ACT-R-BASED HUMAN DIGITAL TWINS OF NUCLEAR POWER PLANT OPERATOR PERFORMANCE FOR ADVANCING HRA DATA COLLECTION

Xingyu Xiao[1], Meng Kong[1], Jiejuan Tong[1], Shunshun Liu[2],
Qianqian Jia[1], Hongru Zhao[1], Jun Zhao[1], Jingang Liang[1],
Haitao Wang[1]

[1] Institute of Nuclear and New Energy Technology, Tsinghua University,
Beijing, 100084, China Email: xxy23@mails.tsinghua.edu.cn, jingang@tsinghua.edu.cn
[2] CNNC Shandong Nuclear Energy Co., Ltd, Qingdao, 266071, Shandong China.

ABSTRACT

Traditional human reliability analysis (HRA) relies predominantly on experiments involving live operators. However, the advent of next-generation reactor designs, with novel interfaces and procedures, has rendered conventional HRA data obsolete. These new systems face significant challenges: insufficient operational experience and the inefficiency inherent in traditional human-in-the-loop experimental methods. This study pioneers an ACT-R-based human digital twins (HDTs) methodology that fully implements operator cognition through the cognitive architecture's declarative memory, procedural knowledge, and perceptual-motor modules to predict operator task completion times and error probabilities. Experiments were conducted on Tsinghua University's HTGR simulator under various conditions, including multi-parameter queries with interface switching, parameter queries without switching, pure three-phase AC operations, and button-press interactions. The reliability of these processes was supported by the predominance of three-phase AC operations, which minimizes error incidence. The results indicate that the ACT-R based HDT simulation framework not only accurately forecasts response times, suggesting a viable alternative to traditional HRA data collection methods for advanced nuclear reactor environments.

Keywords: Human Reliability, Human Performance Management, ACT-R, Human Digital Twins

I. Introduction

Despite ongoing advancements in automation and digital instrumentation, human operators play a pivotal role in ensuring the safety and reliability of nuclear power plants (NPPs), particularly during abnormal or accident conditions. Traditional human reliability analysis (HRA) approaches rely heavily on two main sources of data: (1) historical records from past operational events and (2) operator-in-the-loop (OITL) experiments conducted within simulator environments. The latter category includes well-known programs such as HuRex, SACADA, and SHEEP, which systematically capture human performance data under controlled yet realistic conditions. By combining empirical evidence from actual plant operations with carefully designed experimental scenarios, these methods have helped analysts identify important human error mechanisms and quantify error probabilities.

However, while these approaches have proven effective for conventional reactor designs, their applicability is increasingly challenged by the rapid deployment of next-generation reactors, including small modular reactors (SMRs) [1] and Generation IV systems [2]. There are many innovations involve the adoption of digital Instrumentation and Control (IC) systems [3], computerized operating procedure systems (COPS) [4], and advanced human–machine interfaces (HMIs) [5] associated with next-generation nuclear reactors. While these technological shifts promise to reduce operator workload and improve situational awareness, they also introduce new complexities. For instance, the High-Temperature Gas-cooled Reactor (HTGR) design mandates that a single operator concurrently supervise multiple reactor units [6]. Consequently, error pathways may differ substantially from those observed in legacy systems. Existing HRA data and models, derived from traditional analog control rooms, may therefore be of limited utility, as they do not fully capture the cognitive demands associated with next-generation control rooms.

Chief among them is the scarcity of operational experience with next-generation systems, leading to insufficient or non-representative datasets. Moreover, the resourceintensive nature of traditional OITL experiments—requiring significant time, personnel, and simulator availability—runs counter to the growing need for more agile and cost-effective data collection paradigms. Consequently, while historical data and OITL experiments have long formed the backbone of HRA, the emergence of advanced reactor designs underscores the necessity for innovative, scalable approaches to ensure accurate and reliable human performance assessment.

