Transportation Research Part F 23 (2014) 88–100

Contents lists available at ScienceDirect

Transportation Research Part F

journal homepage: www.elsevier.com/locate/trf

A comparison of immersive and interactive motorcycle simulator configurations

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ARTICLE INFO

Article history:
Received 22 April 2013
Received in revised form 2 August 2013
Accepted 12 December 2013

Keywords:
Motorcycle simulator
Riding configuration
Simulator validity
Eye measures
Mental workload
Lane-change test

ABSTRACT

Two main factors seem to contribute to the development of a riding configuration, and consequently of a motorcycle simulator: the trajectory control modality and the leaning rendering. The goal of this study was to compare two riding simulator configurations through the assessment of the underlying mental workload adopting a multidimensional approach based on psychophysiological, performance, and subjective measures. In the first configuration (*reduced motion*), the trajectory control is obtained by means of positive steering, while the leaning is produced just by tilting the visual scene. Like a real motorbike, the second configuration (*dynamic*) allows a progressive transition between positive and counter steering as the speed increases, whereas the leaning is rendered by splitting the rolling angle between the tilting of the visual scene and the rolling of the platform.

Each participant completed six lane-change tasks per configuration, of which the first three and the last one were single tasks, and the remaining two were dual tasks. The occurrence of three single-task runs at the beginning of the experiment allowed us to examine the process of adaptation to each configuration, which is a critical precondition for simulator validity. The *dynamic* configuration proved to have higher validity, as confirmed by psychophysiological and subjective measures. Findings might have implications for the development of future riding simulators.

1. Introduction

Motorcycles help reducing traffic and parking congestion. However, despite the large number of users, riding a motorcycle is still considered to be a safety hazard. Recent statistics show that while the total number of road deaths is decreasing in European countries, the proportion of motorcycle rider fatalities is rising, together with the number of motorcycles on the road (ONISR, 2010).

The main setting where to study the behavior of this vulnerable group of road users is the simulated environment; however, while driving simulators have been largely used and validated for this purpose (for a review, see Kemeny & Panerai,

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http://dx.doi.org/10.1016/j.trf.2013.12.020

2003; Pinto, Cavallo, & Ohlman, 2008), motorcycle simulators have been rarely employed, and several fidelity and validity issues subsist (Cossalter, Lot, & Rota, 2010; Stedmon et al., 2011). While fidelity generally refers to both the subjective and objective realism of the simulation, validity relies on the correspondence between the simulator and the real world in the way the human operator behaves (Godley, Triggs, & Fildes, 2002; Malaterre & Fréchaux, 2001; Törnros, 1998).

Recently, Sahami and Sayed (2013) argued that when participants start to drive a simulator, they have to learn/observe the simulator outputs to refine their skills and strategies. Consequently, they need time to adapt and transfer their already existing driving skills to the simulator (Sahami & Sayed, 2010). This period of time, called adaptation process, is a crucial critical precondition for validity of experiments carried out using any simulator (Sahami & Sayed, 2013). According to Ronen and Yair (2013), during this period drivers/riders have to transfer motor-cognitive skills that are mainly required to correctly operate the simulator and respond to the simulated environment. These actions impose an extra mental workload on the person, which lasts until driving becomes automatic (Sahami & Sayed, 2013).

In this respect, the goal of this study was to compare different riding simulator configurations, through the assessment of the underlying mental workload. Although a strong link between adaptation and validity has been shown (Ronen & Yair, 2013; Sahami & Sayed, 2013), previous studies concerning riding simulators validation have not explored this crucial phase exhaustively. The literature on driving/riding simulators validation have mainly relied on performance measures such as speed and acceleration (e.g., Cossalter et al., 2010; Godley et al., 2002), braking (e.g., Hoffman, Lee, Brown, & McGehee, 2002), trajectory (Cossalter et al., 2010; Törnros, 1998), road/lane exit and collisions (Stedmon et al., 2011), and subjective measures (Cossalter et al., 2010; Stedmon et al., 2011), without focusing on the adaptation phase. In this study we tried to explore the adaptation process adopting a multidimensional approach based on psychophysiological, performance, and subjective measures (De Waard, 1996; Di Stasi et al., 2009).

From the review of existing interactive riding simulators – whose purpose is to study riders behavior – two main factors seem to contribute to the development of a riding configuration: the visual and inertial leaning rendering, and the modalities for the trajectory control. Concerning the leaning, since in a simulated environment it is physically impossible to reproduce the entire leaning angle of a real motorbike – because of the absence of centrifugal forces – both the tilting of the visual scene (counter-side to the direction of the bend and of the leaning of the motorcycle) and the rolling of the platform should work together to reproduce the leaning rendering. According to Cossalter et al. (2010), appropriate tuning should split the rolling angle into a bigger part, which is operated by the visual output, and a smaller one handled by the platform. As to the trajectory control, in the real world it is made by means of both positive steering at slow speed, i.e. by turning the handlebar toward to the desired direction (steer left to turn left), and counter steering, namely steering counter to the desired direction (steer left to turn right) as the speed increases. To negotiate a turn, the combined center of mass of the rider and the motorcycle must first be leaned in the direction of the turn, and steering briefly in the opposite direction causes the lean. The heavier and faster the motorbike, the more valuable becomes the counter steering since shifting the body weight becomes less effective (Fajans, 1999).

Consistent with Nehaoua, Arioui, and Mammar (2011), three families of riding simulators can be identified within the sparse literature: reduced motion simulators, parallel platform based simulators, and serial platform based simulators. The following is an up-to-date summary of the best-known riding simulators.

The Honda Riding Trainer (HRT) is a low-cost reduced motion motorcycle simulator developed by Honda (Japan), which consists of a tubular chassis, a seat, handlebar, pedals, speed selector, a small screen for the visual output, and software for the simulation of the motorcycle dynamics. Among all the existing motorcycle simulators, it is the most widely used, and has been employed to train and assess riders (Vidotto, Bastianelli, Spoto, Torre, & Sergeys, 2008), to study hazard perception (Liu, Hosking, & Lenné, 2009; Shahar, Poulter, Clarke, & Crundall, 2010), and to assess mental workload (Di Stasi et al., 2009). However, it allows just positive steering, and it reproduces the leaning only by tilting the horizon.

