Validation of a driving simulator for driver distraction research on a two-lane highway

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Abstract

In the last years, a great deal of research has demonstrated that driving simulator studies can be a suitable alternative to field studies. However, a driving simulator must be correctly validated for each specific aspect of driver behavior such as speeds, steering control, driver response, etc.

This paper aims to investigate a behavioral validation of the interactive fixed-base driving simulator in order to verify the DGSIT driving simulator's usefulness as a tool for distraction research on a two-lane highway. Fifteen drivers were asked to complete three levels of a cognitive distraction task (n-back task) concurrently while driving either an instrumented vehicle or the simulator. The three pairs of distacted driving behaviors were analyzed in terms of absolute validity and relative validity. Results suggested that the participants' simulated driving behavior were not significantly different from the on-road driving behavior, establishing the relative validities. Especially, heart rate established absolute validity as well.

Keywords: Driving Simulator, Field Operational Test (FOT), Simulator Validation, Behavior Validity

Introduction

It is known that simulators are essential tools for driver assessment in any task where drivers may be exposed to actual driving hazards such as high probability of collision. Therefore, driving simulators have been extensively used for driver behavior research in a traffic situation. Researchers have demonstrated that simulators are effective tools for research on driving speed [1, 2], driver visual demand [3, 4], and older driver behavior [5]. However, validity of a simulator must be proved to be useful human factors research tools in terms of physical and behavioral validity [6]. Physical validity refers to the physical correspondence of the simulator's layout, parts and dynamics with its real world counterparts and it is often referred to as a simulator's fidelity [2]. However, previous studies suggested that physical validity could not be useful to human factors research if behavioral validity was not able to be established [2]. Thus, this study focused on behavioral validity, which is divided into two levels of validity, i.e. absolute and relative validity [1, 2, 7]. Absolute validity can be claimed when the numerical values between on-road and simulated driving conditions are identical, and relative validity can be proved when the differences between on-road and simulated experimental conditions are in the same direction, and have a similar magnitude [2].

This paper reports on a validation study of the DGIST fixed-base driving simulator for driver's cognitive distraction research by comparing driving performance decrements and behavioral changes under cognitively loaded driving conditions in a driving simulator and in the real world.

Method

Participants

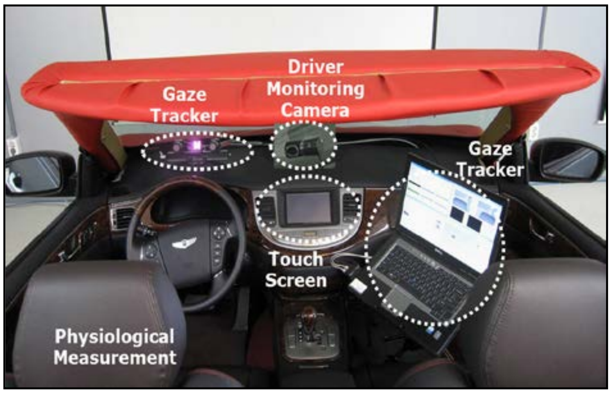
Fifteen male drivers were participated and they met the following criteria: age between 25-35 (M=27.7, SD=3.0), drive on average more than twice a week, be in self-reported good health and free from major medical conditions, not take medications for psychiatric disorders, score 27 or greater on the mini mental status exam [8] to have reasonable cognitive ability for performing a current secondary task while driving.

Experimental setup: Instrumented vehicle

The real world driving experiment was conducted in a full size sedan that was instrumented for collecting time-synchronized data [9]. The DGIST instrumented vehicle consists of six video cameras, i.e. two for recording driver behavior and four for monitoring road environment), a high speed CAN logger for driving information such as vehicle speed and steering wheel angle. A physiological measurement system was integrated to monitor a driver's heart rate and skin conductance level.

Experimental setup: Driving simulator

The simulator experiment was conducted in the DGIST fixed-based driving simulator. As shown in Fig. 1, the car cab was reproduced using the same OEM interior parts of the instrumented vehicle to establish physical validity. STISIM Drive™ software collected driving information including distance, speed, steering, throttle, and braking inputs at a nominal sampling rate of 30 Hz. Two cameras for recording driver behavior and a physiological measurement system were also integrated to observe a driver's behavior.



Note. Laptop was removed during simulation.
Figure 1. Interior of the DGIST driving simulator

Cognitive distraction

An auditory delayed digit recall task, i.e. n-back task, was used to generate periods of cognitive distraction at three different levels [10]. The n-back task requires drivers to say out loud the n^{th} stimulus back in a sequence that is presented via audio recording. The easiest n-back task is the 0-back where the participant is to immediately repeat out loud the last item presented. At the moderate level, i.e. 1-back, the next-to-last stimulus is to be repeated. At the most difficult level, i.e. 2-back, the second-to-the-last stimulus is to be repeated. The n-back was administered as a series of 30-second trials consisting of 10 single digit numbers (0-9) presented in a randomized order at an inter-stimulus interval of 2.5 seconds. Each task period consisted of a set of four trials at a defined level of difficulty resulting in demand periods that were each two minutes long.