To address these gaps, this study proposes a mechanistic simulation framework grounded in the Adaptive Control of Thought-Rational (ACT-R) cognitive architecture. Experiments were conducted on Tsinghua University's HTGR simulator under various conditions, including multi-parameter queries with interface switching, parameter queries without switching, pure three-phase AC operations, and button-press interactions. The reliability of these processes was supported by the predominance of three-phase AC operations, which minimizes error incidence. To further evaluate ACT-R's predictive capabilities regarding operator errors, two rapid-response tasks were designed: one involving state recognition across reactor startup, normal operation, accident conditions, and shutdown; and the other requiring the enumeration of alarm signals on the interface. The main contributions are follows:

• Developing a mechanistic simulation framework that captures operator cognition and decision-making processes with a high degree of fidelity, reducing reliance on costly live-operator experiments.
• Predicting task completion times and error probabilities in the context of advanced nuclear reactor control tasks, including both routine procedures and rapid-response emergency scenarios.
• Validating the proposed framework through systematic experiments conducted on a high-temperature gas-cooled reactor (HTGR) simulator, thereby providing empirical evidence of the model's accuracy and practical relevance.
• Proposing an alternative HRA data collection paradigm that can complement or potentially replace large-scale human-in-the-loop testing, thus improving both the efficiency and the scope of safety analyses for next-generation nuclear power plants.

II. Methodology

II.A. The framework of this study

The methodology framework of this study, as illustrated in Figure 2, comprises three interconnected phases: (1) simulation task and scenario development, (2) ACT-R cognitive architecture modeling, and (3) experimental validation. This structure systematically investigates the human reliability factors in safety-critical systems through computational modeling and empirical verification. The initial phase establishes the operational context through rigorous scenario development using some abnormal operating procedures as a case study. Subsequent cognitive modeling employs the ACT-R architecture to formalize human mechanisms under stress conditions. The final experimental phase validates model predictions through human performance metrics collection and comparative analysis.

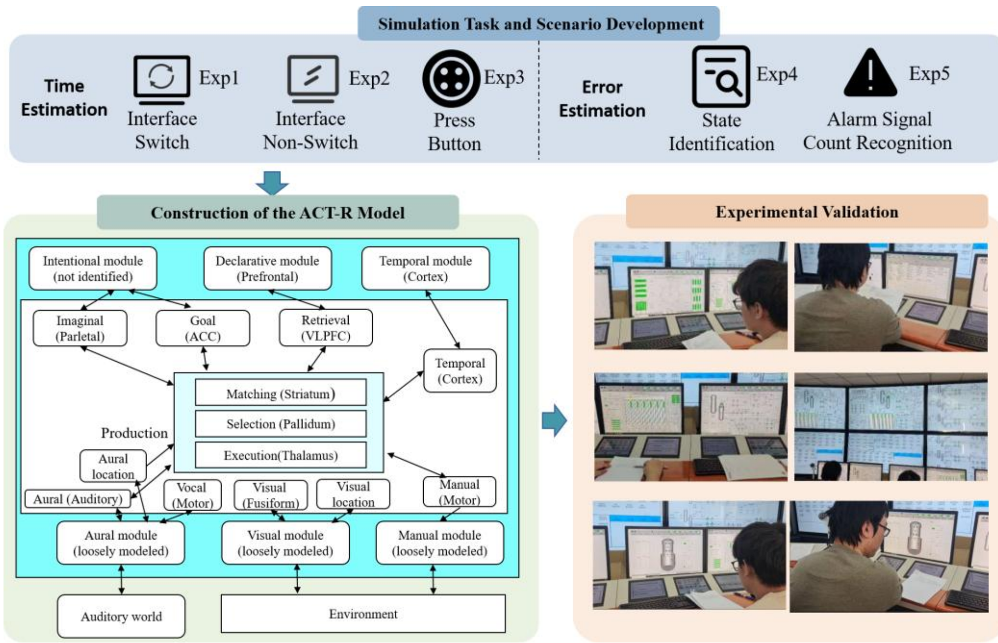

FIGURE 1. THE FRAMEWORK OF THIS STUDY

II.B. Stage 1: Simulation Task and Scenario Development

In this section, some straightforward operational processes were selected for experimentation. Given the unique demands of nuclear power plant operations, every operator action must be accompanied by a three-way communication with the shift supervisor. To simulate this condition, our volunteer engaged in such triadic interactions. Consequently, errors were seldom observed in this experimental setup, and our focus was confined to evaluating the temporal plausibility of the ACT-R simulation. Additionally, two supplementary experiments were designed that required instantaneous responses from the operators, thereby enabling the collection of error data.

