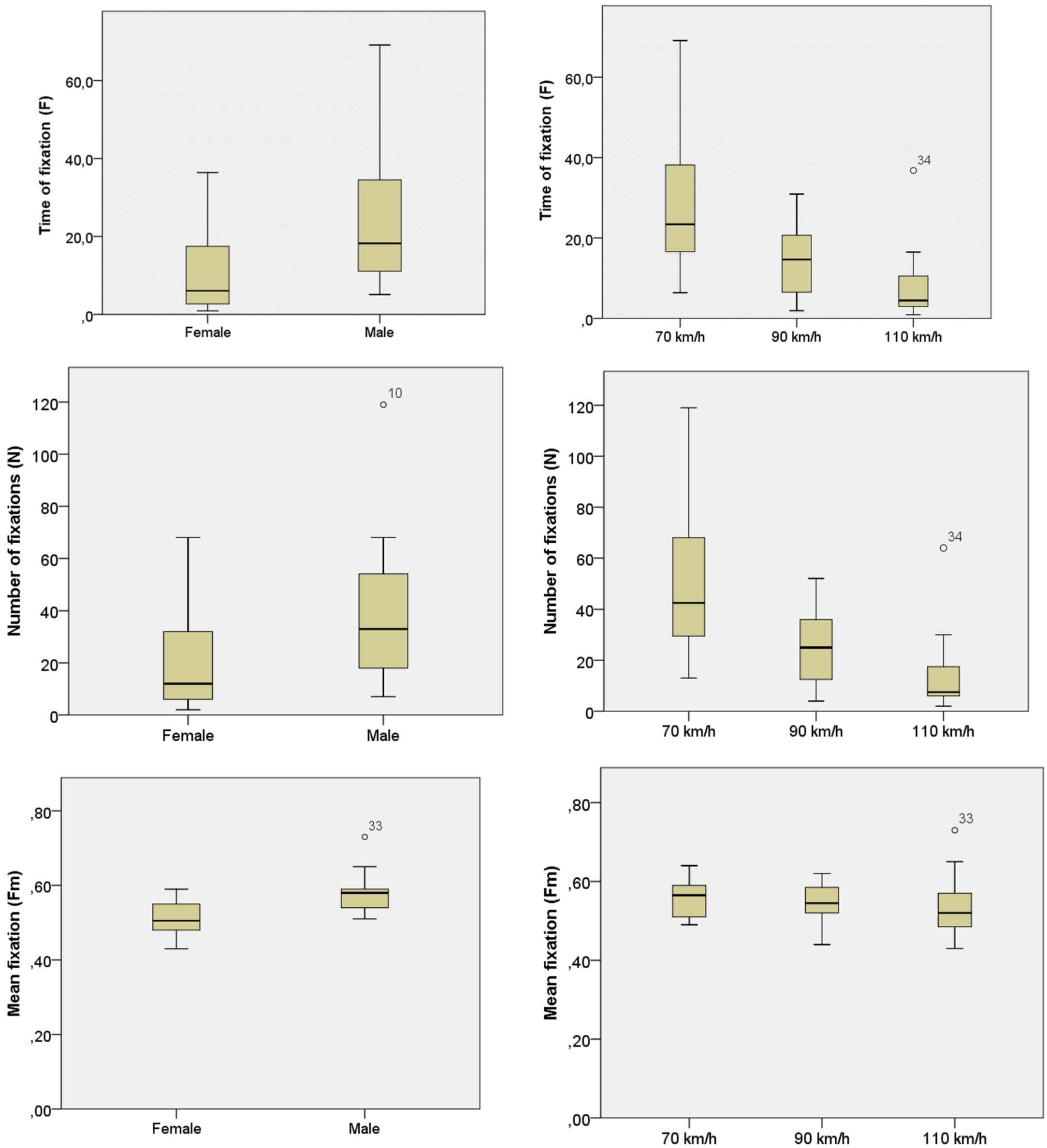



**Fig. 6** Boxplots of **a** time of fixations ($F$) for gender and speed, **b** number of fixation ($N$) for gender and speed, and **c** mean fixation ($F_m$) for gender and speed

of duration of each fixation, was similar between men and women, and approximately 550 ms at the three speeds. Outliers were found in the time of fixation at 110 km/h, in the number of fixation at 70 km/h and 110 km/h, and in the mean fixation at 70 km/h and 110 km/h.