Procedure

The overall procedure consists of two experiments, i.e. simulated driving and on-road driving, in two separate days. In the driving simulator experiment, participants received 10 minutes of driving experience and adaptation time in the DGIST fixed-base driving simulator. The simulation was then stopped and participants were trained in the n-back task while remaining seated in the simulator. When the simulation was resumed, participants drove about 37km of straight highway for about 20 minutes, and performed a concurrent secondary task at a specified area.

For the on-road experiment, following informed consent and completion of a pre-experimental questionnaire about safe driving (safety protocol), participants were trained in the n-back task again to remind the concurrent cognitive task. Then, participants received about 20 minutes of urban road driving experience and adaptation time on the instrumented vehicle. The highway driving experiment began when a subject was confident in safe driving with the instrumented vehicle. In a main experiment session, participants drove about 36km of highway for about 20 minutes. The secondary task was also performed while driving through a specified highway segment.

Results

The data for the two experiments were collected at a rate of 30Hz, and averaged during the distracted driving area. Then, the analyses examined simulator validation for both relative and absolute validity. A repeated-measures GLM (general linear models) were conducted to analyze drivers' performance and behavioral changes under cognitively distracted condition. The effect sizes were calculated using the omega squared (ω^2) statistics [11]. Godley et al. suggested that if ω^2 is small, e.g. ω^2 is less than 0.01, non-significant results can be confidently proclaimed to reflect non-differences [2].

Prior to driving behavior analysis, the secondary task performances in the two experiment conditions were compared. As shown in Table 1, the concurrent n-back task scores were very similar in the two experiments. The main effect for experiment type was not significant and there was also a very small effect size to corroborate on this non-significant results ($F(1,14)=0.05$, $p=.826$, $\omega^2=0$). Thus, it was confirmed that the concurrent secondary task loaded similar levels of cognitive distraction in both experiments.

Table 1. Relative values of drivers' performance and behavior for three levels of cognitive distraction

Variable		0-back	1-back	2-back
N-Back Score (%)	Sim	100.00 (2.56)	97.76 (4.94)	98.84 (4.17)
	Road	100.00 (7.20)	98.92 (5.06)	97.51 (8.23)

Note. Average with standard deviation in parentheses.

Relative validity

For examining relative validation, the data were averaged across each of three difficult levels of cognitive distraction areas for both the real world and simulated driving. Then, the averaged data were divided by the 0-back average values across three levels of cognitive distraction areas, respectively.

When comparing driving performance changes, the relative speed decrements under three different levels of cognitive distraction were similar in both experiments (see Table 2). A repeated-measures GLM yielded that the main effect for experiment type was not significant and an effect size was very small ($F(1,14)=0.002$, $p=.964$, $\omega^2=0$). The relative changes in the steering wheel reversal rate (SRR; see calculation details in Son et al. [12]) also gave similar result ($F(1,14)=.878$, $p=.365$, $\omega^2=0$). Thus, relative validity for driving performance such as the average speed and the steering wheel reversal rate under cognitive distraction was established.

Table 2. Relative values of drivers' performance and behavior for three levels of cognitive distraction

Variables		0-back	1-back	2-back
Speed (km/h)	Sim	100.00	97.76	98.84
		(2.56)	(4.94)	(4.17)
	Road	100.00	98.92	97.51
		(7.20)	(5.06)	(8.23)
SRR (count /min)	Sim	100.00	113.55	117.41
		(23.46)	(28.39)	(22.43)
	Road	100.00	104.95	108.80
		(16.33)	(20.07)	(22.25)
Heart Rate (beat /min)	Sim	100.00	102.91	106.76
		(18.64)	(18.70)	(19.63)
	Road	100.00	100.74	105.19
		(10.38)	(11.07)	(11.59)

Note. Average with standard deviation in parentheses.

For relative validity of driver behavior, the changes in heart rate under cognitive distraction were compared and observed similar patterns in both experimental results (see Table 2). A repeated-measures GLM analysis indicated that the main effect for experiment type was not significant and an effect size was very small ($F(1,14)=0.196$, $p=.664$, $\omega^2=0$). Thus, it was confirmed that relative validity for driver's heart rate change under cognitive distraction was established.

