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Evaluating the effectiveness of a novel virtual driving training system for people with lower limb disabilities

Min-Chi Chiu[1], Hsin-Chieh Wu[2], Yung-Ping Liu[2*], Wei-Hsien Hong[3]

[1] *Department of Industrial Engineering and Management, National Chin-Yi University of Technology, Taichung, Taiwan, R.O.C.*
[2] *Department of Industrial Engineering and Management, Chaoyang University of Technology, Taichung, Taiwan, R.O.C.*
[3] *Department of Sports Medicine, China Medical University, Taichung, Taiwan, R.O.C.*

ABSTRACT

In this study, a virtual driving training system was developed; it allowed people with lower limb disabilities to practice driving. The effectiveness of the virtual driving training system in people with lower limb disabilities and adults without disability was evaluated. Nine people with lower limb disabilities (group A) and 10 adults without disability (group B) were invited to participate in a 10-h virtual driving training program. A virtual driving license examination was conducted before and after the training program to evaluate whether the system was effective. The results indicated that the driving performance of the two groups improved after the training program. Both groups opined that driving had become easy after using the system. However, group A performed better after training than group B. Thus, people with disability require more driving practice than people without disability.

Keywords: Driving simulation; Virtual reality; Human factor evaluation.

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Corresponding Author:
Yung-Ping Liu
ypliu@cyut.edu.tw

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1. INTRODUCTION

The American Community Survey estimates that the overall rate of people with disabilities in the United States in 2015 was 12.6%, of which 28.3% had ambulatory disability (Kraus, 2017). Most of the people with ambulatory disabilities have lower limb disabilities. Driving can enhance their quality of life (Kiyono et al., 2001). In general, for a person with disability, the driving assessment process begins when a client is referred to a driving evaluation service, where a trained occupational therapist or other health professional performs the evaluation. Driving assessment for persons with disability is multidimensional and time consuming (Korner-Bitensky et al., 2006). For people with lower limb disabilities, going to a driving school is inconvenient. In addition, people with lower limb disabilities cannot use foot pedals to accelerate or stop; a car driven by people with disabilities should be modified and include hand-controlled mechanisms for acceleration and braking. If people with lower limb disabilities are deemed suitable for learning driving after evaluation, modified cars with hand-controlled levers are used to provide professional driving training. Driving licenses are provided on successful completion of training.

Studies have indicated that learning to drive in a simulator could be a viable solution for individuals with disabilities because it provides hazard-free real-road practice (Wilson et al., 1997). Teaching driving to a person with lower limb disability requires more time and energy than teaching a person without disability. Virtual reality (VR) technology and driving practice on a simulator can be used to impart initial driving training. Once the participant becomes proficient in driving with the modified controls, the time required for training in real cars can be reduced, consequently reducing the time required for obtaining a driving license. VR uses three-dimensional (3D) visual simulation techniques (Wu et al., 2015). VR is used extensively in business, military, manufacturing, design, medical treatment, and training. Currently, driving simulators are generally used in automobile system development and testing as well as in engineering and driving behavior safety research. For example, Kim et al. (2019) used a VR driving simulator for providing automatic objective data and evaluated driving distraction and safe testing environments.

In rehabilitation hospitals in South Korea, driving simulators have been used for driving training and improvement of driving skills (Ku et al., 2002). The results revealed that 73% of people expressed reduced fear of driving. Tudor (2015) developed a dynamic driving simulator using drive-by-wire (DBW) controls; it is an electromechanical system, and its working principle involves converting electric signals to mechanical signals by using actuators. He revealed that the driving simulators are useful tools for adaptive driving systems because they allow users to test different control devices and practice driving without the dangers associated with being on road, and they provide a safe method for evaluating the driving abilities of drivers with disability. In Taiwan, Sung et al. (2012) revealed that the virtual environment considerably affects the progress of driving rehabilitation and suggested that incorporating VR into rehabilitation programs accelerates the recovery of a patient's driving competence. Driving simulator training for people with spinal cord injuries can reduce their fear of driving and facilitate their rehabilitation.

However, most studies have simulated general road conditions to provide users with driving practice. Few studies have simulated the actual driving license examination venue and its test items. In this study, a virtual driving training system was developed for people with lower limb disabilities to practice driving the test items of the license examination, which allows them to become familiar with the process of the driving license examination and enhances their confidence when driving a car. The purpose of this study was to evaluate the learning effectiveness of the virtual driving training system in people with lower limb disabilities. The training program comprised a 5-day course with 2-h practice sessions per day on the virtual driving training system.