The MotorcycleSim (Stedmon et al., 2011) is a parallel platform based simulator developed by the University of Nottingham (UK), which consists of a fully equipped motorcycle with two pairs of pneumatic actuators that allow leaning, a projection screen, and dedicated software for the simulation of the motorcycle dynamics. However, despite this simulator could theoretically lean to the sides, experimental evidence (Crundall, Crundall, & Stedmon, 2012; Stedmon et al., 2011) showed that no physical bending was allowed as it was used in a static mode with the pneumatic actuators pressurized to stabilise the motorcycle and the rider. The riding experience of leaning into bends was obtained by tilting the horizon, while braking and acceleration effects were simulated by pitching actions in the visual outputs (Crundall et al., 2012). Recent results from Stedmon et al. (2011) showed riders to prefer a tilting horizon rather than a static one. The results also showed that both of these visual output conditions resulted in similar riding performance. Concerning the trajectory control, the simulator allows both positive and counter steering. However, in the current version of MotorcycleSim, the simulator does not allow a progressive transition between slow speed control, where the positive steering is more effective, and increasing speed control, where riders adopt counter steering (Stedmon, Brickell, Hancox, Noble, & Rice, 2012). Experimental comparison of these steering configurations revealed the positive steering to be preferred to the counter steering, together with a higher degree of control with less off road accidents, collisions with other vehicles and time spent out of lane (Stedmon et al., 2011).

The DIMEG simulator, developed by the University of Padova (Italy), is a serial platform based simulator, which consists of a fully instrumented motorcycle mock-up mounted on a cubic cage that supports the frame motion via four steel suspended cables, sensorized handlebar and footpads, software for the simulation of the motorcycle dynamics, and three subsystems for the motion, visual and acoustic cues. This mechanical conception helps reducing frictions and allows a good distribution of the gravity forces. The DIMEG simulator is able to reproduce the counter steering behavior as a response to the rider steering actions, and the rolling angle is split between the tilting of visual scene and the rolling of the platform. This simulator has been objectively and subjectively evaluated (for a detailed discussion, see Cossalter et al., 2010) and has been largely used for studying IVIS (e.g., Biral, da Lio, Lot, & Sartori, 2010; Cossalter, Lot, Massaro, & Sartori, 2009; Huth, Biral, Martín, & Lot, 2012).

With the aim of developing a reliable riding simulator for studying riders' behavior, two different riding configurations were compared using the IFSTTAR motorcycle simulator (see Section 2.3). The first operationalized configuration, called *reduced motion*, was designed to allow comparisons with a simulator in which the trajectory control is obtained by means of positive steering, and the leaning cues are produced just by tilting the scenery. The second configuration, called *dynamic*, was inspired by the functioning of a real motorbike and it was developed in our lab during the past decade, by experts in multiple fields. The major engineering challenge for motorcycle simulators is to achieve a dynamic model that, with respect to the trajectory control, combines positive and counter steering. To this end, this configuration allows a progressive transition between slow speed control, where riders have to manage balance and trajectory – by means of positive steering – and increasing speed control – where riders adopt counter steering. Furthermore, the leaning is reproduced by splitting the rolling angle between the tilting of the visual scene and the rolling of the platform.

For evaluating the two riding configurations, the Lane Change Test (LCT; ISO, 2010), was employed. The LCT is a standardized dual-task method that quantitatively measures performance degradation on a primary driving-like task while a secondary task is performed. Each participant completed six trials for each simulator configuration (*reduced motion* and *dynamic*), of which the first three and the last one were single tasks (performing lane changes alone), and the remaining two were dual tasks. The occurrence of three single-task runs at the beginning of the experiment allowed us to examine the adaptation process to each configuration, which is a critical precondition for simulator validity (Sahami & Sayed, 2013). Assuming progressive improvements – namely decreased mental workload and better riding performance – until the third run for both riding configurations (i.e. adaptation process), the two dual-task runs between the third and the last single-task trial let us investigate how the secondary task impacted on the primary one, and how each configuration was affected.

2. Method

2.1. Participants

Sixteen participants (14 males) were recruited through advertisements on motorcyclists' forums. All of them had normal or corrected-to-normal vision, and were naïve as to the aims and expected outcomes of the experiment. The present study was approved by the IFSTTAR Ethics Committee and a 40 € compensation for each person was established. Selected demographic information are provided in Table 1.

2.2. Experimental design, task and procedure

A full within-subjects design (Fig. 1) was employed, with two levels of mental workload (single task = LCT; dual task = LCT + mental arithmetic), and two riding configurations (*reduced motion* and *dynamic*).

The LCT consisted of performing eighteen lane changes on a straight three-lane road free of traffic (Fig. 2, left). Participants were required to change lanes according to the information provided by two identical road signs placed on both sides of the road. Each scenario had a total length of 3350 m. After starting the virtual engine, participants were asked to ride until they reached the speed of 60 km/h. After leading the motorbike for 500 m, a START road sign appeared on both sides of the road, and the experiment begun. From this moment on, the vehicle speed was limited and controlled via software to 60 km/h. After 2850 m, an END road sign was displayed, indicating that the task had been completed. Lane change signs were pre-

Table 1
Selected demographic variables.

	Age (years)	Driving licence (years)	Driving licence (km/year)	Motorcycle licence (years)	Motorcycle licence (km/year)	Urban (%)	Peri-Urban (%)	Rural (%)
Mean	29	11	16,563	9	10,875	30	32	39
Standard deviation	7	7	19,674	9	7890	25	21	28
Range	22–43	4–26	2000–80,000	2–31	3000–30,000	0–85	5–80	0–90

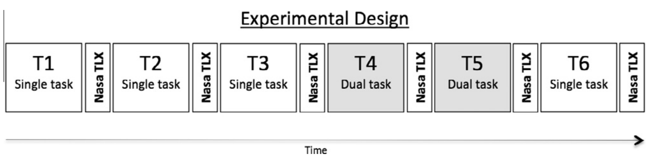

Fig. 1. Experimental design: T1, T2, T3 and T6 are single-task runs (LCT only); T4 and T5 are dual-task runs (LCT + mental arithmetic). Each participant completed 12 runs (6 for the *reduced motion* configuration, 6 for the *dynamic* configuration).