As for time estimation, the experiment involves implementing response procedures under abnormal conditions, as depicted in Figure 2. Three experimental conditions were established: Experiment 1 entails interface switching; Experiment 2 does not require interface switching; and Experiment 3 involves a manual action (i.e., pressing a button).

Emergency Operational Procedure Exp 1

- The supervisor issues the directive to initiate Procedure E0.
- Under Operating Procedure E-0, the following conditions are evaluated: Verify whether the RFP percentage of Unit 3, 4, 5 exceeds 30%.
- Subsequently, the process advances to Operating Procedure E1.
- Under this procedure, if the power generation is less than 300 (units), Procedure ES-1.2 is initiated.
- Within Procedure ES-1.2, the following verifications are conducted: For Reactor 2's primary loop hot helium, confirm whether the temperature is exactly 750 °C and the pressure is 7.01 MPa.
- For Reactor 4's primary loop hot helium, confirm whether the temperature is 749.9 °C and the pressure is 7.01 MPa.
- If the temperature of the steam main pipe exceeds 560 °C, transition to the subsequent procedure.
- End.

Emergency Operational Procedure Exp 2

- The supervisor issues an order to initiate the operating procedure.
- The operator then executes Procedure E-0 by navigating to the "4# Main Helium Fan" interface and verifying whether the inlet temperature of the primary loop A fan exceeds 200 °C; if it does, the operator proceeds to Procedure ES-0.1.
- Next, under Procedure ES-0.1 (Reactor Trip Response), the operator accesses the "4# Reactor SPDS" to determine if the flow ratio between the first and second circuits is exactly 0.984, after which Procedure FH-H.1 is initiated.
- Finally, the operator implements Procedure FR-H.1 by navigating to the "4# SG Accident Venting" display to confirm that the pressure is maintained at 0.1 MPa and the temperature at 20 °C.

Emergency Operational Procedure Exp 3

- The operator must determine whether the power output of Reactor 4 exceeds 30% of the Rated Full Power (RFP).
- If the power is greater than 30% RFP, the operator must press the emergency shutdown button.
- If the power is less than 30% RFP, the operator should not press the emergency shutdown button.

FIGURE 2. CONTENT OF EXPERIMENTED EMERGENCY OPERATIONAL PROCEDURES

II.C. Stage 2: Construction of the ACT-R model

The ACT-R cognitive architecture model was implemented using the Lisp programming language. This required decomposing complex operational tasks into granular procedural branches. The most intricate experimental task (Exp2) was selected as a representative case for detailed modeling. As illustrated in Figure 3, the left panel demonstrates the refined operational protocol of Exp2, while the right panel presents the corresponding Lisp code implementation. This dual representation systematically maps procedural requirements to executable cognitive operations within the ACT-R framework.