Absolute validity

For absolute validation, the averaged data across three difficult levels of cognitive distraction areas for both the real world and simulated driving were used. As shown in Table 3, cognitively distracted driving speeds were slower in the on-road experiment than the simulator experiment. A repeated-measures ANOVA indicated that the main effect for experiment type was significant and an effect size was not small ($F(1,14)=6.889$, $p=.020$, $\omega^2 = 0.101$). Steering wheel reversal rates (SRR) under cognitively distracted conditions were very similar in the two experiments. The main effect for experiment type was not significant and there was also a very small effect size to corroborate on this non-significant results ($F(1,14) = 1.168$, $p = .298$, $\omega^2 = 0.005$). Thus, absolute validity for driving performance was established for the steering wheel reversal rate under cognitive distraction, but the absolute value of the average speed was not proper measure for cognitive distraction research in a driving simulator study.

For absolute validity of driver behavior, the heart rate changes under cognitively distracted condition were analyzed and very similar increases in heart rate were observed in both experiments, as cognitive workload became higher (see Fig. 3.)

Table 3. Absolute values of drivers' performance and behavior for three levels of cognitive distraction

Variable		0-back	1-back	2-back
Speed (km/h)	Sim	98.63	96.42	97.49
		(2.52)	(4.87)	(4.11)
	Road	95.44	94.41	93.07
		(6.88)	(4.83)	(7.86)
SRR (count /min)	Sim	114.13	129.60	134.00
		(26.78)	(32.41)	(25.60)
	Road	128.00	134.33	139.27
		(20.90)	(25.69)	(28.48)
Heart Rate (beat /min)	Sim	80.86	83.21	86.32
		(15.07)	(15.12)	(15.88)
	Road	83.03	83.64	87.33
		(8.62)	(9.19)	(9.62)

Note. Average with standard deviation in parentheses.

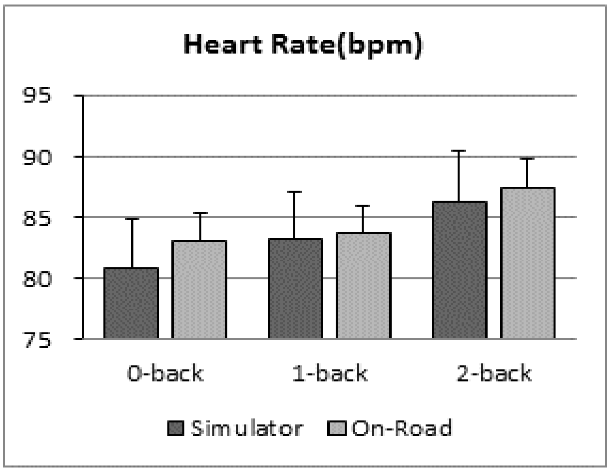


Figure 2. Heart rate changes under three levels of cognitive distraction

A repeated-measures GLM analysis indicated that the main effect for experiment type was not significant and an effect size was very small ($F(1,14)=0.109$, $p=.746$, $\omega^2=0$). Thus, absolute validity for driver's heart rate change under cognitive distraction was established. The result suggested that heart rate can be very useful measure for cognitive distraction research in both the real world and simulated driving conditions.

Discussion and Conclusions

In this study, simulator validity for cognitive distraction research was examined through the simulated driving and on-road driving experiments. Limited physical validity of the DGIST fixed-base simulator was established by applying the same interior parts and layout of the instrumented vehicle (see Fig. 1).

Results from this study were indicated that behavior validity of the DGIST fixed-base simulator was established in terms of absolute and relative validity. The average speed and the steering reversal rate were investigated as driving performance measures. The steering reversal rate, either relative or absolute value, was suggested as a promising measure for cognitive distraction research. However, the average speed, which is one of the most commonly used driver performance measures [5, 12, 13], was found that only relative validity was established in this study. Thus, the decrement of the average speed can be used as an effective measure for cognitive distraction research, but the absolute speed obtained from a driving simulator may differ from the on-road driving performance.

Heart rate was examined as a driver behavior measure, and found that absolute validity and relative validity were established. The result indicated that heart rate is one of the most useful measures for investigating a driver's cognitive workload for both simulated and real world driving as suggested in previous studies [14, 15, 16].

In summary, there is evidence to conclude that speed, steering reversal rate (SRR) and heart rate are valid measures to use for experiments on the DGIST driving simulator involving cognitive distraction. Especially, the absolute numerical values of the SRR and heart rate are also valid for driver distraction research.

However, it should be noted that behavioral validity of a driving simulator is highly dependent on a simulator's configuration parameters such as steering sensitivity, yaw rate scale factor, acceleration limit, deceleration limit, coefficient of drag, yaw instability, speed instability, and so on. Thus, it is recommended that results from a driving simulator study need to be examined behavior validity using the proposed procedural methods in this paper.

Acknowledgments

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