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An Experimental Investigation of Students' Learning Effects When Using a Simplified Nuclear Simulator

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ABSTRACT

This study aims to investigate students' learning effects and performance trends over a certain timeframe when using the Rancor Microworld simulator. Specifically, it focuses on generating insights into the amount of training required to collect human reliability analysis (HRA) data from non-experts (i.e., students) using Rancor Microworld. A longitudinal experiment was conducted with 16 undergraduate students in department of nuclear engineering at Republic of Korea. It consisted of four consecutive trials, each featuring four different Rancor Microworld scenarios. The study considers four human performance measures: workload, situation awareness, task completion time, and accuracy. Finally, the student performance trends were compared with the operator performance data collected from a previous experiment. The collected data were analyzed by ANOVA test. The result of study shows that the statistically significant deference in three human performance measures: situation awareness, task completion time, and accuracy due to the number of trials. Moreover, students' accuracy became similar to the level of actual operators. Overall, this research complements Idaho National Laboratory (INL)'s Simplified Human Error Experimental Program (SHEEP) framework for collecting HRA data, as the results provide insights into the training required to collect HRA data from non-experts, as well as into the human performance differences seen when comparing students with professional operators.

Keywords: Human Reliability Analysis Data, Simplified Simulator Study, SHEEP Framework, Rancor Microworld, Human Performance, Simulator Study

1. INTRODUCTION

Securing sufficient and appropriate data is critical for reducing uncertainty in human reliability analysis (HRA) quantification [1, 2]. Adequate HRA data allows for representative samples of variable human performance, and helps in estimating the possibility of human error under various scenarios [1]. However, the lack of appropriate data remains a major challenge in the field of HRA [3, 4]. Many nuclear power plant (NPP) utilities and regulatory agencies still rely on HRA methods that utilize Technique for Human Error Rate Prediction (THERP)-generated data from the 1980s—data in fact based on non-nuclear experience [5, 6]. Expert judgment is also used to supplement insufficient empirical and experience-based data [7].

For these reasons, various institutions and researchers have continued to collect HRA data. In current research, this is often accomplished using full-scope simulators. This method offers the advantage of allowing researcher to track the actions taken by operators under various conditions. Representative examples of this type of research include the U.S. Nuclear Regulatory Commission's SACADA (Scenario

Authoring, Characterization, and Debriefing Application) project and the Korea Atomic Energy Research Institute's HuREX (Human Reliability data Extraction) project [8, 9].

Idaho National Laboratory (INL) proposed its Simplified Human Error Experimental Program (SHEEP) to enable HRA data to be collected using small scale simulators and non-operators [10]. Data collection using full-scope simulators is resource-intensive, yet the amount of data obtained is relatively small. For example, preparing a full-scope simulator facility and hiring participants are expensive processes. Furthermore, experiments using full-scope simulators extend for a long period of time between the experiment preparation and the result analysis. The SHEEP framework, on the other hand, enable HRA data to be collected using fewer resources, thanks to the utilization of simplified simulators and non-operators (i.e., students). Within the SHEEP framework, INL and Chosun University have collaborated on previous studies [10-12] that compared human performance in light of expertise (i.e., actual operators vs. students), and simulator complexity (i.e., the simplified simulator Rancor Microworld vs. the Compact Nuclear Simulator).

To further support the SHEEP framework, the present study investigated students' learning effects and performance trends, as determined over consecutive trials using Rancor Microworld. The objective was to generate insights into the amount of training required before students could being producing generalizable HRA data. Furthermore, the students' performances were also compared to that of actual operators who participated in a previous study. This paper is organized as follows. Section 2 briefly introduce to the SHEEP framework. Section 3 describes how the experiment was designed to investigate students' learning effects. Section 4 presents the statistical analysis of the experimental results, then discusses those results. Finally, Section 5 presents the various conclusions that were reached.

2. SHEEP FRAMEWORK

The SHEEP framework provides a systematic approach for combining full- and small-scale data collection activities. INL’s implementation of the SHEEP framework is meant to complement—not replace—full-scope studies, and mainly aims to collect HRA data for estimating nominal/basic human error probabilities (HEPs) needed for the HRA quantification process. In fact, using a simplified simulator and student participants circumvents several of the challenges that plague full-scope studies. For example, the entry point for being able to collect HRA data is lowered, and large sample sizes can be acquired at reasonable cost and with minimal labor. But the biggest advantage over full-scope studies is that a high degree of freedom is guaranteed in designing the experiments [10].