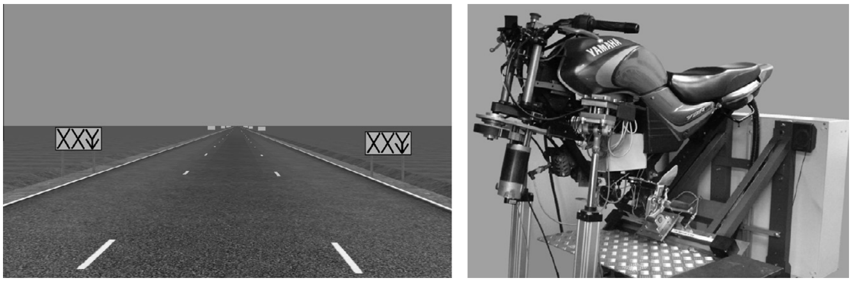

Fig. 2. LCT scenario (left); IFSTTAR motorcycle riding simulator (right).

sented every 150 m and were always visible but blank until participants were 40 m far from them. Participants were instructed to keep their lane until required to change, and to start the lane change as soon as they saw the signs, but not before (for further details see ISO 26022, 2010).

The dual task condition consisted of summing a two-digit number and a one-digit number. Calculations were presented by a pre-recorded voice and participants had to respond out loud. There was a 4 s interval between each calculation (i.e. between voice offset and onset), totalling 28 calculations per riding trial. Verbal responses were recorded and analyzed offline. No instructions were provided about how to prioritize attention between the primary and the secondary task.

After having been explained the basic principle of the experiment, participants signed an inform consent form and demographic data were collected. They then underwent training for the mental arithmetic task. Each participant completed six riding trials per configuration (6 $\times$ 2 configurations = 12 riding trials). The first three and the last trials were single tasks, while the remaining two were dual tasks. Pauses between all the experimental trials allowed subjective ratings data collection (*NASA-TLX*, Hart & Staveland, 1988) whereas a questionnaire for the evaluation of the riding configurations was carried out at the end of the experiment (*RCEQ*, see Section 2.4.3). The whole experiment lasted approximately 1 h30 min. The configuration order was counterbalanced: eight participants performed the *dynamic* configuration before the *reduced motion* configuration, while eight participants performed the *dynamic* configuration after the *reduced motion* configuration.

2.3. Equipment

2.3.1. Motorcycle riding simulator

The experiment was conducted on the IFSTTAR powered motion-based motorcycle simulator, comprising a motion platform, an image-generation software, a screen-projection, and a sound system (Fig. 2, right). The simulator consists of a standard motorcycle frame (125 cc) equipped with all basic parts including steering column with handlebars, gas tank, seat, footrests, throttle, front and rear brakes, and gear shifting devices. Motion on the three axes is obtained by means of actuators and sensors. The front fork is replaced by two lateral electric actuators (for pitch and roll movements), the rear part of the motorcycle rests on a powered horizontal track (used for yaw movements), and the steering column is equipped with a force feedback motor. The highest roll, pitch and yaw angles are ±12.5°, 10° and 10° respectively. Additionally, the rolling center is located approximately 30 cm below the simulator's seat. In accordance with real-world riding, higher speeds and larger lean angles resulted in faster movement on the three axes. Motion was refreshed at a frequency of 250 Hz and steering feedback at a frequency of 100 Hz. The simulator conception, design and functioning was fully described in Arioui, Nehaoua, Hima, Séguy, and Espié (2010). With respect to this earlier version of the simulator, some improvements were made. From a hardware point of view, the hub for rear platform rotation was moved towards the saddle, allowing better leaning, the handlebar force-feedback was empowered, and pressure transducers were installed on the head of the two actuators placed on the front of the platform, giving the possibility to take in consideration the actions made by riders when shifting their body weight.

The simulated scene was displayed onto a 185 cm width $\times$ 124 cm height white screen subtending a visual angle of 60 $\times$ 40°, with participants facing the screen at a distance of approximately 165 cm when seated on the simulator. The images (refreshed at 30 Hz) were calculated and projected at the participant's eye height, and the simulated viewing angle was aimed to the vanishing point of the simulated scenario. According to the specifications of ISO 26022 (2010), the displayed scene consisted of a three-lane roadway located on a plain green field, road surface was gray and lane markings were white (Fig. 2, left). Simulated engine sound was provided by using a 4.1 speaker system.

2.3.2. Riding configurations

In this paper, the definition of riding configuration lies on two basic concepts: the vehicle dynamics model and the movement restitution algorithm. The vehicle dynamic model aims at measuring riders' actions in order to determine the trajectory. On the basis of the obtained trajectory, the movement restitution algorithm triggers the physical output by activating the platform motor units and the visual output. Both riding configurations are identical with regard to longitudinal movements (i.e. speed and acceleration), but different with respect to the lateral movements (i.e. rolling and steering). A schematic representation of simulator lateral control is provided in Fig. 3.

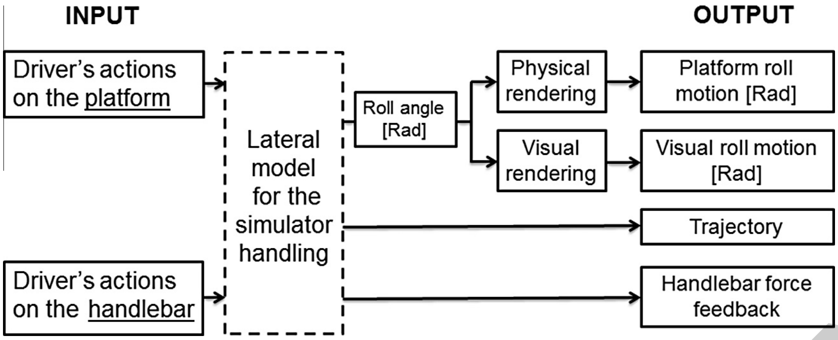

Fig. 3. Schematic representation of simulator lateral control: φ is the virtual motorcycle roll angle [rad]; φ_{visual} is the visual roll motion (tilt) [rad]; $\varphi_{platform}$ is the platform roll motion [rad].