Speed-related boxplots showed an inversely proportional relationship between time of fixation ($F$) and speed developed (Fig. 6a), also observed with number of fixations ($N$) (Fig. 6b). In other words, since such two dependent variables are indicative of driver's attention, the results show the increase in speed caused a decrease in the driver's attention during driving. A small variation in speed in the mean fixation ($F_m$) is shown graphically.

Outliers in the time of fixation, number of fixations, and mean fixation were observed at 110 km/h. During the simulation, minimal losses of signal from the driver's eye movement were found, due to the sudden movements of the driver's head. However, such losses did not compromise the data analysis.

## Parametrical Analysis

### Time of Fixation (*F*)

According to Mauchly's test, the assumption of sphericity was not violated ($\chi^2_{(2)} = 2.1$, $p = 0.35$). There was a main effect of speed ($F_{(2,20)} = 20.90$, $MS_e = 1\ 148$, $p < 0.001$) on the time of fixation. The post hoc analysis revealed no significant difference between 90 and 110 km/h ($p = 0.09$), and the interaction between speeds and participants' gender had no effect on the total fixation ($F_{(2,20)} = 1.63$, $MS_e = 89$, $p = 0.22$). A main effect of gender was observed in the time of fixation ($F_{(1,10)} = 5.06$, $MS_e = 1\ 374$, $p < 0.05$).

### Number of fixations (*N*)

Sphericity was not violated ($\chi^2_{(2)} = 1.6$, $p = 0.44$). There was a main effect of speed ($F_{(2,20)} = 22.16$, $MS_e = 3531$, $p < 0.001$) on number of fixations. The post hoc analysis showed no significant difference between 90 and 110 km/h ($p = 0.09$), and the interaction between speeds and participants' gender had no effect on the number of fixations ($F_{(2,20)} = 1.21$, $MS_e = 192$, $p = 0.32$). Finally, there was no effect of gender on the number of fixations ($F_{(1,10)} = 4.50$, $MS_e = 3640$, $p = 0.6$).

### Mean fixation ($F_m$)

Sphericity was not violated ($\chi^2_{(2)} = 5.2$, $p = 0.07$). Speed had no effect ($F_{(2,20)} = 0.365$, $MS_e = 0.001$, $p = 0.70$) on mean fixation. The interaction between speed and participants' gender had no effect on the mean fixation ($F_{(2,20)} = 2.67$, $MS_e = 0.006$, $p = 0.09$). A main effect of gender was observed in the mean fixation ($F_{(1,10)} = 13.69$, $MS_e = 0.043$, $p < 0.01$).

## Non-parametrical Analysis

### Time of Fixation (F)

Friedman test revealed an effect of speed on the time of fixation ($\chi^2_{(2)} = 17.167$; $p < 0.001$). Multiple comparisons showed no significant difference between 90 km/h and 110 km/h, and no main effect of gender was observed in time of fixation ($U = 74.500$; $p = 0.06$).

### Number of Fixations (*N*)

Friedman test revealed a main effect of speed on the number of fixations ($\chi^2_{(2)} = 17.167$; $p < 0.001$). Multiple comparisons showed no significant difference between 90 and 110 km/h ($p = 0.09$), and a main effect of gender was observed in the number of fixations ($U = 78.000$; $p < 0.05$).

### Mean Fixation ($F_m$)

Friedman test showed no effect of speed on the mean fixation ($\chi^2_{(2)} = 1.644$; $p = 0.439$). A main effect of gender was observed in the mean fixation ($U = 53.000$; $p < 0.05$).

## Comparison Between Parametrical and Non-parametrical Analyses

Both analyses provided quite similar responses, thus validating the results. Differences between both analyses were detected only on the effect of gender in time of fixation (*F*) and number of fixations (*N*). Table 4 shows the results from the parametric and nonparametric statistical tests.

The differences between the two analyses may have been caused by the different evaluation methods of the tests. Nonparametric tests evaluate whether there are differences

**Table 4** Comparison between parametric and nonparametric tests

| | Parametric analysis | Non-parametric analysis |
|---|---|---|
| 1. Speed had a main effect on the time of fixation | Yes | Yes |
| 1.a. Time of fixation at 70 km/h and 90 km/h was different | Yes | Yes |
| 1.b. Time of fixation at 70 km/h and 110 km/h was different | Yes | Yes |
| 1.c. Time of fixation at 90 km/h and 110 km/h was different | No | No |
| 2. Speed had a main effect on the number of fixations | Yes | Yes |
| 2.a. Number of fixations at 70 km/h and 90 km/h was different | Yes | Yes |
| 2.b. Number of fixations at 70 km/h and 110 km/h was different | Yes | Yes |
| 2.c. Number of fixations at 90 km/h and 110 km/h was different | No | No |
| 3. Speed had a main effect on the mean fixation | No | No |
| 4. Gender had a main effect on the time of fixation | Yes | No |
| 5. Gender had a main effect on the number of fixations | No | Yes |
| 6. Gender had a main effect on the mean fixation | Yes | Yes |

among groups considering the position of data in the variables, while parametric tests evaluate differences as a function of the mean of data considering adjustments by certain distributions.