Figure 1 presents an overview of the SHEEP framework. This framework can be divided into three steps: 1) identification of HRA items collectible in a simplified simulator; 2) treatment of the HRA items based on experimentation; and 3) integration of the data into the full-scope database and HRA methods. The first step classifies into two groups all HRA items collectible in either type of simulator: (1) items collectible in both full-scope and simplified simulators, and (2) items only collectible in simplified simulators.

The second step suggests how the relevant HRA items that were classified in the first step can be measured in experiments. For HRA items that are collectible in both simplified and full-scope simulators, this involves differentiating participant type (i.e., operator vs. student) and simulator complexity (i.e., simplified vs. full-scope). Specifically, this step entails collecting the qualitative and quantitative differences (e.g., human error mechanisms, HEPs, or performance-shaping factors) needed to develop full-scope inference models in the final step. In the case of HRA items that are only collectible in a simplified simulator, this step contributes to collecting new HRA data missed when using a full-scope simulator.

This final step integrates the experimental data obtained in the previous step into a comprehensive (i.e., full-scope) database for potential incorporation into HRA methods. In this step, inference models are developed based on differences stemming from participant type and simulator complexity. For further information on the SHEEP framework, refer to [10].

The goal of this study is to support the second step of the framework, in which the participants are differentiated in term of expertise. This study investigates students' learning effects meaning the performance improvements that come with each increment of gained experience. An experiment was designed to examine the student performance changes that occurred over consecutive trials conducted in Rancor Microworld. The overall trends in student performance were then analyzed for comparison with the operator performance trends detailed in the present authors' previous work [10, 11].