Action Decomposition of Exp 2

1. Upon hearing the instruction "Enter operational procedure E0."
2. Verbally repeat the phrase "Confirm entry into operational procedure E0."
3. Receive the auditory confirmation "Correct."
4. Observe the directive "Enter 4 Main Helium Blower."
5. Locate and click the "Screen Search" button on the interface.
6. From the drop-down menu, identify and select the entry "4# Reactor."
7. Within the list of codes, locate and click on "Main Helium Blower."
8. Receive the auditory confirmation "4# Reactor."
9. Observe the instruction: "Within the set of parameters displayed on the interface, locate the inlet temperature of the primary loop A blower and determine whether it exceeds 200°C. If it does, proceed to the subsequent procedure."
10. Examine the inlet temperature of the primary loop A blower and confirm that the value is 220°C, which exceeds 200°C.
11. Transition the active procedure to the next procedural step.
12. Observe the directive "Enter 4# Reactor SPDS."
13. Click on the "Reactor SPDS" option.
14. Observe the instruction: "Check if the flow ratio between the primary and secondary loops is 0.984. If it is, proceed to Procedure FH-H.1."
15. Locate the parameter "flow ratio between the primary and secondary loops" on the interface and verify that its value is 0.984.
16. Transition to Procedure FH-H.1.
17. Observe the instruction indicating entry into "4 Steam Generator Accident Discharge."
18. Locate and click the "Screen Search" button on the interface.
19. From the drop-down menu, identify and select the entry corresponding to "4# Reactor."
20. Within the displayed list of screens, locate and click on "4 Steam Generator Accident Discharge."
21. Observe the directive: "Check if the pressure is 0.1 MPa and the temperature is 20°C."
22. Locate the "pressure" parameter on the interface and confirm that its value is 0.1 MPa.
23. Locate the "temperature" parameter on the interface and confirm that it registers 20°C.
24. Upon verifying that all conditions conform to the procedural requirements, verbally state "Procedure operation completed."
25. Finally, receive the auditory confirmation "Completed."

Lisp

```
(clear-all)
(define-model interface-navigation
(sgp :seed (123456 0))
(sgp :v t
     :show-focus t
     :trace-detail high
     :esc t
     :visual-attention-latency 0.085
     :motor-feature-prep-time 0.05
     :motor-initiation-time 0.05)

 (chunk-type goal state)

 (add-dm
  (start-search isa chunk)
  (find-search-button isa chunk)
  (find-4-heap isa chunk)
  (find-main-helium-blower isa chunk)
  (hear-feedback isa chunk)
  (task-done isa chunk)
  (attending-search-button isa chunk)
  (clicking-search-button isa chunk)
  (attending-4-heap isa chunk)
  (clicking-4-heap isa chunk)
  (attending-main-helium-blower isa chunk)
            ……………
```

FIGURE 3. INTEGRATED SCHEMATIC DIAGRAM OF EXP2 BASIC OPERATIONS AND REFINED PROTOCOLS FOR LISP MODEL CONSTRUCTION

For simpler experimental tasks (Exp1 and Exp3), analogous decomposition was performed as shown in Figure 4. The modeling process systematically addressed six core cognitive components: (1) auditory processing of system alerts, (2) verbal response generation, (3) button press operations, (4) decision-making mechanisms, (5) parameter retrieval from interface elements, and (6) procedural switching logic. Each cognitive operation was encoded as production rules with associated latency parameters derived from empirical human performance data.

Action Decomposition of Exp 1

1. Upon receiving the auditory signal indicating entry into operational procedure E0.
2. A verbal confirmation is issued stating, "Confirm entry into operational procedure E0."
3. An auditory acknowledgment is received confirming the command.
4. The procedural content is visually reviewed, with the following evaluations:
   - Determine whether the RFP percentage for Unit 3 exceeds 30%.
   - Determine whether the RFP percentage for Unit 4 exceeds 30%.
   - Determine whether the RFP percentage for Unit 5 exceeds 30%.
5. Conduct a systematic search and assessment on the graphical user interface.
6. It is determined that the RFP percentages for all specified units are above 30%.
7. Transition to the subsequent operational procedure.
8. The following instruction is observed on the display: "If the power generation output is below 300, proceed to ES-1.2."
9. Execute a search and evaluation on the interface.
10. It is determined that the power generation outputs are all below 300.
11. Transition to the next procedural step.
12. The following directive is observed: "For Unit 2's reactor primary circuit hot helium, verify whether the temperature is 750°C and the pressure is 7.01 MPa."
13. Perform a search and assessment on the interface.
14. It is confirmed that both the temperature and pressure comply with the specified criteria.
15. The next instruction is observed: "For Unit 4's reactor primary circuit hot helium, verify whether the temperature is 749.9°C and the pressure is 7.01 MPa."
16. Conduct a search and evaluation on the interface.
17. It is verified that the temperature is exactly 749.9°C and the pressure is 7.01 MPa.
18. The following instruction is observed: "If the main steam line temperature exceeds 560°C, proceed to the subsequent procedure."
19. A search and evaluation on the interface confirms that the temperature is indeed greater than 560°C.
20. A verbal command is issued stating, "End."