## Validation of the Experiment

The driving simulator was validated by the concept of presence through a self-reported questionnaire and visual behaviour during the simulation.

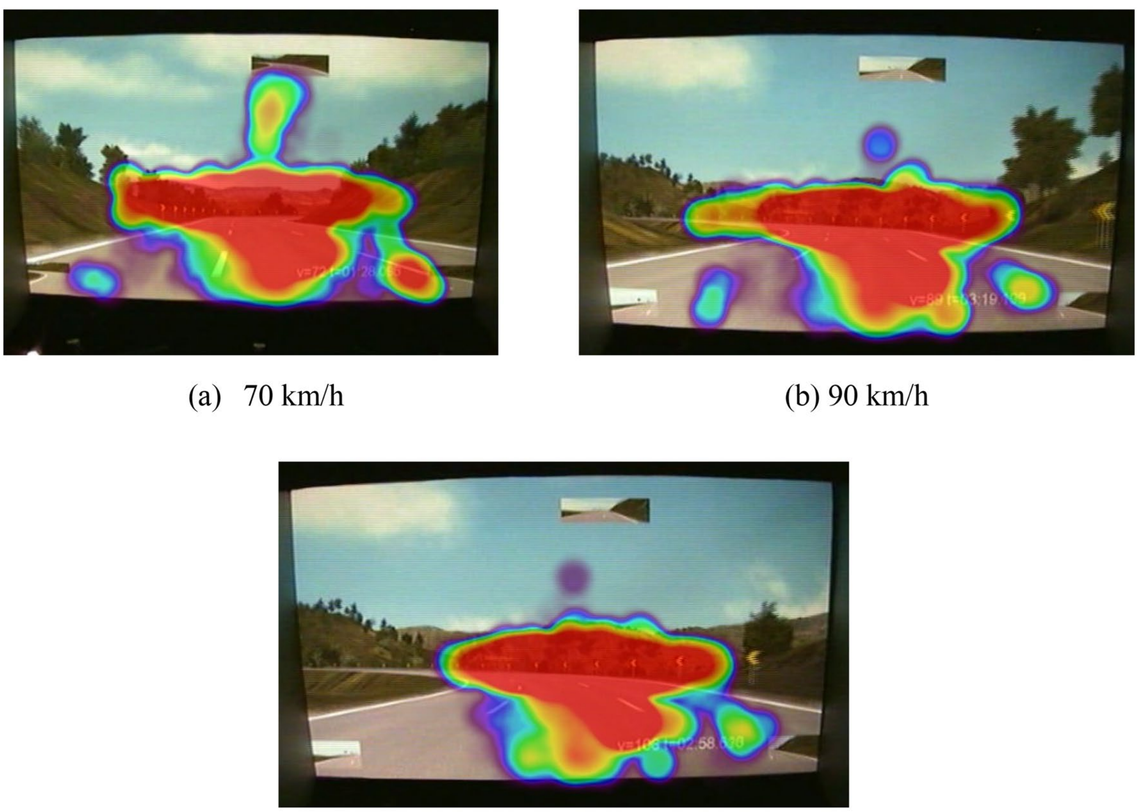
**Table 5** Degree of immersion in the simulation

| Categories of immersion | Mean | Standard deviation |
|---|---|---|
| Degree of reality | 4.25 | 1.29 |
| Possibility of action | 5.25 | 1.06 |
| Interface quality | 6.25 | 1.22 |
| Possibility of exploration | 5.75 | 0.97 |
| Self-evaluation of performance | 4.92 | 1.00 |
| Sounds | 4.83 | 1.64 |

Presence refers to the ‘ecological’ validity of an observed behaviour [47]. The participants self-reported their experience in the virtual environment through an adapted version of the Presence Questionnaire [46], which classifies the immersion level into seven categories, namely degree of reality, possibility of action, interface quality, possibility of environment exploration, self-evaluation of control performance, sounds, and tactile quality. The latter is applicable only in tactile virtual environments, therefore, it was not used in this study. The remaining six categories were evaluated on a 1–7 scale.

