Development and assessment of a tractor driving simulator with immersive virtual reality for training to avoid occupational hazards

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Abstract

Tractor overturns are the leading cause of fatalities in the agricultural sector. When drivers misuse the foldable roll over protective structure (ROPS) in tractors, it becomes highly inefficient as a rollover protection system. To solve this problem, the purpose of the present paper is to detail the development and assessment of a tractor driving simulator with immersive virtual reality for training to minimize this risk. In the agricultural sector, tractor driving simulators make it possible to train drivers in risk situations that are not feasible in the real field due to the high risk of roll over. The simulator includes a motion platform for this particular application. The findings of this study suggest that participants with safety knowledge make fewer errors in deploying the ROPS. To reduce the consequences of tractor accidents in the agricultural sector, the promotion of training courses is essential to avoid the misuse of the ROPS. On the contrary, the perception of risk and safety increased after the tractor driving simulator experience for all of the participants but increased significantly more so for non-frequent users of tractors. All of the groups of participants reported that the use of the tractor driving simulator was a positive experience because it can help them to drive more safely, and they feel that they need more training programmes in occupational safety.

Keywords: Tractor safety; Overturn; ROPS; Injury; Safety devices

1. Introduction

Tractor overturns are the leading cause of fatalities in the agricultural sector. In the European Union (EU), a survey conducted by the European Commission of EU member states revealed that 40% of serious injuries and deaths during tractor overturns occurred when a foldable roll over protective structure (ROPS) was not deployed into its protective position (Hoy, 2009). In the Region of Murcia (Spain), over the 2005-2012 period, there were 44 accidents with tractors, and in three of every four of those accidents, the ROPS was in the horizontal position (rest-unsafe) (Martin-Gorriz et al., 2012). Narrow-track tractors and standard tractors equipped with foldable ROPS are permitted in orchards and vineyards with the ROPS lowered. The tractor driver alone is responsible for keeping the tractor safe. However, due to their complicated ergonomics and the difficulty of handling by the operators, the ROPS tend to be left folded at all times. The consequence is clear: a misuse of the ROPS makes it highly inefficient as a rollover protection system.

New technologies offer favourable solutions to prevent the ROPS from being in its horizontal position when the tractor overturns (Powers et al., 2001; Silleli et al. 2007; Ballesteros et al. 2015). In the same context, Ojados et al. (2016) developed and tested an automatically deployable front-mounted ROPS for narrow tractors using hydraulic power. The safety device allows the automatic deployment of the ROPS when the tractor exceeds a specific tilt angle. In addition, the driver can deploy the ROPS when there is a risk of turning over. Following this research topic, the purpose of the present paper is to show the development and assessment of a tractor driving simulator with immersive virtual reality for training to minimize occupational hazards.

Immersive virtual reality has been widely used to train professionals in domains as diverse as firefighting (Cha et al., 2012), traffic (Backlund et al., 2007) and aviation safety (Chittaro and Buttussi, 2015). In addition, it is increasingly being used as a tool for training workers in tasks with risk, such as electric power network maintenance (Rosendo et al., 2011), or working in confined environments, such as the mining industry (Grabowski and Jankowski, 2015). Certain situations require motion platforms to simulate the real environment; typical examples of this are cars, boats and flights. Immersive learning experiences, according to some studies, have 90% retention of the knowledge in key messages compared to traditional training methods that provide a return of between 10% and 20% (Ruiz, 2015). In the agricultural sector, tractor driving simulators make it possible to train drivers in risk situations that are not feasible in the real field due to the high risk of roll over (Ochoa et al., 2016).

In this context, we developed and assessed a tractor driving simulator with immersive virtual reality for training in the prevention of this risk. The paper is organised as follows: Section 2.1 describes the tractor driving simulator focused on the appropriate use of the ROPS. Section 2.2 details the tests performed to achieve an assessment of our tractor driving simulator, and Section 2.3 describes the statistical analysis used. Section 3 provides an analysis of the results of the pilot test of participants in the tractor driving simulator. Finally, in Section 4, we summarise the primary conclusions drawn from our study and outline future work.