For the *reduced motion* configuration, the trajectory control consists of positive steering and the rolling effect is provided by tilting the visual scene in the opposite direction with respect to steering direction. This configuration is based on the following equations, where φ is the theoretical roll angle:

$$\varphi_{visual} = -0.5 \cdot \varphi$$
$$\varphi_{platform} = 0$$

The *dynamic* configuration allows a progressive transition between slow speed control, where riders have to manage trajectory and balance, and increasing speed control, where riders adopt counter steering. Riders could control balance and trajectory by using the handlebar and/or by shifting the body weight ("leaning left to go left"). The rolling effect is provided by leaning the motorcycle mock-up in the same direction of the turn, and tilting the horizon line in the opposite direction. This configuration is based on the following equations, where φ is the theoretical roll angle:

$$\varphi_{visual} = -0.5 \cdot \varphi$$
$$\varphi_{platform} = 0.4 \cdot \varphi \text{ (limited to } \pm 0.2 \text{ rad)}$$

2.3.3. Eye-tracking

A Pertech head-mounted monocular eye-tracker was used to record participants' ocular behavior. This device, based on the principle of a pair of glasses (without lenses), has 0.25° of accuracy and 50 Hz sampling rate and uses a pupil tracking technology with an image processing algorithm to define the ocular direction. A seven-point calibration was performed for each participant at the beginning of each experimental trial. Room lighting was kept constant during all the experimental trials.

2.4. Dependent Variables (DVs)

A multiple measures approach that includes psychophysiological, performance and subjective measures was used. For each dependent variable, values were extracted for 192 trials (16 participants × 6 experimental conditions × 2 riding configurations). For psychophysiological and performance measures, all data points before the START and after the END signs were discarded.

2.4.1. Psychophysiological measures

Two eye measures were chosen. The blink rate (*BR*), i.e. the number of eye blink events that take place in each experimental run (Stern, Boyer, & Schroeder, 1994), and the average pupil size (*APS*), which represents the mean of all pupil size values collected during each trial. Concerning *BR*, two eye blink duration limits were selected: a minimum duration of 80 ms, and a maximum of 500 ms (Benedetto et al., 2011). As to *APS*, means were calculated after removing all blink artefacts from the pupil surface column.

2.4.2. Performance measures

The Lane Change Delay (LCD) was defined as the time elapsed between the moment the sign appears and the initiation of the lane change (ISO, 2010).

Starting from the LCD, two DVs were employed: the average LCD over the eighteen lane changes (*ALCD*) as well as the LCD standard deviation (*Lane Change Delay Variability – LCDV*). Recent experimental evidence (Benedetto et al., 2011) showed this last measure to be particularly sensitive to mental workload manipulation. Missed lane changes were excluded from the calculation.

The *Wrong Lane Change Rate* (*WLCR*) corresponded to the number of lane changes where either (a) the participant did not respond to the lane change sign at all or (b) a lane change was made, but to the wrong lane (ISO, 2010).

The percentage of wrong responses on the arithmetic task (*Wrong Response Percentage – WRP*) was calculated as the percentage of mistakes on the 28 calculations.

2.4.3. Subjective measures

The *NASA-Task Load Index (NASA-TLX* – Hart & Staveland, 1988), a fully validated tool, was intended to measure the operator's perceived workload along six dimensions: mental demand, physical demand, effort, own performance, temporal demand and frustration.

Table 2
Means and standard deviations (italic) for each dependent variable and experimental condition.

Dependent variables	**Riding configuration**	**Experimental conditions**					
		T1 *Single task*	**T2** *Single task*	**T3** *Single task*	**T4** *Dual task*	**T5** *Dual task*	**T6** *Single task*
BR (count)	*Reduced motion*	22 *(17)*	28 *(19)*	24 *(19)*	34 *(22)*	36 *(23)*	26 *(16)*
	Dynamic	16 *(13)*	19 *(14)*	22 *(15)*	30 *(15)*	33 *(19)*	23 *(15)*
APS (px)	*Reduced motion*	4205 *(526)*	3885 *(505)*	3733 *(475)*	4685 *(663)*	4476 *(613)*	3760 *(469)*
	Dynamic	4623 *(586)*	4286 *(543)*	4138 *(542)*	4695 *(664)*	4756 *(653)*	4084 *(520)*
ALCD (s)	*Reduced motion*	0,84 *(0,23)*	0,82 *(0,19)*	0,87 *(0,20)*	0,91 *(0,31)*	0,90 *(0,28)*	0,82 *(0,19)*
	Dynamic	1,15 *(0,23)*	1,19 *(0,25)*	1,21 *(0,24)*	1,30 *(0,36)*	1,28 *(0,40)*	1,35 *(0,28)*
LCDV (s)	*Reduced motion*	0,23 *(0,18)*	0,19 *(0,06)*	0,20 *(0,06)*	0,31 *(0,15)*	0,28 *(0,14)*	0,19 *(0,06)*
	Dynamic	0,23 *(0,10)*	0,25 *(0,05)*	0,24 *(0,08)*	0,36 *(0,12)*	0,40 *(0,18)*	0,28 *(0,07)*
WLCR (count)	*Reduced motion*	0	0	0	5	0	0
	Dynamic	0	0	0	6	4	0
WRP (%)	*Reduced motion*				7 *(9)*	7 *(6)*	
	Dynamic				6 *(10)*	6 *(6)*	
NASA-TLX (0-100)	*Reduced motion*	21 *(12)*	18 *(9)*	18 *(9)*	38 *(14)*	41 *(17)*	18 *(11)*
	Dynamic	35 *(19)*	27 *(13)*	23 *(11)*	44 *(15)*	43 *(19)*	20 *(14)*