Action Decomposition of Exp 3

1. Upon receiving the auditory signal "Enter operational procedure E1."
2. Verbally state "Use operational procedure E1."
3. Receive the auditory confirmation "Correct."
4. Observe the instruction: "Assess whether Reactor 4's power exceeds 30% RFP. If it does, press the button; if it does not, do not press the button."
5. Locate the parameter "Reactor 4 Power" on the interface.
6. Evaluate the parameter and determine that it exceeds 30% RFP.
7. Press the button.

FIGURE 4. REFINED PROTOCOLS OF EXP1 AND EXP3 FOR LISP MODEL CONSTRUCTION

All model implementations incorporated ACT-R's default temporal parameters for basic cognitive operations. Task-specific adjustments were made through declarative memory chunk activation levels and procedural rule conflict resolution mechanisms. This multi-layered approach enabled the model to simulate both routine operations and exception handling scenarios observed in human operators.

II.D. Stage 3: Experimental Validation on HTGR

To ensure the relevance and validity of the experimental data, all participants were graduate students majoring in nuclear engineering at Tsinghua University and had prior exposure to control room simulators. Before the experiment, the first author served as the lead experimenter and provided a standardized training protocol to all participants. This included: (1) a briefing on the background and functional logic of the HTGR plant and its emergency procedures; (2) a step-by-step interface walkthrough to ensure participants were familiar with all interactive elements of the simulator; and (3) a series of pre-experimental rehearsal sessions designed to help participants internalize the operational context, understand the procedural logic, and reduce task unfamiliarity. All training activities were conducted in a consistent and structured manner to improve the reproducibility of the study and ensure that participants' cognitive behavior during the experiment reflected realistic nuclear operational scenarios.

TABLE I. Overview of Data Collection Across Experimental Paradigms: Time and Error Estimation

Exp	1	2	3
Sample	5	5	12

Table I summarizes the data collection across the experimental paradigms for time and error estimation. For the time estimation experiments, three distinct protocols were implemented, Exp1, Exp2, and Exp3, with sample sizes of 5, 5, and 20, respectively. In contrast, the error estimation paradigm was evaluated using two protocols (Exp4 and Exp5), yielding sample sizes of 20 and 26, respectively.

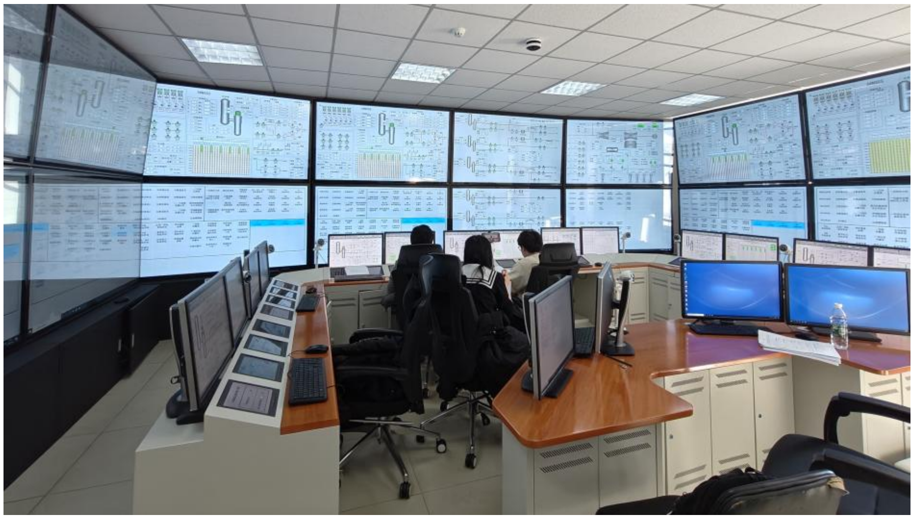

FIGURE 6. HTGR SIMULATOR AT TSINGHUA UNIVERSITY'S INSTITUTE OF NUCLEAR ENERGY TECHNOLOGY (1:1)