2. Materials and Methods

2.1. Tractor driving simulator

2.1.1. Virtual tractor design

The tractor model selected for the driving simulation was a CASE IH-2120 (CNH Industrial N.V., London, UK) because that model was the first commercial tractor onto which the automatic safety device was installed. This model is a narrow-type tractor designed specifically for working in vineyards and orchards (Fig. 1a).

A full three-dimensional tractor design was executed with Solidworks2014 (Waltham, Massachusetts, USA). The key components of the tractor were modelled, assembled and parameterised according to the technical specifications of the tractor. Finally, texture and rendering were applied to provide a realistic appearance (Fig. 1b). The next step was to calculate the physical properties (mass, centre of gravity and moment of inertia) of the components to ensure the real behaviour of the model. This process was conducted for the 45 key components of the tractor, e.g., tyres, axles, seat and steering wheel (Fig. 2), as well as the components of the deployable ROPS for manual and automatic activation (Fig. 3).

[Figure 1. insert here]

Figure 1. (left) real CASE IH-2120 tractor. (right) 3D model of CASE IH-2120 tractor.

[Figure 2. insert here]

Figure 2. 3D model of tractor components: a) rear axle with wheels; b) front axle; c) front wheel.

[Figure 3. insert here]

Figure 3. 3D model of ROPS components. (left) up position, (right) down position.

2.1.2. Virtual driving scenario design

The software package used to create a virtual reality system was Unity 5 (Unity Technologies, San Francisco, CA, USA). The version of Unity used for the development of the scene design included basic features, a powerful physics engine by NVIDIA PhysX, 3D audio and the possibility to add more than one user to interact with the created scenario. A route was designed where the driver faced situations entailing a risk of overturning. The virtual road was constructed using Unity road simulation software, which contained a large quantity of information on the virtual roads. Effort was taken to increase the degree of accuracy of objects to extend the authenticity of the scene. Additionally, a shed for the tractor and equipment, greenhouses, orchards, hedgerows of trees, terrace cultivation, sloping roads and roads crossing were added to the environment to create a more realistic and more informative driving environment simulation platform. Finally, the virtual tractor design (3D model of CASE IH-2120) with the physical properties described in the previous section was added to the scene design.

The route starts in the tractor shed, which has access to the main road. The route continues along a secondary road to a farm, where there are orchards, hedgerows of trees, greenhouses and terrace cultivation, which are accessed by driving up and down slopes. Along the route, the driver goes through places where it is mandatory to move the ROPS into the vertical position to guarantee the safety of the driver, e.g., driving on the main road or up and down slopes in terrace cultivation. In other places of the route, there is no risk of overturning, and the ROPS can be folded in order to avoid damaging the trees (Fig. 4).

[Figure 4. insert here]

Figure 4. Route plan in the virtual scene design.

Finally, in order to evaluate our tractor driving simulator, the following data were measured: (1) total driving time; (2) total time stopped on route; (3) number of times that the driver had not deployed the ROPS, despite being in places with a risk of overturning (8 times is the maximum value on the route); and (4) route plan pointing to the places of the errors of item (3).

2.1.3. Simulation motion platform

The motion platform was a 3-DoF (Degrees of Freedom) powered by three electrical motors. The platform can handle up to 200 kg and provides up to ±12° of pitch and roll motions and 100 mm of vertical displacement (ARTEC research team; Institute on Robotics and Information Technology and Communications, University of Valencia). The simulation motion platform was composed of a screen (3.2 m x 2.4 m) with a rear-projection system, a 3-DoF motion platform with a sensorised real-speed tractor on it, a passenger tractor seat, steering wheel and pedals (Fig. 5). As an auxiliary device, the motion platform has the ability to connect to virtual-reality goggles for a single user or a rear-projector located to the front, which offers the possibility of viewing the scene both by the driver, as well as by other viewers. Oculus Rift (Oculus VR, Menlo Park, CA, USA) was used with a 110° horizontal field of view. Sound is also integrated into the simulator in the form of a 5.1 surround-sound system. It should be noted that a safety belt is incorporated in the platform for its mandatory use. The goal is to prevent the risk of falling off the platform, and the use of safety belts is encouraged in addition to seat belt use in tractors, since safety belts are currently not mandatory in Spain, but their use is advisable for safer driving.