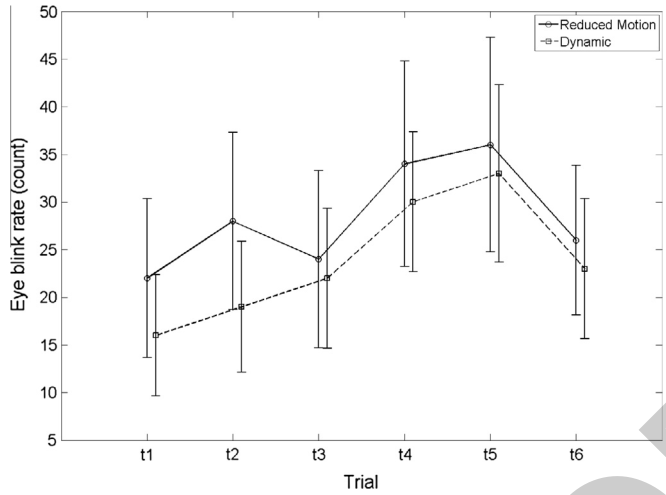

Fig. 4. Average BR for each configuration and experimental trial. Vertical bars denote 95% confidence intervals (mean ± 1.96 ∗ SE). $N = 16$.

The *Riding Configuration Evaluation Questionnaire* (*RCEQ*), which is a seven-point tailor-made Likert scale (1 = very bad; 7 = very good) made by four items (Realism with respect to a real motorcycle; Easiness to familiarize; Easiness to handle and Personal evaluation), aimed at evaluating riding configurations. The *RCEQ* was administered at the end of the experiment.

3. Results

Experimental data were analyzed with a repeated measures ANOVA (rmANOVA) using $trial_{12}$ (*t1* through *t6* for *reduced motion* configuration, *t1* through *t6* for *dynamic* configuration) as within factor. Reported *p* values were adjusted following a Greenhouse–Geisser correction (Greenhouse & Geisser, 1959). The significance level was set at 0.05 for all statistical analyses. The effect size (η^2) was also computed. Means and standard deviations for each of the dependent variables are provided in Table 2.

Besides rmANOVA, planned contrasts were computed to answer the following questions:

(a) Within and between the configurations are there any differences among the first three single-task runs (*t1*, *t2*, *t3*)?
(b) Within and between the configurations are there any differences between single- (*t1*, *t2*, *t3*, *t6*) and dual-task runs (*t4*, *t5*)?

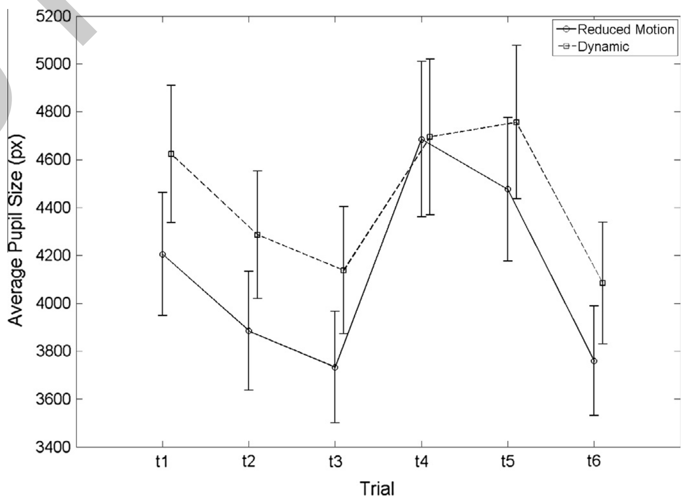

Fig. 5. APS for each configuration and experimental trial. Vertical bars denote 95% confidence intervals (mean ± 1.96 ∗ SE). $N = 16$.

3.1. Psychophysiological measures

3.1.1. Blink Rate (BR)

A *trial* effect was found ($F(11,165) = 4.56$, $p < .001$, $\eta^2 = .23$, Fig. 4).

Question (a) Within each configuration, no differences were found between *t1*, *t2* and *t3*, whereas when comparing the two configurations, lower *BR* was found in *t1 dynamic* ($F(1,15) = 4.45$, $p = .05$) and *t2 dynamic* ($F(1,15) = 5.63$, $p < .05$), with respect to *t1* and *t2 reduced motion*. Such a decrease might be due to the higher demand required by the *dynamic* configuration, which in turn inhibits *BR*. No differences between the two riding configurations were found in *t3*.

Question (b) When single-task trials were grouped and compared with grouped dual-task trials (i.e. group *t1*, *t2*, *t3*, *t6* compared with group *t4*, *t5*), *BR* was higher in dual-task trials for both the *reduced motion* ($F(1,15) = 4.49$, $p = .05$) and the *dynamic* ($F(1,15) = 6.1$, $p < .05$) configurations. Previous research provided contrasting results on *BR* under mental load: some studies reported increasing rates, while others found decreases. One important modulating factor is verbalization, which is known to increase *BR* (for a review, see Stern, Walrath, & Goldstein, 1984). This seems in line with our study, since participants had to speak out loud the calculation results. No differences between the two configurations were found in the dual task.

3.1.2. Average Pupil Size (APS)

A *trial* effect was found ($F(11,165) = 16.74$, $p < .001$, $\eta^2 = .53$, Fig. 5).

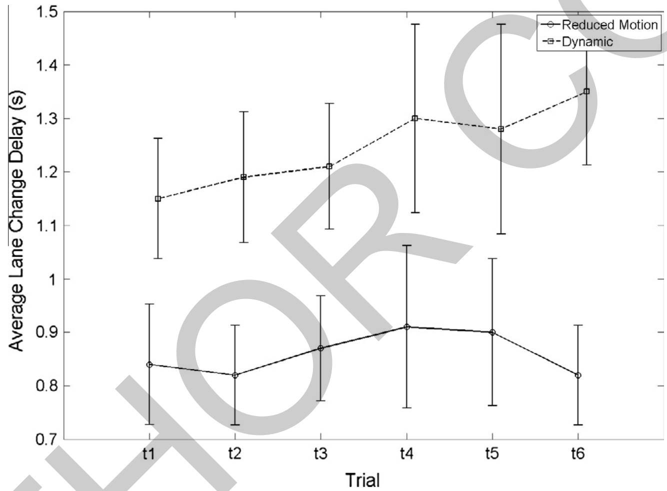

Fig. 6. ALCD for each configuration and experimental trial. Vertical bars denote 95% confidence intervals (mean ± 1.96 * SE). $N = 16$.