2. METHODS

2.1 Equipment

A desktop computer, portable projector, projection screen (120 × 120 cm), steering wheel, throttle and brake (Logitech G25), refitted hand-controlled controller (Fig. 1) with a forward push mechanism for acceleration and down push mechanism for braking, and the Virtools Dev 4.0 software package were used in the system.

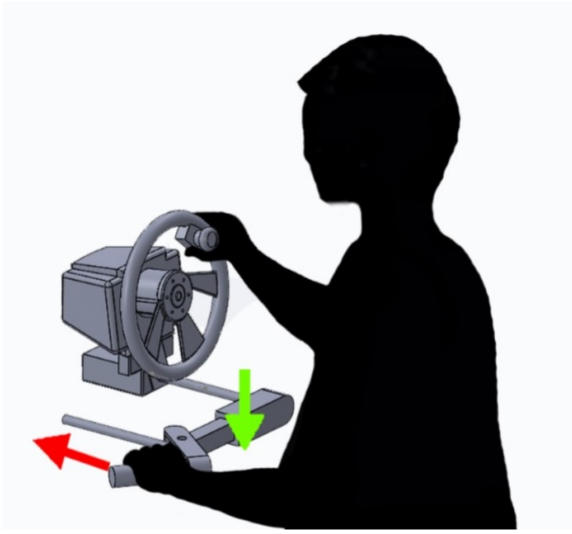

Fig. 1. Refitted manual controller (red arrow/pushing forward corresponded with acceleration, whereas green arrow/pushing down corresponded with braking)

2.2 Construction of the Virtual Field

The virtual field was constructed using Virtools Dev 4.0 according to the scale of an actual driving training class using 3D Max, as depicted in Fig. 2. The test items in this study were consistent with the actual road test items used in Taiwan. The tests included eight simulated driving training items, that is, S-shaped forward and backward movement, reversing the car into a garage, performing parallel roadside parking, moving up and down a hill, railroad crossing, forked road intersection (traffic lights), crosswalk (flashing yellow lamp), and stability when changing gears (linear acceleration). Subjects were asked to randomly complete the following eight tasks:

1. S-shaped forward and backward movement: drive forward or backward along an S-shaped curve and ensure that the car does not touch any curb or line.
2. Reversing the car into a garage: park in a garage (reversing 90° into the parking area and driving out) and ensure that the car does not touch the curb or line.
3. Parallel parking: parallel park on a road side parking area and ensure that the car does not touch any curb or line.
4. Moving up and down a hill: stop and start from a small hill, go up and down a hill, and ensure that the car does not touch any curb or line.
5. Railroad crossing: stop before the line railway crossing without touching the curb or line.
6. Crosswalk: slow down before pedestrian crossings and stop before the yield sign and traffic lights.
7. Forked road intersection: slow down before forked road intersections and stop before the yield sign and traffic light.
8. Stability when changing gears: driving on a straight road and practice smooth change of gears.

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Fig. 2. Virtual field for completing eight tasks established in this study

2.3 Experimental Environment

The length, height, and width of the desk used for the experimental environment were 70, 67, and 67 cm, respectively. The desk was located 180 cm away from the projection screen, and the projector was located 185 cm away from the screen. The subject was positioned 190 cm away from the projection screen. Fig. 3 depicts the experimental environment.

Fig. 3. Experimental environment

2.4 Dynamic Simulation Program Design

The following interactive features were added to the virtual scene to enhance the VR experience:

1. Sensing lines were used for various items. A warning was sounded if a wheel touched the sensing lines, and the counter would the number times the car touched a line.
2. Each of the eight items had criteria for deduction of points according to the regulations of the Taiwan driver's license examination. When a subject violated a regulation, the score board displayed deducted points immediately, a warning sound was heard, and the counter recorded the total number of line touches.
3. The virtual instructional car was a 3D car object from the Virtools software package; the user could use the camera setup function to switch between first- and third-person perspectives. The first-person perspective was adopted in the experiment to simulate the field range of real driving.

2.5 Training Effect Evaluation Test

2.5.1 Subjects

For the experiment, nine people (mean age = 34.8 years) with lower limb disabilities who could not drive were included into the experimental group, and 10 adults without disability (mean age = 22 years) who also could not drive were included in the control group. The subjects were required to be at least 18 years and to have no color blindness to qualify for the driving license examination.

2.5.2 Experimental Design

The performance of the subjects without and with disability before and after training on the virtual driving training system was compared.