The visual system, the motion platform, the operator console and the sensorised interface are controlled by a Workstation PC, with an Intel C612 processor, 2.1 GHz CPU, 16 MB of RAM, 8Gb of DDR3 memory and an NVIDIA M4000 graphics card with PhysX support. The OS is 64-bit, Windows 7 Professional.

[Figure 5. insert here]

Figure 5. Motion platform. (left) front view, (right) side view.

2.1.4. Integration of components

Unity 5 enables the virtual tractor design (section 2.1.1) to be integrated with the virtual driving scenario design (section 2.1.2) and the simulation motion platform (section 2.1.3). As a result, a tractor driving simulator (TDS) with immersive virtual reality was developed and manufactured for training tractor drivers in occupational risk prevention (Fig. 6).

A virtual driving scenario for tractors with foldable ROPS was developed. To begin the test, the driver will rise to the tractor, buckle up the seat belt and begin driving. Along the route by the farm, the road goes up and down slopes, and there is a risk of overturning. As the driver must compulsorily pass through these areas with the ROPS in its vertical position, two possible options are available: (1) manual deployment of the ROPS by pressing a button on the console when the driver recognises a risk situation or (2) automatic deployment of the ROPS without the intervention of the driver when the risk of overturning is imminent. The driver in option (1) needs to stop the tractor to deploy the ROPS, and in option (2), the safety device automatically deploys the ROPS when the tractor exceeds a specific tilt angle; it is not necessary for the tractor to be stopped. As soon as the route is finished, the test results are projected onto the screen (Fig. 7).

[Figure 6. insert here]

Figure 6. Participant driving the simulation motion platform.

[Figure 7. insert here]

Figure 7. Screen with the results of a participant’s test.

2.2. User evaluation

To evaluate the use of immersive virtual reality for training in the prevention of occupational hazards, a sample of people were invited to test the tractor driving simulator (TDS) at two places: (i) the technology park of Fuente Alamo in the *Universidad Politécnica de Cartagena* building and (ii) a rural community fair in Torre Pacheco (FAME INNOWA 2017) in southeast Spain. The TDS was used as an educational aid in master's degree courses (e.g., master's degree in occupational risk prevention) and training courses concerning occupational safety and health for farmers.

The research project was orally explained to participants. Before starting the test, each participant was orally instructed regarding safe driving on tractors. In the TDS, two assistance levels were established for the elevation of the foldable ROPS. In the first level, the driver decides to change the ROPS' position, and this change is made using the manual activation on board. In the second level, an automatic change to the operative position occurs in situations of impending rollover without the driver's intervention. During testing, the researcher stood behind the motion platform and communicated with the participant. Testing lasted approximately 10 minutes for each participant. When the test finished, a summary of the most important results achieved by the participant appeared on the screen. These results were later discussed between the researcher and the participant.

After the simulator tests concluded, participants were asked to complete a follow-up questionnaire. The first section of the questionnaire contained several questions regarding demographic information. The second section contained 10 questions regarding tractor experience, size of the tractor most often operated, ROPS type of that tractor and how to use it, tasks most often done with the tractor, how they learned to operate tractors, frequency of tractor usage, and occupational safety and health knowledge. These questions were used for establishing the statistical analysis. Finally, participants were asked to assess the activity (the perception of the risk before and after the test), TDS evaluation and their opinion regarding the experience.

The participants were offered the option of submitting written comments after participating in this research project. Participation was limited to individuals aged 16 years and above. Not all participants answered all questions.

The participants ($n = 127$) were categorised into three groups according to safety knowledge and their experience with tractors: Group 1 ($n = 37$), students with “safety training courses”; Group 2 ($n = 39$), farmers with “experience in driving tractors”; and Group 3 ($n = 51$), “without experience in driving tractors”. Group 3 consisted of participants in the rural community fair who could not be included in the two previous groups.

2.3. Data analysis

Statistical analyses of the data were performed with a standard analysis of variance (ANOVA) using Statgraphics software (Statpoint Technologies Inc, Warrenton, VA, USA). Unless otherwise noted, the results are given as the mean ± SD. When a significant ($P < 0.05$) treatment effect was observed, the mean values were compared using the Scheffe’s test ($P < 0.05$), and significant differences ($P < 0.05$) within each group are indicated by different lower-case letters (a, b). Only data for participants who had valid data for the dependent variables were analysed and presented in this report. This procedure provided a sample size (n) of 127. However, not all participants answered all the questions in the survey and, consequently, the sample size varied for different analyses.