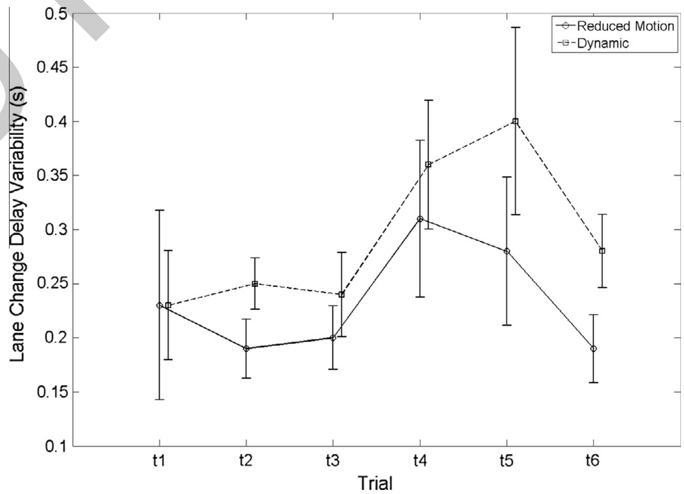

Fig. 7. Average LCDV for each configuration and experimental trial. Vertical bars denote 95% confidence intervals (mean ± 1.96 * SE). $N = 16$.

Question (a) Both riding configurations yielded lower and lower *APS* until the third single task run, as confirmed by the planned contrasts *t1* vs. *t2* (all $Fs(1,15) > 16.55$, $ps < .001$) and *t2* vs. *t3* (all $Fs(1,15) > 9.30$, $ps < .005$). Moreover, when comparing the two configurations, significant differences were found between *t1*, *t2* and *t3* (all $Fs(1,15) > 4.76$, $ps < .05$), with lower *APS* in the *reduced motion* configuration.

Question (b) When single-task trials were grouped and compared with grouped dual-task trials, *APS* was higher in dual-task trials for both *reduced motion* ($F(1,15) = 34.07$, $p < .001$) and *dynamic* ($F(1,15) = 27.33$, $p < .001$) configurations. For the *reduced motion* configuration, *APS* was higher in the dual-task trials with respect to the single-task ones (all $Fs(1,15) > 8.64$, $ps < .05$), except when *t1* was compared to *t5* ($F(1,15) = 3.59$, $p = .08$). For the *dynamic* configuration, *APS* was higher in the dual-task trials with respect to the single-task ones (all $Fs(1,15) > 11.56$, $ps < .005$), except when *t1* was compared to *t4* ($F(1,15) = 3.26$, $p = .09$) and when *t1* was compared to *t5* ($F(1,15) = 0.69$, n.s.).

When the *reduced motion* configuration was compared to the *dynamic* one, there was no difference in the dual-task trials. Furthermore, a decrease of *APS* was found for both configurations when the dual task was performed for the second time (*t5*), with respect to the first one (all $Fs(1,15) > 6.50$, $ps < .05$). Results on *APS* are in line with previous studies reporting increased pupil size as a function of increased mental workload (see Beatty & Lucero-Wagoner, 2000).

3.2. Performance measures

3.2.1. Average Lane Change Delay (ALCD)

A *trial* effect was found ($F(11,165) = 25.12$, $p < .001$, $\eta^2 = .63$, Fig. 6).

Question (a) No differences within and between the configurations were found between the first three single-task runs (*t1*, *t2*, *t3*).

Question (b) When single-task trials were grouped and compared with grouped dual-task trials, no significant differences were found on *ALCD* scores for both configurations.

When the *reduced motion* configuration was compared to the *dynamic* one, *ALCD* was higher for the *dynamic* configuration ($F(1,15) > 83.31$, $p < .001$). More in detail, *ALCD* was higher for the *dynamic* configuration in all the single- and the dual-task trials (all $Fs(1,15) > 23.79$, $ps < .001$).

3.2.2. Lane Change Delay Variability (LCDV)

A *trial* effect was found ($F(11,165) = 6.8$, $p < .001$, $\eta^2 = .31$, Fig. 7).

Question (a) No differences within the configurations were found between the first three single-task runs (*t1*, *t2*, *t3*). However, a significant difference between the configurations was found in *t2* ($F(1,15) = 8.72$, $p < .05$).

Question (b) When single-task trials were grouped and compared with grouped dual-task trials, *LCDV* was higher in dual-task trials for both *reduced motion* ($F(1,15) = 8.27$, $p < .05$) and *dynamic* ($F(1,15) = 30.83$, $p < .001$) configurations. For the *reduced motion* configuration, *LCDV* was higher in the dual-task trials with respect to the single-task ones (all $Fs(1,15) > 5.38$, $ps < .05$), except when *t1* was compared to *t4* ($F(1,15) = 2.59$, n.s.) and when *t1* was compared to *t5* ($F(1,15) = 1.26$, n.s.). For the *dynamic* configuration, *LCDV* was higher in the dual-task trials with respect to the single-task ones (all $Fs(1,15) > 11.29$, $ps < .005$).

When the *reduced motion* configuration was compared to the *dynamic* one, LCDV was higher for the *dynamic* configuration ($F(1,15) = 6.86$, $p < .05$). Nevertheless, just few trials triggered significant results *t2* ($F(1,15) = 8.72$, $p < .05$); *t5* ($F(1,15) = 5$, $p < .05$); *t6* ($F(1,15) = 10.77$, $p < .01$). No differences between the two riding configurations were found in the remaining trials.