The individuals without disability controlled the brake and throttle with their feet during the training process, whereas individuals with disability controlled the brake and throttle by using the refitted hand-controlled controller. A virtual road test was conducted before and after training, and driving performance was evaluated and subjective assessments were conducted during the road test process. In the driving performance assessment, points were deducted for violations, and the number of violations and the driving time were recorded. The number of points deducted from a full score of 100 for a violation depended on the severity of the violation. For example, in the task of parallel parking, a flameout resulted in the subtraction of 8 points, a curb or line touch resulted in the deduction of 16 points. The subjective assessment included a subjective difficulty rating according to the NASA Task Load Index. The control variables included the simulated driving environment temperature inside common cars (26 ± 1°C). Furthermore, none of the subjects had a driver's license. A set of speakers was used to imitate sounds typically occurring on roads.

2.5.3 Experimental Procedure

The driving simulator system and other experimental equipment were preset to a predetermined module. The experimental process, experimental objective, and other related precautions were explained to the subjects before they signed the letter of consent for the experiment for providing their basic data.

When the formal experiment began, to prevent subjects' unfamiliarity with the driving simulator's operation from influencing the experimental results of subsequent formal driving training, the subjects were given 30 min to practice. If a subject's driving was unstable, he or she was allowed to continue practicing until they had become sufficiently proficient to proceed with the tests. The subjects were required to complete the aforementioned eight test items. The road test score after training was obtained using the built-in program. The experiment was stopped immediately if the subjects experienced any discomfort during the experiment. After the first test, the subjects filled the subjective evaluation after the experiment and NASA-TLX (task load index).

After the initial experiment, the subjects participated in 2-h sessions per day for 5 days. The second virtual road test was conducted after these 5 days of training, and the subjects were required to complete the eight test items again. Once the experiment was completed, various experimental data, including objective performance (deducting points for violations and recording the number of violations and the driving time) and subjective ratings (NASA-TLX) were collected to compare them and determine the training results. For deducting points for violations, it depends on the severity of violation status and each violation occurs will be subtract from the full scores (100 points) continuously. For parallel parking, if the car touches any curb or line, it deducts 16 points, forget to turn on direction light while turning, it deduces 2 points. For number of violations, it summarized how many violation times.

2.5.4 Experimental Data Analysis

The collected experimental data were processed using Microsoft Excel and SPSS10.0. The descriptive statistics of various variables were calculated, and significant differences in driving performance and subjective assessments were then determined before and after training. Paired sample *t*-test analysis was adopted, with the significance level set at $\alpha = 0.05$. Furthermore, to test whether any significant differences existed in the performance of the participants without and with disability, independent sample *t*-test analysis was conducted, with the significance level set at $\alpha = 0.05$.

3. RESULTS

The analytical results revealed that the average number of points deducted in the virtual road test before and after training for the subjects without disability was 89.60 and 4.80, respectively. Furthermore, their average number of violations before and after training was 26.5 and 0.2, respectively, which was a significant decrease. The average

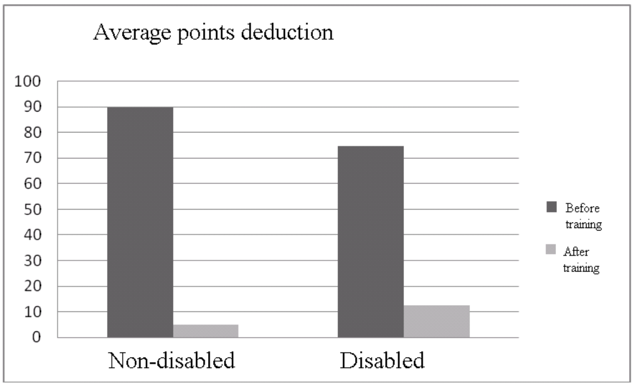

Fig. 4. Number of points deducted

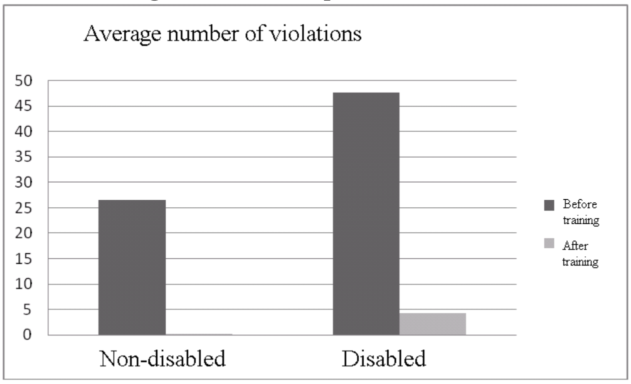

Fig. 5. Number of violations

number of points deducted for the subjects with disability before and after training was 74.67 and 12.44, respectively. Moreover, their average number of violations before and after training was 47.67 and 4.33, respectively, which was also a significant decrease. Figs. 4 and 5 illustrate the results.