3. Results and Discussion

3.1. Characteristics of participants

One hundred twenty-seven subjects participated in this study. Participants ranged from 16 to 56 years old. Children under 16 years old were not allowed to participate in the test. In the three groups, the most frequent age was between 22 and 24 years old (Table 1). The vast majority of the total participants were male (73.23%), and by groups: 64.86% in group 1, 82.05% in group 2, and 72.55% in group 3.

Questions regarding the use of video games and having a driving license were asked to evaluate their possible relationship with the results of the tests regarding the realism of the simulator in general or of driving skills. Forty-three percent of the participants were regular users of video games. The group without experience in driving tractors was the one that played more video games (47%). With regard to the driving license, 85% of the total participants had one and hence were accustomed to driving a car (steering wheel, throttle, reverse).

[Table 1. insert here]

Table 1. Characteristics of participants.

3.2. Tractor driving simulator results

The measurement of the total driving time of the test showed the driving ability of the participants. The participants that commonly used video games completed the test in less time than non-users (397.2 s and 428.1 s for video games users and not video games users, respectively). There were no statistically significant differences among groups for the participants who used video games (Table 2). Nevertheless, for the participants who were not users of video games, the results showed that there were differences in the total time required to complete the test among groups (P value= 0.0012). Group 1, “safety training courses”, needed more time to do the test than the other two groups. There were no statistically significant differences between group 2, “experience in driving tractors”, and group 3, “without experience in driving tractors”. A possible explanation for this result was that the non-video game users needed more time to become accustomed to the driving of the TDS. This result indicated that the participants who were not accustomed to the use of new technologies required extra time to perform the test. This factor should be taken into account in subsequent tests to avoid possible masking of results.

[Table 2. insert here]

Table 2. Results of tractor driving simulator by groups.

A participant could make a maximum of eight errors in the test. An error was considered to be when the ROPS was not deployed (safety position) in slope areas and on roads. Mean errors in the test were 3.5 out of 8. This suggested that the participants understood the safety instructions that the researchers had explained prior to starting the test. However, with 95% confidence, the results showed that the group 1 students with “safety training courses” made fewer errors in deploying the ROPS than the group with experience in driving tractors and the group without experience in driving tractors (P value = 0.0045) (Fig. 8). A possible cause for groups 2 and 3 showing a higher value was that group 1, being safety students, were potentially more primed to choose a safety response than were the other two groups. It is important to note that according to Brahm and Singer (2013), training is effective in reducing accidents.

[Figure 8. insert here]

Figure 8. Errors in deploying the ROPS by groups. Bars are mean ± Std. error. Different letters indicate statistically significant differences ($P < 0.05$).

3.3. Results regarding perception of the risk and safety

After the simulator tests concluded, participants were asked to assess the activity. In relation to question 1, regarding the increase in the perception of risk after this activity, the scores of groups 1 and 3 were very similar, being 84% and 86%, respectively. Thirty-one out of 37 participants in group 1 and 44 out of 51 participants in group 3 said “yes.” Consequently, there were no significant differences between groups 1 and 3 (Table 3). In group 2, “experience in driving tractors”, the number of participants that increased their perception of risk after the test was 22 of the 39 participants (56%). One possible interpretation of this result may be that the participants with experience in driving tractors had already been aware of the risk.

In any case, this experience was highly positive, as a mean 76% of the participants increased their perception of the risk after taking this activity. Similar results have been found by Tillapaugh et al. (2010), suggesting that the use of driving simulators for tractors showed an educational benefit because several participants indicated that they would probably reconsider their safety while they were operating on steep slopes.

Regarding question 2, concerning working safely in the future, there were no significant differences among groups (Table 3). After this experience, 101 of the 127 participants (80%) stated that they will consider working more safely. This result supported the idea that training in risk prevention is highly appreciated by the participants.