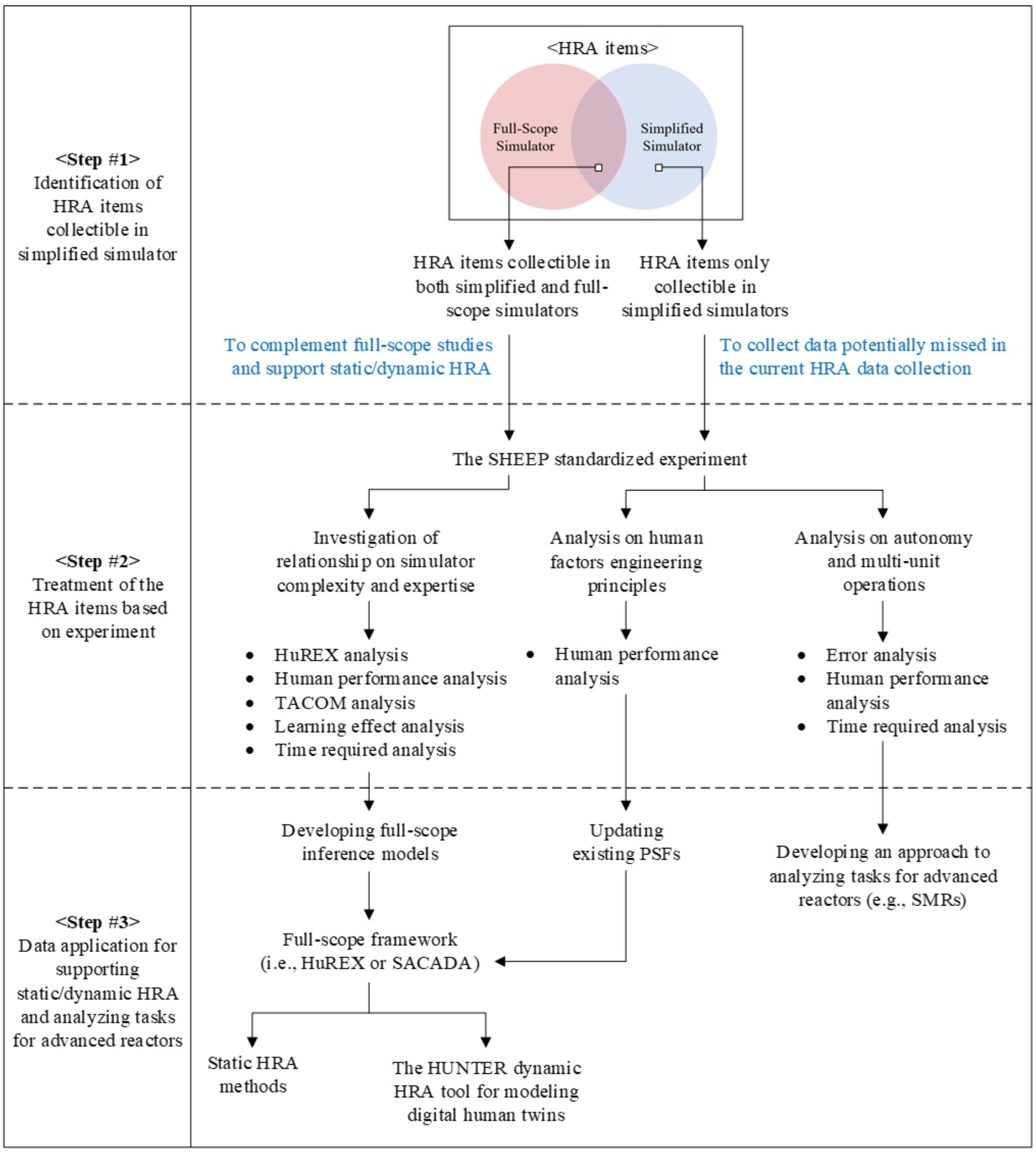

Figure 1. SHEEP framework [10]

3. EXPERIMENT DESIGN

This section introduces an experimental design to identify differences stemming from students' learning effect in the second step of the SHEEP framework development. The basic experimental design is showed in Figure 2. In the experiment, four scenarios per trial were given to each participant.

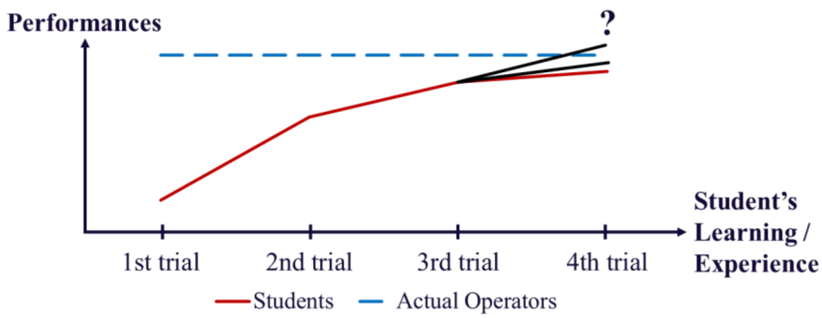

Figure 2. Trends in student performance as a result of learning effects

3.1. Objective

The experiment objectives were 1) to investigate students' learning effects over repeated trials, and 2) to compare student performance with operator performance. To meet the first objective, this study designed a longitudinal experiment in which the participants operated Rancor Microworld per the relevant procedures. In each trial, four human performance measures (i.e., workload, situation awareness, task completion time, and accuracy) were collected and the trends analyzed (see Figure 2). For the second objective, student performance was compared with operator performance to investigate how students' experiences are built.

3.2. Rancor Microworld

Rancor Microworld is a simplified simulator for collecting representative performance data. Developed by INL [13], it has been used to examine theoretical and practical design concepts, providing a graphical user interface that enables researchers to generically create process control systems. It is based on a reduced-order thermo-hydraulics model that follows a simplified Rankin cycle reminiscent of small modular reactors.

Rancor Microworld is available for the Microsoft Windows operating system and runs on a personal laptop. This configuration is physically favorable for collecting HRA data, since any experiment can be performed wherever a laptop, desk, chair, and power source are available. In addition, the simulator is programmed using C# and Windows Presentation Foundation in Microsoft Visual Studio. Thus, the system and interface are relatively easy to modify compared to full-scope simulators, which often have multiple layers of vendor proprietary tools that are necessary when making changes.