III. Results and Evaluation

In order to assess the temporal validity of the HDT constructed using ACT-R, we simulated the entirety of Exp1-Exp3 and identified several key time points within these experiments. The corresponding simulation times were then extracted to facilitate a comparison between the experimental results and the simulation outcomes.

Figure 7 (a) illustrates the five experimental trials of Exp1, comparing the duration of each procedural step as well as the cumulative time between the simulation and the actual experiment. The comparison indicates that both the overall and the individual component times are in close agreement. In the right panel (b), the figure presents a comparison of the mean and variance for two specific segments: (i) from hearing the correct stimulus to switching to Procedure E1, and (ii) from the initiation of Procedure E1 to the initiation of Procedure ES-1.2. For the first segment, the actual mean duration is 5.3722 s while the simulated mean is 5.4777 s, with variances of 1.4922 and 0.0139, respectively. For the second segment, the actual and simulated means are 5.7667 s and 5.485 s, respectively, with corresponding variances of 1.5103 and 0.01136. These results suggest that, overall, the mean durations are largely consistent between the experimental data and the ACT-R simulation, although the simulation exhibits significantly lower variance.

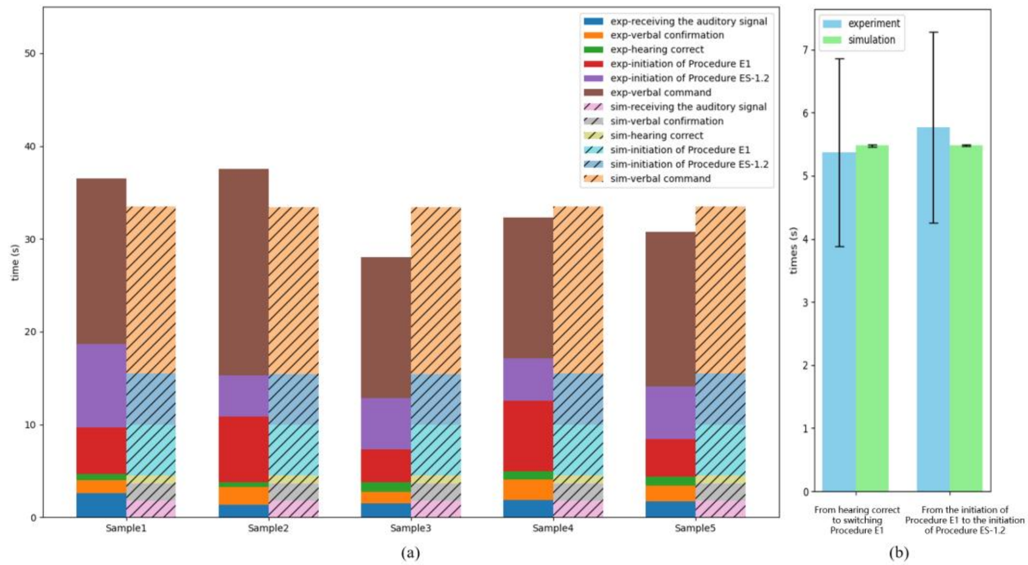

FIGURE 7. TEMPORAL ANALYSIS OF EXPERIMENTAL AND SIMULATED PROCEDURES IN EXP1

Figure 8 presents the results from five experimental trials of Exp2, comparing the durations of individual procedural steps as well as the cumulative time between the simulation and the actual experiment. The comparison demonstrates that both the overall total time and the time allocated to each step are consistent.