For question 3, “Do you feel that you need a training course in occupational safety?”, there were no significant differences among the three groups. Nevertheless, group 1 presented the lowest value compared with groups 2 and 3, which showed similar percentages. In group 1, 21 of the 37 participants said “yes” (57%), versus 28 of the 39 participants in group 2 (72%), and 38 of the 51 participants in group 3 (75%) (Table 3). The lowest value in group 1 could be observed because this was a group of occupational safety students. To assess whether the economic cost of the training course could be a handicap to do it, the participants who had responded positively to question 3 were also asked if they would do a training course if it were free of cost. The answer was positive for 100% in groups 1 and 3 and for 89% in group 2.

[Table 3. insert here]

Table 3. Results about perception of the risk and safety.

3.4. Opinion regarding the experience

At the end of the questionnaire, three general questions were asked to gather opinions about the experience. Table 4 shows the results of the three questions that participants were asked. The general opinion of the participants regarding the experience was very positive with mean scores of 9.42 (enjoyable), 9.27 (useful) and 8.74 (learning) out of 10 points.

With regard to the first question (enjoyable experience), there were significant differences between groups 3 and groups 1 and 2 (Table 4). For the participants of group 3, it was a more enjoyable experience. One possible interpretation of this result may be that the age of the participants of group 3 included younger people, and such people usually enjoy these experiences more. Approximately 24.6% of participants in group 3 were under 30 years old versus 18.25% and 19.84% in groups 1 and 2, respectively.

No significant differences were observed among groups with regard to the usefulness of the experience (Question 2, Table 4). The simulator was a useful training tool with a mean score of 9.27 notes of 10 points.

Regarding the last opinion (Question 3) regarding the learning experience, the lowest score was for group 2, “expert in driving tractors”. A comparison between group 2 and groups 1 and 3 demonstrated significant differences. Participants were offered the option to submit written comments after participating in the experience. Several group 2 participants commented, “This is my daily work". This comment reinforced the lowest score for group 2.

[Table 4. insert here]

Table 4. Opinion regarding the experience.

4. Conclusions

A tractor driving simulator was developed and constructed with a particular focus on the appropriate use of the ROPS. A sample of people was invited to a pilot test in order to evaluate the use of this tractor driving simulator for training programmes to minimize occupational risk. The following conclusions were drawn:

- Those participants who were students of training courses made fewer errors in deploying the ROPS;
- The perception of risk and safety increased after the tractor driving simulator experience for all of the participants but significantly more so for non-frequent users of tractors;
- In the opinion of the participants, the use of the tractor driving simulator can help them to drive more safely; and
- All participants considered the training to be a very positive experience.

Future work on the TDS will be to design a virtual driving scenario with overturning experience to raise awareness of risk. According to the comments made by the participants in the pilot test, those that had experienced a real overturn with the tractor in the field never forgot it. However, the major limitation to designing this future virtual driving scenario will be the slope degree according to overturning. We are aware that a 12-degree slope is not sufficiently steep for overturning a tractor in a real situation.

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Figure 1. (left) real CASE IH-2120 tractor. (right) 3D model of CASE IH-2120 tractor.

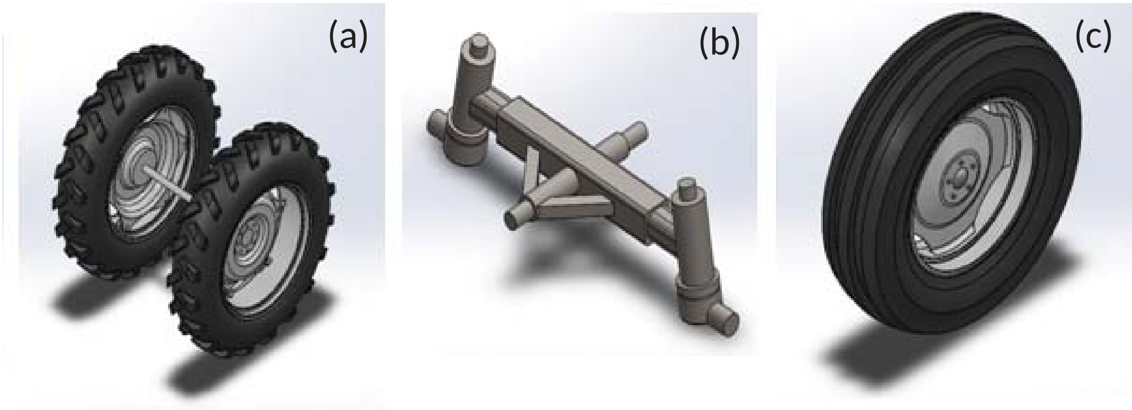

Figure 2. 3D model of tractor components: a) rear axle with wheels; b) front axle; c) front wheel.