3.3. Experiment Scenarios

Ten scenarios and related procedures simulated by the Rancor Microworld were developed for the experiment. These scenarios are relatively simple compared to those for full-scope studies. The scenarios include non-events such as normal startup and shutdown (i.e., Scenarios #1 to #4) and events such as abnormal and emergency situations (i.e., Scenarios #5 to #10), as below.

- Scenario #1: Fully auto start-up

- Scenario #2: Shut-down
- Scenario #3: Manual rod control during start-up
- Scenario #4: Manual feedwater flow control during start-up
- Scenario #5: Failure of a reactor cooling pump under full power operation
- Scenario #6: Failure of a control rod under full-power operation
- Scenario #7: Failure of a feedwater pump under full-power operation
- Scenario #8: Turbine failure under full-power operation
- Scenario #9: Steam generator tube rupture
- Scenario #10: Loss of feed-water

3.4. Participants

A total of 16 students participated in the experiment. All were undergraduate seniors or graduate students from Chosun University's Department of Nuclear Engineering. They were knowledgeable about NPP systems and operations, having already completed a significant portion of their coursework, which included courses such as "Introduction to Nuclear Engineering," "Reactor Theory," "Reactor Control," and "Simulator Operation."

3.5. Experiment Schedule

Four experimental trials were conducted for every participant. In each, the participant underwent four of the 10 possible scenarios. The interval between trials was about two weeks. The experiments were performed from April 26th to June 17th in 2021.

3.6. Performance Measures

In the trials, four human performances measures were considered: workload, situation awareness, accuracy, and task completion time. The modified Cooper-Harper (MCH) questionnaire [14] was used to measure workloads, while the Situation Awareness Rating Technique (SART) questionnaire [15] was applied to measure situation awareness. The average task completion time (i.e., procedural step) was also measured, along with the number of errors per task (i.e., error rate).

4. RESULT AND ANALYSIS

Table I summarizes the results of the four experimental trials. It also, include the operator performance scores taken from the authors' previous study. Table II shows the results of analyzing the data from Table I using an ANOVA (analysis of variance) test.

Table I. Summary of average student performance

Human Performance	Measure	Trials				Operator [10, 11]
		1st	2nd	3rd	4th	
Workload	MCH (Score)	2.89	2.81	2.94	2.67	3.117
Situation Awareness	SART (Score)	28.93	30.28	29.19	33.60	20.21
Accuracy	Error Rate	0.0236	0.0125	0.0075	0.0067	0.0059
Task Completion Time	Average Time to Complete Task (sec)	9.20	8.15	7.76	6.49	4.78

Table II. ANOVA test results for considering the student performance measures in each trial, in addition to the average operator performance measures

Human Performance Measure	p-value
MCH (Score)	0.424
SART (Score)	0.000
Error Rate (%)	0.001
Time per Task (sec)	0.000

4.1. Workload

Figure 3 shows the trend of average workload over four trials. The ANOVA test shows that there is no statistically significant difference among the trials, as shown in Table II. The test also indicates that the students' workload is not different from the operators.

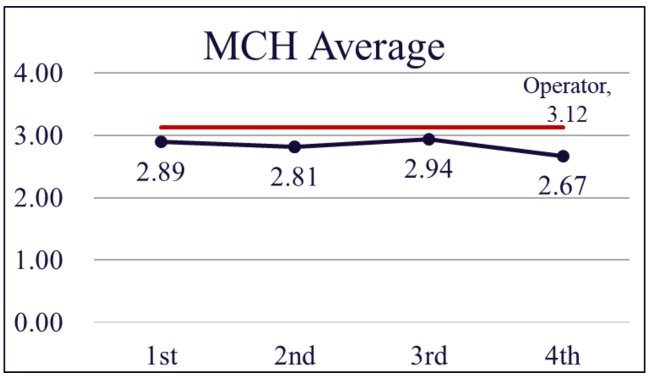

Figure 3. Student workloads for each of the four experimental trials, as compared to the operator workload

4.2. Situation Awareness

Figure 4 presents the change of average situation awareness during trials. The ANOVA test indicates that there is a significant difference between the trials, as shown in Table II. As shown in Table III, the Tukey test also shows that the situation awareness of the third and fourth trials were higher than that of the first trial.