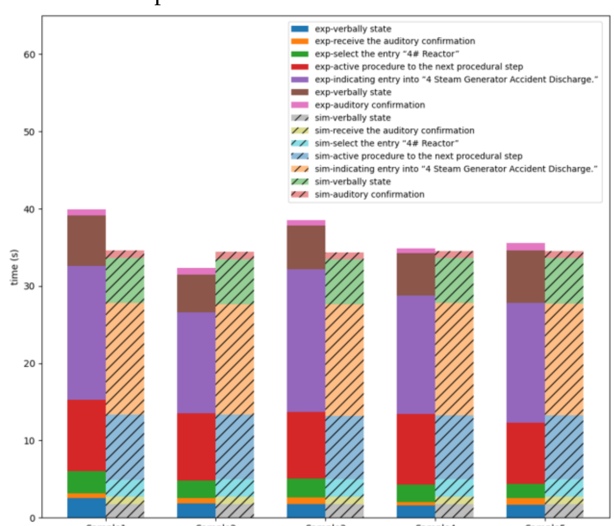

FIGURE 8. TEMPORAL ANALYSIS OF EXPERIMENTAL AND SIMULATED PROCEDURES IN EXP2

Figure 9 provides a comparative analysis of the means and variances for four specific processes: (i) from hearing the correct stimulus to selecting the entry “4 Reactor”, (ii) from selecting the entry “4 Reactor” to switching procedure, (iii) from the initiation of Procedure to indicating entry into “4 Steam Generator Accident Discharge,” and (iv) from indicating entry into “4 Steam Generator Accident Discharge” to verbally stating. For these processes, the actual mean durations are 2.3200 s, 8.7333 s, 15.9200 s, and 5.9000 s, respectively, while the corresponding simulated means are 2.2656 s, 8.2916 s, 14.4428 s, and 5.8858 s. The actual variances are 0.3030, 0.4551, 1.8847, and 0.7121, compared to the simulated variances of 0.0300, 0.0668, 0.0833, and 0.0098. Overall, the mean durations are largely consistent between the simulation and the experimental results; however, the ACT-R simulation exhibits considerably lower variance.

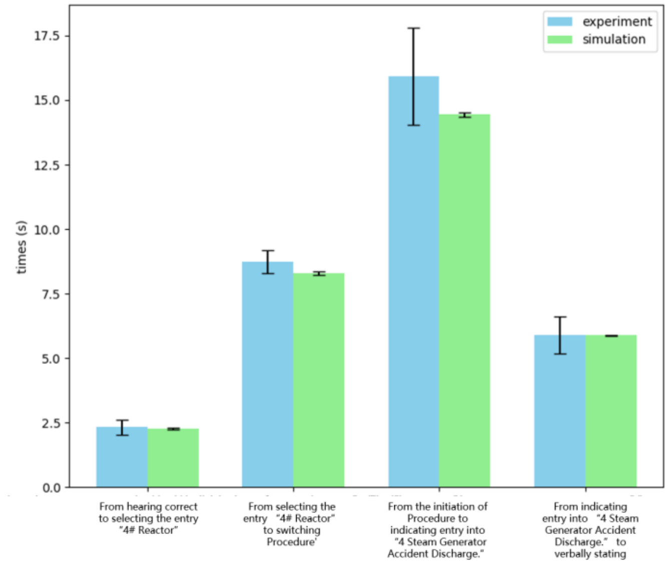

FIGURE 9. COMPARATIVE ANALYSIS OF EXPERIMENTAL AND SIMULATED PROCEDURES IN EXP2

Figure 10 (a) illustrates the 12 experimental trials of Exp3, comparing the durations of individual procedural steps and the cumulative time between the simulation and the actual experiment. The results indicate that both the overall total time and the durations of the individual segments are consistent. In the right subfigure (b), a comparison of the mean and variance for the process ”From hearing correct to pressing the button” is presented. The actual mean is 1.9583 s, while the simulated mean is 2.1723 s, with corresponding variances of 0.5841 and 0.0232, respectively. Overall, the mean values are closely aligned, though the ACT-R simulation exhibits a notably lower variance.