Figure 3. 3D model of ROPS components. (left) up position, (right) down position.

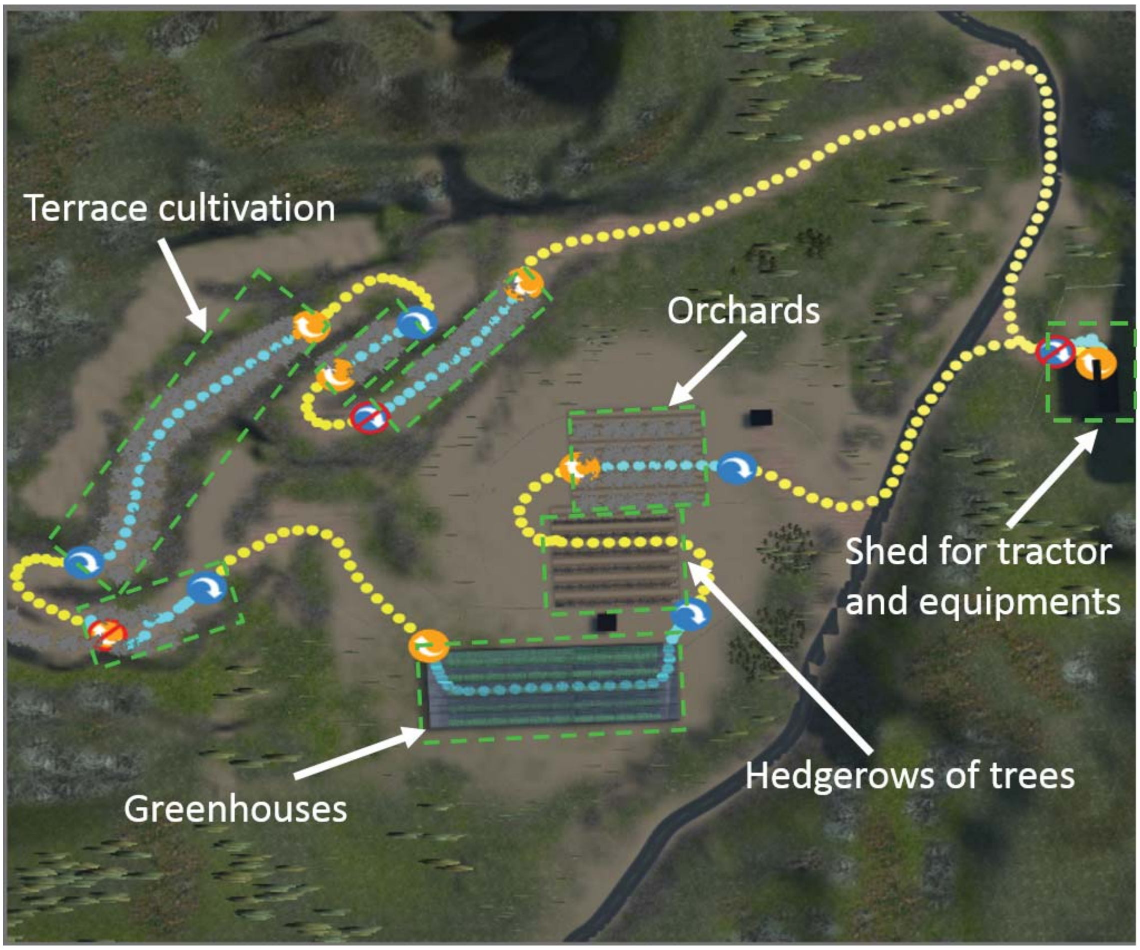

Figure 4. Route plan in the virtual scene design.

