Impacts of a Multi-Module Operation on Human Performance Across Cognitive Activity Types

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1. Introduction

Small Modular Reactors (SMRs) exhibit distinct operational characteristics compared with conventional large-scale nuclear reactors, such as multi-module operations managed from an integrated Main Control Room (MCR) [1, 2]. Such operational conditions cause a fundamental shift in human factors—operator roles and responsibilities, and staffing configurations—which can significantly affect human performance by imposing unprecedented cognitive workload and situation awareness [3]. Consequently, it is crucial to empirically evaluate how these environmental shifts affect human performance to ensure the operational safety of SMRs [4].

In the previous study, empirical human performance data were acquired via simulator experiments involving licensed operators managing multi-modules [5]. Initial analyses confirmed that multi-module environments significantly elevate operator mental workload and degrade situation awareness compared with single-module baselines. However, to construct a human performance database specialized for multi-module operation supporting Human Reliability Analysis (HRA), it is essential to classify the cognitive activity types in the cognitive process where these errors are manifest. This follow-up study presents an advanced statistical analysis of the acquired dataset, systematically evaluating the impact of defined control variables across discrete cognitive activity types and error modes.

2. Methodology

2.1. Data Segmentation

The data analyzed in this study consists of empirical operator performance data acquired and processed during multi-module simulation experiments in the previous study. In the previous work, operator behaviors were decomposed into Primitive Task Units (PTUs), which consist of cognitive activities and task types based on a modified HuREX framework [6] taxonomy for multi-module environments. Building upon the acquired data, this study categorizes and systematically analyzes the PTUs according to discrete cognitive activity types and corresponding error modes.

Cognitive activity types were categorized into three distinct types: Response Planning (RP), Information Gathering (IG), and Execution (EX). Similarly, error modes were categorized into two types: Error of Omission (EOO) and Error of Commission (EOC). Table 1 summarizes the acquired frequencies of successful and erroneous PTUs (i.e., Unsafe Act) resulting from this data segmentation scheme.

Table 1 Frequencies of Successful and Erroneous PTUs

	Success	EOO	EOC
RP	11,477	111	12
IG	9,432	3	12
EX	1,115	8	17
Sum	22,024	122	41

2.2. Statistical Hypothesis Testing Framework

The control variables examined in this study are comprised of the following: Accident Modules per Operator and Accident Homogeneity (AMO-AH), Surveillance Existence (SS), Supportive Human-System Interface (HSI), Malfunction of Safety Systems (MALF), Accident Scenarios (ACC), and Experimental Phase (PHASE). Table 2 summarizes the types of control variables.

Table 2 Control Variable Types

Control Variable	Variable Type
AMO-AH	Categorical
SS	Binary
HSI	Categorical
MALF	Categorical
ACC	Categorical
PHASE	Categorical

A tiered non-parametric hypothesis testing approach was employed to statistically evaluate the variations in Human Error Probabilities (HEPs) as follows.

- Omnibus test: The Fisher-Freeman-Halton Exact Test [7] was executed across all variables and cognitive modes to detect overall statistical significance, applying a threshold of $p < 0.1$. The following detailed test was performed on the groups that satisfied the significance level in the omnibus test.
- Detailed analysis for binary variables: For control variables characterized by binary type, the

Barnard Exact Test [8] was applied. Results were evaluated at significance level of $p < 0.05$.

- Detailed analysis for Categorical Variables: For variables with categorical types, post-hoc analysis involved pairs of Barnard Exact Tests. To control the family-wise error rate, a Bonferroni correction was applied, adjusting the required significance threshold of $p < 0.05/3 \sim 0.016$.

3. Results

3.1.Overall Significance for Omnibus Test (Fisher-Freeman-Halton Exact Test)

The initial Fisher-Freeman-Halton Exact testing revealed several statistically significant associations between control variables and specific cognitive types-error modes. Table 3 presents the variables that met the predefined significance threshold where superscript * means $p < 0.1$, ** means $p < 0.05$, *** means $p < 0.01$.