Table 5 shows the drivers’ evaluation results regarding level of immersion of the six aspects analyzed. The results were above mean.

Behavioural validation was analyzed from the data collected by the eye tracking system. Figure 7 shows heat maps of the driver’s gaze fixations on the simulated stretch segment during simulation. Figure 7a displays the driver’s gaze fixations at 70 km/h—the driver gazes the left, right and rear view mirrors for longer time, due to the reduced speed. According to Fig. 7b, at 90 km/h, the driver gazes the mirrors, but for shorter fixation time. Figure 7c shows the driver’s gaze fixation at 110 km/h, whose gaze field is



(a) 70 km/h

(b) 90 km/h

(c) 110 km/h

**Fig. 7** Heat maps of fixation for **a** 70 km/h, **b** 90 km//h and **c** 110 km/h concentrated in the center of the highway, revealing the driver rarely gazes the mirrors and is focused on the driving task.

Despite the limitations inherent to the fixed base simulator, the behavioural patterns of the driver's eyes in the virtual stretch reflected the driver's behaviour in a real situation at different speeds. The result contributes to the ecological validity of the driving simulator in this research.

## Conclusions

This study analyzed drivers' eyes movement behaviours for detecting the influence of different speeds on the drivers' visual attention while driving, according to time of fixation, number of fixations, and mean of fixations at different speeds (70 km/h, 90 km/h and 110 km/h) in a driving simulator experiment. An eye tracking system registered the eye movements and assessed visual attention and fixation in ROIs, specifically speedometer, right mirror, left mirror, and rear view mirrors. The key findings are summarized in what follows.

1. Low values of time of fixation and number of fixations were obtained for the right, left and rear view mirrors, which may be related to the sample composed of novice participants (under two years' driving experience) and the low traffic in the scenario. Konstantopoulos et al. [43] observed a similar tendency for low fixation on mirrors in novice drivers.
2. Time of fixation ($F$) and number of fixations ($N$) supported the hypothesis that speed affects drivers' attention while driving. According to both parametric and nonparametric statistical analyses, at decreasing speeds, drivers clearly deployed increased attention in the driving task. Although the present study has not established the most adequate speed for roads, the results show speed is inversely proportional drivers' attention, which is important for investigations on road designs.
3. Dependent variables time of fixation ($F$) and number of fixations ($N$) obtained at 90 km/h and 110 km/h provided similar results, probably due to the sinuosity of the road scenario (the radii of some curves were smaller than 150 m), which hampered drivers' maintaining 110 km/h speed. Therefore, the effective speeds reached in both situations were similar (83.39 and 93.52 km/h, respectively), which may explain the similar results.
4. The mean fixation ($F_m$) did not differ with speed—regardless of the speed of the vehicle, drivers took the same time interval to interpret the information exhibited by the simulation. Regarding gender, the mean fixation ($F_m$) significantly differed, and showed a lower value for female drivers, thus revealing female drivers required lower processing time than male drivers, evidenced by the lower mean fixation. The ability to deploy short fixations can be crucial in hazardous situations, since drivers must be aware of several potential sources of hazards without focusing on only one for a long time interval [43].

A difference between the nonparametric and parametric analyses was observed in the influence of gender on both time and number of fixations, and may be related to differences in the methods of the analyses. The nonparametric analysis considers the position of data in the variables, whereas the parametric analysis considers the mean of the data, with adjustments by certain distributions.

Designers must verify the geometry of roads in association with project speeds and implement necessary decreases in speed indicated by roadside signals towards safe driving, improved highway designs, and elimination of hazardous locations. The substantial safety benefits of lower speed limits have been recognized. This result was also reported by Pauw et al. [2], which demonstrates that reductions in rural speed limits from 90 to 70 km/h can reduce approximately 33% casualties.

The development of the experiment in the highway would be practically impossible, and put the participant's life at risk, since this highway has a high accident rate [48]. The driving simulator enables a safe running of the experiment, and its use for training novice drivers can improve visual search and anticipate hazards prior to their driving on rural highways.

Despite such important findings, this study has limitations. The results showed differences between low (70) and high (90 and 110) speeds, which implies the need for future experiments with a larger sample in stretches over long tangents so that drivers can drive at the required speed with no influence of geometry.

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