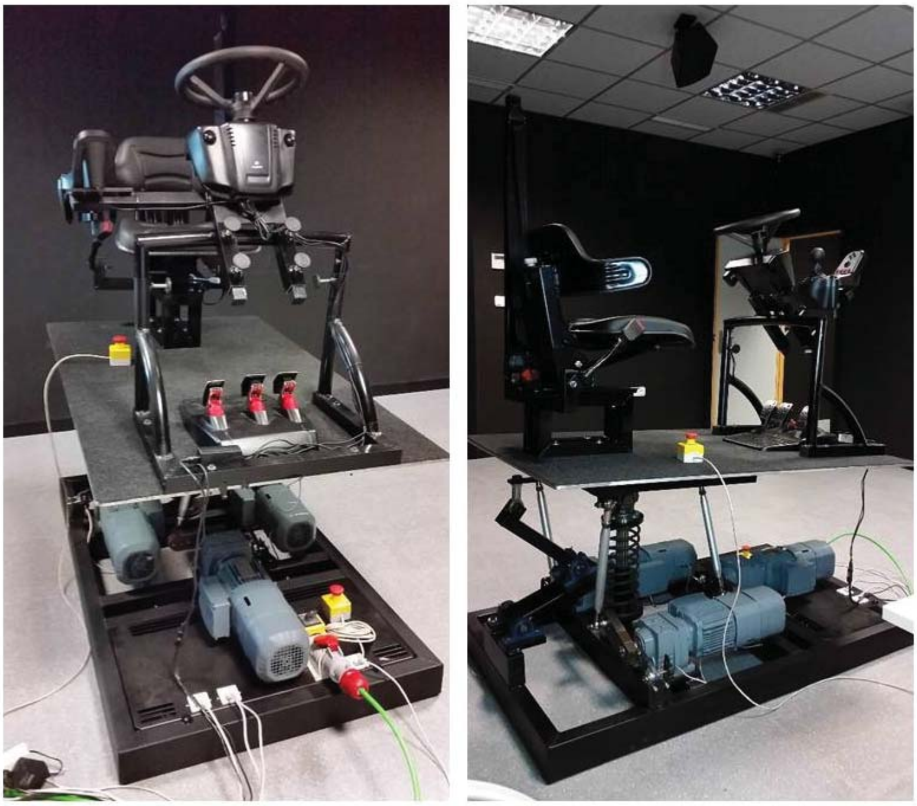

Figure 5. Motion platform. (left) front view, (right) side view.

Figure 6. Participant driving the simulation motion platform.

Figure 7. Screen with the results of a participant’s test.