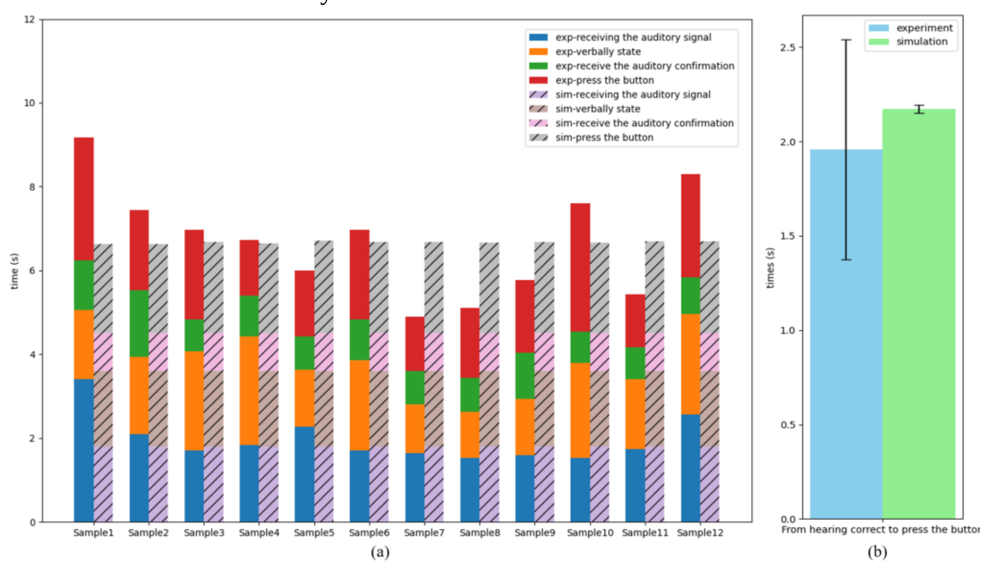

FIGURE 10. TEMPORAL ANALYSIS OF EXPERIMENTAL AND SIMULATED PROCEDURES IN EXP3

II. CONCLUSIONS

This study presents a novel ACT-R-based human digital twin (HDT) framework that provides a robust, theoretically grounded, and highly interpretable alternative to traditional human reliability analysis (HRA) data collection methods. In contrast to artificial neural network (ANN) approaches, our method leverages the cognitive architecture's declarative memory, procedural knowledge, and perceptual-motor modules to replicate the complete cognitive processes of nuclear power plant operators. The simulation framework was rigorously evaluated on Tsinghua University's HTGR simulator under a variety of operating conditions, including multi-parameter queries with interface switching, parameter queries without switching, and three-phase AC operations, which notably demonstrated lower error incidence during collaborative multi-operator interactions.

Our experimental results confirm that the ACT-R-based HDT framework accurately predicts operator task completion times and error probabilities (HEPs) across diverse procedural scenarios. The HEPs are derived through model-internal tracking of production rule conflicts, goal failures, and decision latencies, which serve as mechanistic indicators of error likelihood under time pressure or cognitive overload. This model-based quantification provides a transparent and traceable way to estimate human error potential in simulated scenarios, offering significant advantages over expert-judgment-based or statistical surrogate methods.

The ability to generate scenario-specific HEP predictions enables fine-grained human reliability assessments that are context-sensitive and dynamically responsive. Such capabilities are highly valuable for nuclear safety applications, including early-stage procedural design reviews, operator training customization, and real-time risk-informed decision support systems. Unlike existing methods such as IDAC, our approach offers enhanced explainability and a comprehensive cognitive modeling capability that can inform both design and training processes.

Looking ahead, future research should focus on integrating the ACT-R-based HDT framework with traditional HRA methodologies to explore simulation-driven HRA approaches. Furthermore, incorporating advanced simulation environments, large language models (LLM), and 3D digital human representations holds significant promise for enhancing operator training and optimizing reactor safety protocols.

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