Table 3 Fisher-Freeman-Halton Exact Test Result

Control Variable	Test Result
AMO-AH	EX-EOC**
SS	IG-EOC*, EX-EOC**
HSI	RP-EOC***, IG-EOC***
MALF	RP-EOO***, RP-EOC***, EX-EOC*
ACC	RP-EOO***, RP-EOC**
PHASE	RP-EOC**

3.2. Detailed Analysis for Binary Variables (Barnard Exact Test)

Applying the Barnard Exact Test to binary variables yielded insights into the role of supervisory oversight. Specifically, the presence of a Shift Supervisor (SS) resulted in marginally significant differences in the probabilities of IG-EOC and EX-EOC ($0.05 \leq p < 0.1$).

3.3. Detailed Analysis for Categorical Variables (Barnard Exact Test with Bonferroni Correction)

For categorical variables comprising three categories, post-hoc pairwise Barnard Exact Tests were conducted, with significance evaluated against Bonferroni-adjusted thresholds ($p < 0.1$ adjusted to $p < 0.033$, $p < 0.05$ adjusted to $p < 0.016$, and $p < 0.01$ adjusted to $p < 0.003$).

- Malfunction of Safety Systems (MALF): Significant deviations in RP-EOO were observed between No Malfunction and SI Malfunction and between SI and AFW Malfunction ($0.003 \leq p < 0.016$), both satisfying the strict $p < 0.016$ criteria.
- Accident Scenarios (ACC): The type of accident heavily influenced RP-EOO. Significant differences were isolated when comparing SGTR to ESDE and ESDE to LOCA ($p < 0.003$).
- Supportive HSI (HSI): The provision of supportive interfaces impacted commission errors. Comparing No Supportive HSI against Partial Supportive HSI yielded a significant difference in RP-EOC ($0.016 \leq p < 0.033$). Furthermore, comparing No Supportive HSI against Full Supportive HSI showed significant variance in IG-EOC ($0.016 \leq p < 0.033$).
- Accident Modules per Operator and Accident Homogeneity (AMO-AH): Execution errors (EX-EOC) were significantly different ($0.016 \leq p < 0.033$) when comparing a single module off-normal state to two modules of the same state.

4. Discussion

By analyzing HEPs across distinct cognitive activity types, this study identified operational vulnerabilities within the context of multi-module environment.

First, safety system malfunctions and the kind of accident predominantly induce EOO during the RP phase, as operators struggle to formulate appropriate mitigation strategies when confronted with unexpected system failures. This underscores the imperative of providing operators with multi-module, SMR-specific training regimes alongside robust procedural guidance tailored for accurate diagnosis and accident mitigation.

Second, structural support mechanisms substantially modulate EOC during the IG and EX phases. Consequently, establishing robust operational support frameworks such as comprising optimized staffing architectures, advanced interface designs, and standardized communication protocols are vital for mitigating commission errors.

However, it is important to acknowledge a methodological limitation regarding the assumption of independence among PTU observations. The current statistical framework does not account for potential clustering effects inherent to the data, such as specific crew dynamics, or experimental session dependencies. Future research will employ advanced statistical modeling techniques to systematically address these clustering effects and rigorously validate the findings.

5. Conclusion

In conclusion, this study advances the understanding of human performance in multi-module environments by systematically analyzing HEPs into discrete cognitive activity types and error modes. Through rigorous non-parametric statistical testing, the analysis successfully isolated specific operational vulnerabilities, revealing that human performance is highly dependent on the operational context. Specifically, unexpected safety system malfunctions predominantly induce EOO during the RP phase. Conversely, structural supports such as supportive HSI directly modulate the probability of EOC during the IG and EX phases, while supervisory

oversight exhibited a marginally significant tendency to influence these commission errors.

These findings underscore that mitigating human error in multi-module environments requires targeted, phase-specific interventions. Improving SMR-specific training systems and procedural instructions is critical for proper response planning against complex malfunctions, while optimizing MCR staffing and interface designs is vital for supporting accurate information gathering and task execution. Ultimately, the empirical evidence provided in this study establishes a robust technical foundation for developing a specialized multi-module HRA database, thereby contributing to the operational safety of future SMR deployments.

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