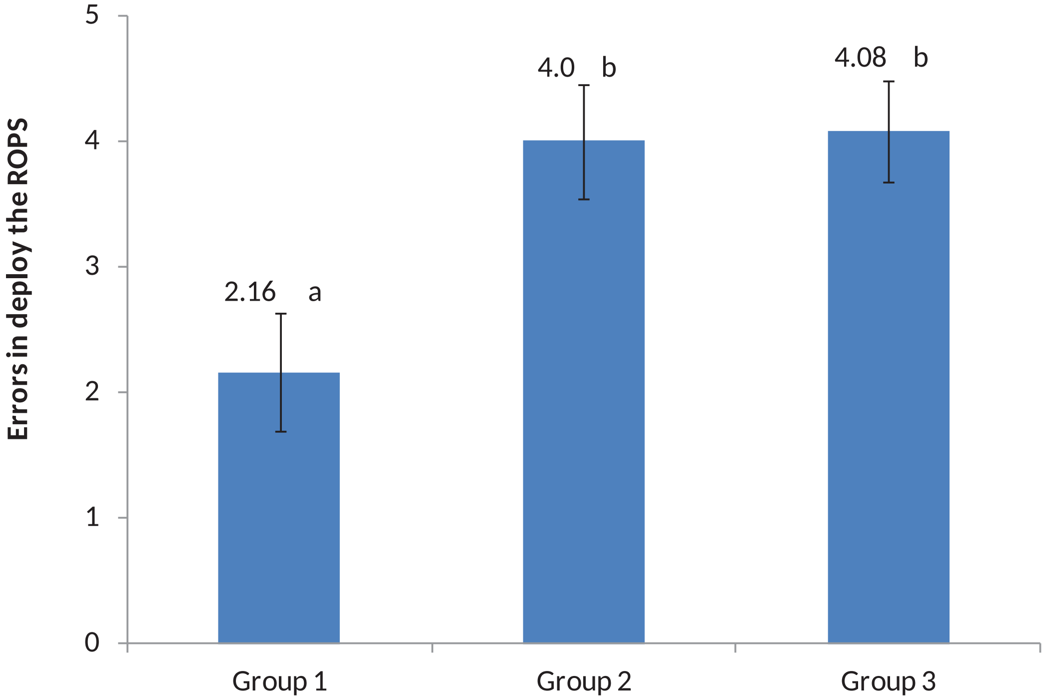

Figure 8. Errors in deploying the ROPS by groups. Bars are mean ± Std. error. Different letters indicate statistically significant differences ($P < 0.05$).

Table 1. Characteristics of participants.

Items	Group 1. Safety training courses (n = 37)	Group 2. Experience in driving tractors (n = 39)	Group 3. Without experience in driving tractors (n = 51)	Total (n = 127)
Mean age (range)	31 (21-51)	28 (16-56)	29 (16-56)	30 (16-56)
Mode age	24	23	22	24
Gender (male/female)	24/13	32/7	37/14	93/34
Video games user (%)	32	46	47	43
Driver’s license (%)	97	79	80	85

Table 2. Results of tractor driving simulator by groups.

Variable	Factors	Group 1. Safety training courses	Group 2. Experience in driving tractors	Group 3. Without experience in driving tractors	Mean	F Ratio	P Value
Total driving time (s)	Video games user	402.3 ± 27.4 a	422.1 ± 22.4 a	376.1 ± 19.4 a	397.2	1.23	0.3016
	No video games user	479.8 ± 17.5 b	419.0 ± 19.0 a	387.4 ± 16.8 a	428.1	7.43	0.0012

Mean ± Std. error. Mean values denoted by a different letter were significantly different at $p < 0.05$ level by ANOVA testing conducted with Scheffe's test.

Table 3. Results about perception of the risk and safety.

Questions	Group 1. Safety training courses (n = 37)	Group 2. Experience in driving tractors (n = 39)	Group 3. Without experience in driving tractors (n = 51)	Mean (n = 127)	F-Ratio	P-Value
1. Have you increased your perception of risk after this experience? (0 = no, 1 = yes)	0.84 ± 0.07 b	0.56 ± 0.06 a	0.86 ± 0.06 b	0.76	6.78	0.0016
2. Will you drive more safely after this experience? (0 = no, 1 = yes)	0.84 ± 0.06 a	0.67 ± 0.06 a	0.86 ± 0.06 a	0.80	2.97	0.0551
3. Do you think that you need a training course in occupational safety? (0 = no, 1 = yes)	0.57 ±0.08 a	0.72 ±0.07 a	0.75 ±0.06 a	0.69	1.71	0.1845

Mean ± Std. error. Mean values denoted by a different letter were significantly different at $p < 0.05$ level by ANOVA testing conducted with Scheffe's test.

Table 4. Opinion regarding the experience.

Questions	Group 1. Safety training courses (n = 37)	Group 2. Experience in driving tractors (n = 39)	Group 3. Without experience in driving tractors (n = 51)	Mean (n = 127)	F-Ratio	P-Value
1. Did you have an enjoyable experience? (0 = very bad 10 = very much)	9.14 ± 0.13 a	9.26 ± 0.12 a	9.75 ± 0.11 b	9.42	7.96	0.0006
2. Do you consider the experience to be useful? (0 = very bad 10 = very much)	9.11 ± 0.13 a	9.13 ± 0.13 a	9.49 ± 0.11 a	9.27	3.42	0.0359
3. Do you feel that you have learned with the experience? (0 = very little 10 = very much)	8.97 ± 0.22 b	8.26 ± 0.21 a	8.94 ± 0.19 b	8.74	3.77	0.0259

Mean ± Std. error. Mean values denoted by a different letter were significantly different at $p < 0.05$ level by ANOVA testing conducted with Scheffe's test.