Table 1 presents the driving time for various items before and after training. Statistical analysis results indicated that the total time spent by both subjects without and with disability on the virtual road test after 10 h of training reduced significantly (the average time saved for the subjects without and with disability was 226.9 and 357.89 s). The time spent by both subjects without and with disability driving on the S-shaped curve, reversing into a garage, parallel roadside parking, and moving up and down a hill reduced significantly after training, which revealed that driving skills such as driving on the S-shaped curve, reversing into a garage, parallel roadside parking, and moving up and down a hill can be improved by virtual driving practice. However, no significant differences ($p \geq 0.05$) existed for railroad crossings and traffic lights before and after training. Moreover, no significant differences ($p \geq 0.05$) existed in the time spent by the subjects with lower limb disability on flashing yellow lamps and linear acceleration before and after training. These results revealed that virtual driving practice has a limited learning effect on simple driving tasks.

Table 2 presents the results of the subjective difficulty level of various items before and after training. Statistical analysis results revealed that both subjects without and with disability perceived most of the items to be remarkably easier after training. However, people with lower limb disabilities exhibited no significant differences ($p \geq 0.05$) for railroad crossings, traffic lights, and flashing yellow lamps before and after training.

According to the NASA-TLX evaluation results, the mental load (9), physical load (5.8), time load (7.2), difficulty level (7.5), and frustration level (3.7) of the subjects without disability decreased after training, but the performance level increased (15.9). The mental load (7.9), physical load (4.3), difficulty level (5.3), and frustration level (5.3) of the subjects with disability also decreased after training, and the performance level also increased (16.89), as presented in Table 3.

4. DISCUSSION

For subjects without disability, the average number of points deducted in the virtual road test before and after training was 89.60 and 4.8, respectively. Furthermore, their average number of violations before and after training was 26.5 and 0.2, respectively, which was a significant decrease. According to the driving test criteria of the class, all subjects failed before training, whereas only one subject failed after training (32 points deducted). Notably, the average number virtual road test before and after training was 74.67 and 12.44 points, respectively. Furthermore, their average number of violations before and after training was 47.67 and 4.33, respectively, which was also a significant decrease. In this study, the individuals without disability controlled the brake and throttle using their feet, whereas the individuals of points deducted for the subjects with disability in the with disability controlled the brake and throttle by using the hand-controlled refit. The subjects without disability applying the brake and throttle pedals caused fewer violations but had more points deducted than subjects with

Table 1. Completion time of each test item

Test item	Group	Completion time (s)		Significance
		Before training	After training	p value
S-curve	Nondisability	154.80	49.00	0.01*
	Disability	281.33	157.56	0.04*
Reversing into a garage	Nondisability	84.30	40.70	0.01*
	Disability	244.89	87.89	0.04*
Roadside parking	Nondisability	81.00	37.60	0.00*
	Disability	120.78	70.56	0.01*
Moving up and down a hill	Nondisability	41.20	26.60	0.01*
	Disability	45.89	22.33	0.01*
Railroad crossing	Nondisability	24.70	22.20	0.13
	Disability	25.33	29.44	0.27
Traffic lights	Nondisability	20.10	15.10	0.05*
	Disability	28.67	26.33	0.73
Flashing yellow lamp	Nondisability	27.70	20.00	0.03*
	Disability	30.78	26.33	0.21
Linear acceleration	Nondisability	15.40	11.10	0.02*
	Disability	29.67	24.78	0.37
Total driving time	Nondisability	449.20	222.30	0.00*
	Disability	807.33	445.22	0.05

*p < 0.05 was considered significant.

Table 2. Subjective difficulty rating of each test item

Test item	Group	Subjective difficulty rating		Significance p value
		Before training	After training	
S-curve	Nondisability	4.20	1.70	0.00*
	Disability	4.67	2.22	0.00*
Reversing into a garage	Nondisability	3.80	1.60	0.00*
	Disability	3.78	2.33	0.00*
Roadside parking	Nondisability	3.70	2.00	0.00*
	Disability	3.78	1.89	0.00*
Moving up and down a hill	Nondisability	2.20	1.20	0.01*
	Disability	2.22	1.44	0.02*
Railroad crossing	Nondisability	2.10	1.00	0.00*
	Disability	1.78	1.22	0.05
Traffic lights	Nondisability	2.10	1.00	0.00*
	Disability	1.44	1.11	0.20*
Flashing yellow lamp	Nondisability	2.00	1.10	0.00*
	Disability	1.56	1.11	0.10*
Linear acceleration	Nondisability	2.00	1.10	0.02*
	Disability	2.00	1.11	0.04*

*$p < 0.05$ was considered significant.