In comparison with the operators, the ANOVA and Tukey tests shows that the students' situation awareness was better than the operators. This is a somehow unexpected result. We may assume that students were overconfident about their situation awareness.

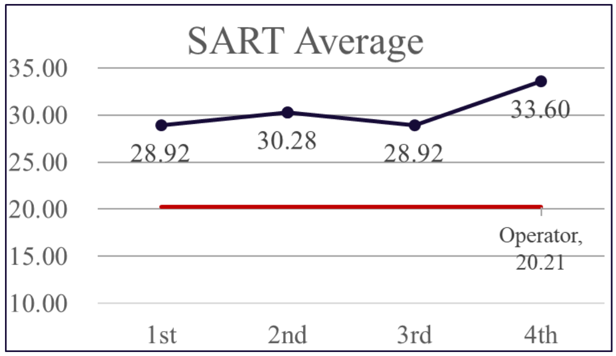

Figure 4. The student's situation awareness SART scores for each of the experimental trials, as compared to the operators' situation awareness SART score

Table III. SART scores determined using the Tukey test

SART			
Trial	Average		
	Subset 1	Subset 2	Subset 3
Operator	20.21		
1st		28.93	
3rd		29.19	
2nd		30.28	30.28
4th			33.60

4.3. Accuracy

Figure 5 shows the trend of the average error rate during trials. The ANOVA test shows that there is a significant difference between the trials as shown in Table II. As shown in Table IV, the Tukey test indicates that the third and fourth trials were more accurate than that of the first trial.

In comparison with the operators, the ANOVA and Tukey tests show that the students' error rates from the second to the fourth trials have no statistically significant difference since the second trial. It can be postulated that students approached the similar accuracy level to the operator in this study.

Figure 5. Student's error rates for each of the experimental trials, as compared to the operators' error rate

Table IV. Error rates determined using the Tukey test

Error Rate		
Trial	Average	
	Subset 1	Subset 2
Operator	0.0059	
4th	0.0067	
3rd	0.0075	
2nd	0.0124	0.0125
1st		0.0236

4.4. Time

Figure 6 shows the trend of the average time to complete a task during trials. As shown in Table II, the ANOVA test indicates that there is a significant difference in the time to completion between the trials. The Tukey test also shows that the average time to complete a task in the third and fourth trials was faster than in the first trial, as shown in Table V.

In addition, the students' average time to complete a task was approaching the operators' one over trials. However, As shown in Table V, the Tukey test shows that the operators' average time to complete a task was faster than the students.

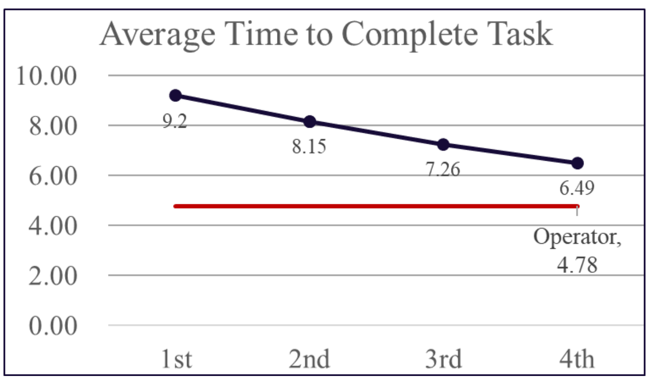

Figure 6. Students' average task completion time for each of the experimental trials, as compared to the operators' average completion time

Table V. Average time to complete task, as determined using the Tukey test

Average Time to Complete Task			
Trial	Average		
	Subset 1	Subset 2	Subset 3
Operator	4.78		
4th		6.49	
3rd		7.26	
2nd		8.15	8.15
1st			9.20

5. CONCLUSIONS

This paper introduced an experimental study to investigate students' learning effects using a simplified simulator and analyzed the results. The results of this study indicated that as the number of trials increased, there is a significant change in students' situation awareness, accuracy, and time to complete tasks. We could see that students' accuracy became similar to the level of operators.

This study was performed as a part of SHEEP framework. The results will be integrated with other efforts in the framework to support HRA data collection.

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