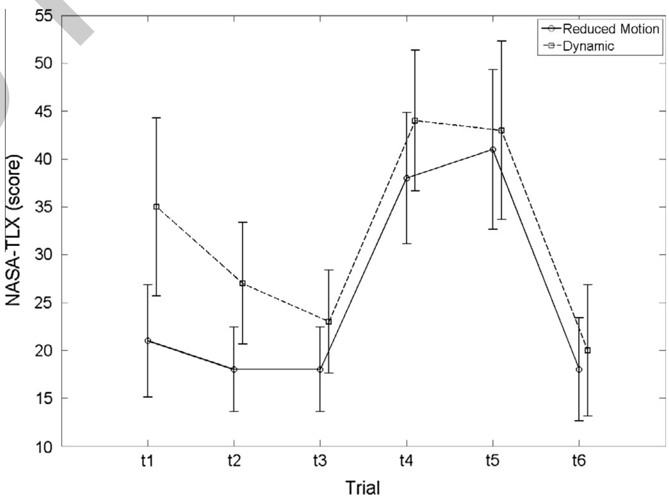

Fig. 8. Average NASA-TLX scores for each configuration and experimental trial. Vertical bars denote 95% confidence intervals (mean ± 1.96 ∗ SE). $N = 16$.

3.2.3. Wrong Lane Change Rate (WLCR)

As to the *reduced motion* configuration, the totality of *WLCR* was found in *t4*, while no missing lane changes were found in the remaining trials. In *t4*, five participants over sixteen missed the lane change one time over a total of eighteen lane changes.

With regard to the *dynamic* configuration, the missed or erroneous lane changes were found in both *t4* and *t5*. Six participants missed the lane change one time over eighteen in *t4* and four in *t5*.

3.2.4. Wrong Response Percentage (WRP)

The paired *t*-test on *WRP* did not disclose any significant difference between the two dual task conditions (*t4* and *t5*) on both the *reduced motion* and the *dynamic* configurations. No significant differences were found between the two configurations.

3.3. Subjective measures

3.3.1. NASA-TLX

A *trial* effect was found ($F(11,165) = 16.86$, $p < .001$, $\eta^2 = .53$, Fig. 8).

Question (a) Higher *NASA-TLX* scores were found at the beginning of each riding session, with gradually lower levels until the third single task run just when the *dynamic* configuration was performed, as confirmed by the planned contrasts *t1* vs. *t2* ($F(1,15) = 10.16$, $p < .01$), and *t2* vs. *t3* ($F(1,15) = 24.28$, $p < .001$).

Question (b) When single-task trials were grouped and compared with grouped dual-task trials (i.e. group *t1*, *t2*, *t3*, *t6* compared with group *t4*, *t5*), *NASA-TLX* scores were higher in dual-task trials for both the *reduced motion* ($F(1,15) = 49.23$, $p = .001$) and the *dynamic* ($F(1,15) = 6.1$, $p < .001$) configurations. For the *reduced motion* configuration, *NASA-TLX* scores were higher in the dual-task trials with respect to the single-task ones (all $Fs(1,15) > 23.94$, $ps < .001$). For the *dynamic* configuration, *NASA-TLX* scores were higher in the dual-task trials with respect to the single-task ones (all $Fs(1,15) > 9.27$, $ps < .01$), except when *t1* was compared to *t4* ($F(1,15) = 3.54$, $p = .08$) and when *t1* was compared to *t5* ($F(1,15) = 1.71$, n.s.).

As to the configuration comparison, higher scores were found in *t1 dynamic* ($F(1,15) = 24.41$, $p < .001$), and *t2 dynamic* ($F(1,15) = 10.70$, $p < .01$), with respect to *t1* and *t2 reduced motion*. No differences between the two riding configurations were found in the remaining trials (*t3*, *t4*, *t5*, *t6*).

3.3.2. Riding Configuration Evaluation Questionnaire (RCEQ)

The *dynamic* configuration was perceived as being more realistic than the *reduced motion* one ($t(15) = 10.44$, $p < .001$). In turn, the *reduced motion* configuration was found to be easier to familiarize with ($t(15) = 4.34$, $p < .001$). No differences were found on perceived ease of use. Overall, participants declared they preferred the *dynamic* configuration ($t(15) = 8.12$, $p < .001$).

4. Discussion

The goal of this study was to compare two riding simulator configurations – which differ from one another in the modality for the trajectory control and in the leaning rendering – through the assessment of the underlying mental workload. The *reduced motion* configuration was designed to allow comparisons with a simulator in which the trajectory control is obtained by means of positive steering, and the leaning cues are reproduced just by tilting the visual scene. Similarly to the functioning of a real motorbike, the *dynamic* configuration allows a progressive transition between positive steering at slow speed and counter steering as the speed increases, while the leaning is reproduced by splitting the rolling angle between the tilting of the visual scene and the rolling of the platform.

Since now, the great majority of driving/riding simulator validation studies have mainly relied on performance (e.g. speed, braking, trajectory, driving errors) and subjective measures. In this study, psychophysiological measurements were also collected and analyzed. Particular relevance was given to the adaptation process, which is a critical precondition for validity of experiments carried out using a simulator, and is a crucial yet under-researched issue (Ronen & Yair, 2013; Sahami & Sayed, 2013).

Concerning psychophysiological measures, lower *BR* was found in *t1* and *t2 dynamic*, since more information processing was needed in the adaptation process with respect to *reduced motion*. This result is in line with the *RCEQ* and with the *NASA-TLX*, since the *dynamic* configuration was found to be more difficult to familiarize with, and more mentally demanding than the other one. According to Stern (1980), in both simulated and real automobile driving, blinks occur most frequently at times of reduced information processing. In the dual task, an increase of *BR* due to the verbalization of the mental arithmetic calculation was found (Oh, Han, Peterson, & Jeong, 2012; Schuri & von Cramon, 1981; Stern et al., 1984; von Cramon & Schuri, 1980).