Table 3. NASA-TLX evaluation result of each item

Evaluation item	Group	Score		Significance p value
		Before training	After training	
Mental load	Nondisability	13.50	9.00	0.03*
	Disability	14.44	7.89	0.00*
Physical load	Nondisability	8.50	5.80	0.12
	Disability	7.44	4.33	0.04*
Time load	Nondisability	9.90	7.20	0.10
	Disability	5.56	6.67	0.66
Performance level	Nondisability	7.90	15.90	0.00*
	Disability	10.22	16.89	0.01*
Difficulty level	Nondisability	13.80	7.50	0.01*
	Disability	10.33	5.33	0.02*
Frustration level	Nondisability	10.70	3.70	0.00*
	Disability	9.00	5.33	0.17

*$p < 0.05$ was considered significant.

disability. Even though more number of violations, but fewer deducting points for disability person using refitted manual controller. It implied that refitted manual controller could be better for disability individuals to precisely control the car avoiding severe point deduction. According to the driving test criteria of the class, all subjects failed before training, but only two failed after training (32 points deducted).

The total driving time of the subjects without disability before and after training was 449.2 and 222.3 s, that is, a difference of 226.9 s. By contrast, the total driving time of the subjects with disability before and after training was 807.3 and 445.2 s, that is, a difference of 362.1 s. The most significant differences in both groups occurred in the S-curve, reversing into a garage, roadside parking, and moving up and down a hill tasks.

The time spent by the two groups on the road test was considerably reduced after training because the subjects had become acquainted with the test process and conditions. However, significant differences existed between the groups in the total driving time; furthermore, the driving performance of the disability group after training was worse than that of the no disability group; 10 h of training was found to be insufficient for the disability group.

After 10 h of training, the average of specific test items for both groups was relatively low; that is, the virtual driving training system was satisfactory. In terms of the operation mode and degree of confidence enhancement, disability groups subjects were more satisfied with the system after training. In addition, significant differences existed in the evaluation results of the subjects for the difficulty levels of various items before and after training, which indicated the subjects opined that driving, especially the S-curve, reversing into a garage, and roadside parking tasks, was easier after training.

According to the NASA-TLX evaluation results, the mental load, physical load, time load, difficulty level, and frustration level decreased after training, but the performance level increased. The subjects' subjective cognition and determination were observed, and they were better acquainted with the driving operation after training, satisfied with their performance, and exhibited decreased frustration levels after training than before training.

Briefly, in this study, driving performance improved significantly after 10 h of training using the virtual driving training system. This system could help novice drivers become acquainted with various items of the road test more rapidly as well as master the road conditions, thereby reducing their number of violations, deducted points, and road test time as well as enhancing their confidence when driving a car.

According to this study, the virtual driving training system only required a computer, software, and a projection space. A large area is not required, and the drivers' safety could thus be enhanced. However, a virtual vehicle's space design differs from that of a real vehicle; for example, the simulated viewing angle of the rearview mirror is smaller, and the scene model is fixed. Therefore, when a person learns to drive using a virtual driving training system, practicing in a real vehicle is still necessary.

5. CONCLUSIONS

This study discussed whether the virtual driving training system is applicable to individuals without driving experience, and the conclusions are as follows:

1. The points deducted, number of violations, and driving time of both the subjects without and with disability improved after 10 h of training, which demonstrated that this system can help all individuals who lack driving experience.
2. According to the subjective evaluation questionnaire results, the confidence of the subjects in the two groups in driving a car was enhanced after virtual driving training.
3. The performance of the disability group was less advanced than that of the nondisability group after training. Thus, people with disability require more time to practice driving than people without disability do.

This study indicated that the virtual driving training system had a positive learning effect on adults with and without disability. Both groups exhibited significantly improved driving performance after training. Moreover, the limitations of this study include the simulator fidelity, predictive validity of driving simulators, and simulator-to-reality transfer of learning. Only eight driving tasks were simulated in this study. In future studies, additional road situations should be considered to improve the simulator-to-reality transfer of learning.

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