As to *APS*, larger *APSs* were found in all of the single task conditions when performing the *dynamic* riding configuration with respect to the *reduced motion* one. Both the *dynamic* and the *reduced motion* configurations showed progressively lower *APSs* until the third single-task run. In the dual task, both riding configurations yielded an increase of *APS*, as well as a decrease of *APS* when the dual task was performed for the second time (*t5*), with respect to the first one (*t4*). These outcomes are in line with a large body of literature reporting the ability of pupillometry to reflect different levels of task difficulty (Beatty, 1982; Beatty & Lucero-Wagoner, 2000; Goldwater, 1972).

Regarding performance measures, no significant results on *ALCD* were found: one might have expected longer lane change delays in a dual-task condition, which did not occur. However, longer *ALCD* were found in the *dynamic* configuration. We attribute this result to the higher motor demand required by this configuration.

Consistent with Benedetto et al. (2011), *LCDV* was found to be higher in the dual task, reflecting the impossibility to react with homogeneity to all the eighteen lane changes required by the riding task, while performing the secondary task. Such an increase was found for both riding configurations.

Although the missed or erroneous lane changes were sporadic events, results suggested the *WLCR* could be used as a reliable indicator of central inattentional blindness, revealing possible failures of visual awareness stemming from late-stage bottlenecks when more mental workload occurs (Most, 2010). Effectively, the totality of wrong lane changes was found in the dual task trials. For the *reduced motion* configuration all of the mistakes are concentrated in *t4*. For the *dynamic* riding configuration, the missed or erroneous lane changes were found in both *t4* and *t5*. These results point to the aforementioned lower familiarization ease of the *dynamic* configuration.

Concerning subjective measures, higher *NASA-TLX* scores were found at the beginning of each riding session, with gradually lower levels until the third single task run, just when the *dynamic* configuration was performed. In the dual task, both configurations yielded higher *NASA-TLX* scores (Benedetto et al., 2011; Hart, 2006; Recarte, Pérez, Conchillo, & Nunes, 2008).

Regarding question (a) (i.e. "Within and between the configurations, are there any differences among the first three single-task runs (*t1*, *t2*, *t3*)?"), results revealed tangible differences between the two configurations. As confirmed by both BR and Nasa-TLX, the *dynamic* riding configuration triggered higher levels of mental workload with respect to the *reduced motion* one during the first time of exposition (*t1* and *t2*), with progressively decreased levels until the third run (*t3*). Such higher workload levels could be attributed to the substantial immersive (i.e. leaning coupled between physical and visual roll angle) and interactive (i.e. higher degrees of freedom to control the steering) differences between configurations. The absence of such an effect would have been strongly correlated to the reduced validity of the configuration. This result is in line with the assertion of Sahami and Sayed (2013) that when participants start to drive a simulator, an extra mental workload is imposed on the person and it lasts until participants refined their skills and strategies. Overall, these results suggested that the *dynamic* configuration was more demanding than the *reduced motion* one, but just during the adaptation process, as confirmed by psychophysiological, performance and subjective measures.

As to question (b) (i.e. "Within and between the configurations are there any differences between single (*t1*, *t2*, *t3*, *t6*) and the dual (*t4*, *t5*) task?"), results indicated that the mental arithmetic task could successfully perturb the riding task. Higher levels of mental workload were found in the dual task, as confirmed by the large majority of the DVs. As to the configuration comparison, no differences between the two configurations were found in the dual task, suggesting that participants were perturbed in a similar way by the introduction of a secondary task independently from the configuration.

At last, results from subjective evaluation showed the *dynamic* configuration to be more realistic than the *reduced motion* one. Participants preferred the *dynamic* configuration even if the *reduced motion* configuration was found to be easier to familiarize with. The positive evaluation of the counter steering configuration is in line with Stanney, Kingdon, Graeber, and Kennedy (2002) who showed that higher degrees of freedom should be privileged to maximize experience in VR systems. Coupled with objective measures, our findings are in contrast with those of Stedmon et al. (2011) who showed positive steering to be preferred to counter steering. This difference could be explained by the fact that the *dynamic* configuration does not consist of neat counter steering rather allow a progressive transition between positive steering and counter steering.

5. Conclusion

According to Stedmon et al. (2011), simulators should offer an abstraction from the real world, in which users can experience characteristics of a real system. The results showed the *dynamic* configuration to have higher validity. This configuration, which simulates the effect of the rider leaning and allows a progressive transition between positive steering and counter steering, capitalized the potential of our parallel simulator. In the light of these findings, we suggest that parallel and serial mechanical platforms based simulators might be preferred to reduced motion ones, as they could potentially replicate with more realism the behavior of a real motorcycle, making the simulator a valid research instrument. The limitations of the current study might be concerned with the absence of real world comparisons. To the best of our knowledge, only one remarkable study by Cossalter et al. (2010) compared riding simulator performance in terms of trajectory to that in the real world; however no statistical analysis was carried out since just two skilled riders performed the test. If it is true that real-world comparison is a key element for the validity of riding/driving simulators, it can lead to problems with confounds and with noise in the data (Carsten, Kircher, & Jamson, in press). Real-world comparison is useful only if reliable instruments for recording unfailing data are developed (Espié, Boubezoul, Aupetit, & Bouaziz, in press).

The encouraging results from this experiment showed the LCT to be a reliable tool for studying task demand on a motorcycle simulator. Although the LCT has been specifically designed to apply to the operation of a typical passenger car, our results suggest that it could be extended to the motorcycle simulation environment. Future studies should explore the effects of the configuration on riding performance in terms of trajectory control (e.g. Minin, Benedetto, Pedrotti, Re, & Tesauri, 2012).

Furthermore, results showed that riding performance is affected even when neither visual attention nor manual response are required, due to the increased cognitive workload generated by the conversation (Recarte & Nunes, 2003). These findings – in line with previous research on cars (Horrey & Wickens, 2006; Matthews, Legg, & Charlton, 2003; Mazzae, Ranney, Watson, & Wightman, 2004; Strayer, Drews, & Johnston 2003; Young & Regan, 2007) can have important practical implications for motorcycles.

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