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WIP: Assessing Student Cognitive Engagement in an Interactive Advanced Virtual Radiation Detection and Measurement Lab

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WIP: Assessing Student Cognitive Engagement in an Interactive Advanced Virtual Radiation Detection and Measurement Lab

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This study aims to assess student cognitive engagement in a novel interactive virtual radiation detection and measurement lab developed for nuclear science and engineering education. As virtual labs become increasingly vital for delivering flexible and scalable technical training, this research aims to investigate how students interact with simulated radiation detection systems and with each other in the virtual environment and analyze real-time data to enhance learning outcomes.

Using the ICAP (Interactive, Constructive, Active, Passive) framework and thematic analysis, this work-in-progress study aims to evaluate different levels of engagement, focusing on how actively students construct knowledge and participate in meaningful learning processes. Data will be collected through surveys, student self-assessments, and interaction analytics to evaluate how students' interactions with the virtual tools, each other, and their instructor relate to higher-order thinking and problem-solving skills.

While the research is ongoing, we anticipate the findings will provide valuable insights into optimizing virtual lab environments to promote deeper cognitive engagement, particularly in STEM education. These findings could impact future virtual laboratory designs and instructional strategies for complex technical subjects, such as radiation detection and measurement, and other related labs in nuclear science and engineering.

Keywords: Virtual Lab, Radiation Detection and Measurements, Nuclear Science and Engineering, Online Education, Student Engagement

Introduction

The School of Nuclear Science and Engineering (NSE) at Oregon State University offers a fully online Master of Radiation Health Physics (MHP) program. This program is highly regarded and produces the most graduates of any program in the nation [1], [2]. To support the needs of our E-campus students and provide a completely online MHP curriculum, the NSE partnered with Spectral Labs [3] to develop an Advanced Virtual Radiation and Detection Measurement Laboratory (AVR-DML), the first and only advanced virtual radiation detection lab designed for graduate studies nationwide, making it a unique course. The AVR-DML has a realistic environment that allows students to experience the same system they would work in a real Nuclear Science and Engineering lab. This virtual environment has a web-based learning management system located on a central server and a 3D simulation package, downloaded locally to user machines, allowing students to coexist, interact, and engage with a real STEM lab in all its dimensions. The virtual lab's interfaces provide students with full functionality for changing the experimental setup and parameters and live data collection with real-time updates for each experiment. Experimental results can then be tracked and analyzed in an oscilloscope, Multi-channel (MCA), or Single-Channel Analyzer (SCA). Fig. 1 (a)-(b) shows snapshots of the virtual environment. Fig. 2 also depicts snapshots of (a) actual lab equipment and (b) the same virtual equipment.

(a) **(b)**

Fig. 1: Snapshots of the AVR-DML environment. (a) Data Processing Lab and (b) Spectroscopy with a NaI Detector Lab.

(a) **(b)**

Fig. 2 Snapshots of (a) a NIM bin module/oscilloscope and a GM detector in the real lab setting and (b) the same devices in the virtual environment.

The first version of this lab did not support collaboration or group work, requiring students to complete all lab tasks individually. As a result, they spent hours working in isolation without interacting with peers. Additionally, the instructor or teaching assistant was unable to monitor student progress or provide feedback. This lack of interaction could lead to feelings of anxiety, discontentedness, and loneliness, which can directly impact cognitive engagement and performance [4], [5], [6]. Student engagement and satisfaction are crucial indicators of students' academic learning and experiences. Lack of interaction in the learning environment often leads to poor student engagement, lower performance, and satisfaction [7], [8]. This issue is even more critical in online settings, where students often feel isolated and disengaged [9], [10], [11].

To address this issue, we once again collaborated with Spectral Labs to integrate Student-Student (SS) and Student-Instructor/TA (SI/TA) interactive and collaborative features into the virtual lab environment. Our goal was to enable students to conduct the lab experiments in a way that closely resembles a traditional lab setting, allowing for real-time partnership and collaboration. The new version allows students to join their designated group in the virtual environment from anywhere worldwide, facilitating real-time collaboration with their peers. In addition, they have access to all the virtual lab equipment, enabling them to interact with and adjust settings as needed during the experiment in real-time. Once students arrive in the lobby of the virtual labs, they can choose their play mode to start the lab experiments, either in single-player or multiplayer mode. Up to 10 groups of four students can simultaneously join the virtual environment and perform the lab activities. Fig. 3 displays a screenshot of the NaI detector Lab lobby, showing what students see as they enter the virtual labs.

To enhance student engagement and collaboration, we also incorporated a built-in chat box within the virtual environment, allowing students to message each other in real time. In addition to this feature, we encourage students to use a secondary communication platform such as Zoom, Teams, or Discord to facilitate their interactions. These new interactive tools will enable students to collaborate remotely and engage with their instructional team for assistance, similar to what they would experience in a traditional lab setting. This approach aims to boost student engagement, reduce feelings of loneliness and anxiety, and allow the instructor/TA to collaborate effectively with students and provide timely feedback.

Due to budget constraints, we could only add the new collaborative features to two of the five lab experiments. Once the collaborative features were completed, we piloted the labs and invited students to participate in group sessions voluntarily. This allowed us to gather feedback on the lab experience and gain insights into the usability and effectiveness of the interactive and collaborative features developed for the virtual labs. We focused on how students engaged with these features and interacted with one another while conducting the lab activities. Additionally, a student researcher conducted all the lab experiments and provided feedback. The feedback we gathered offered valuable insights into students' experiences with the virtual labs and student groupings. We addressed technical glitches in the labs and enhanced their overall appearance by refining color schemes, shadows, and usability. Our aim was to enhance both the realism of the experience and the platform's user-friendliness, ensuring smooth and engaging interactions for all users.

Furthermore, we addressed the logistical challenge of grouping students from different time zones. To tackle this issue, we will send out a survey at the beginning of the term to collect information about students' availability and preferred times. This data will assist us in forming effective groups for their lab experiments.

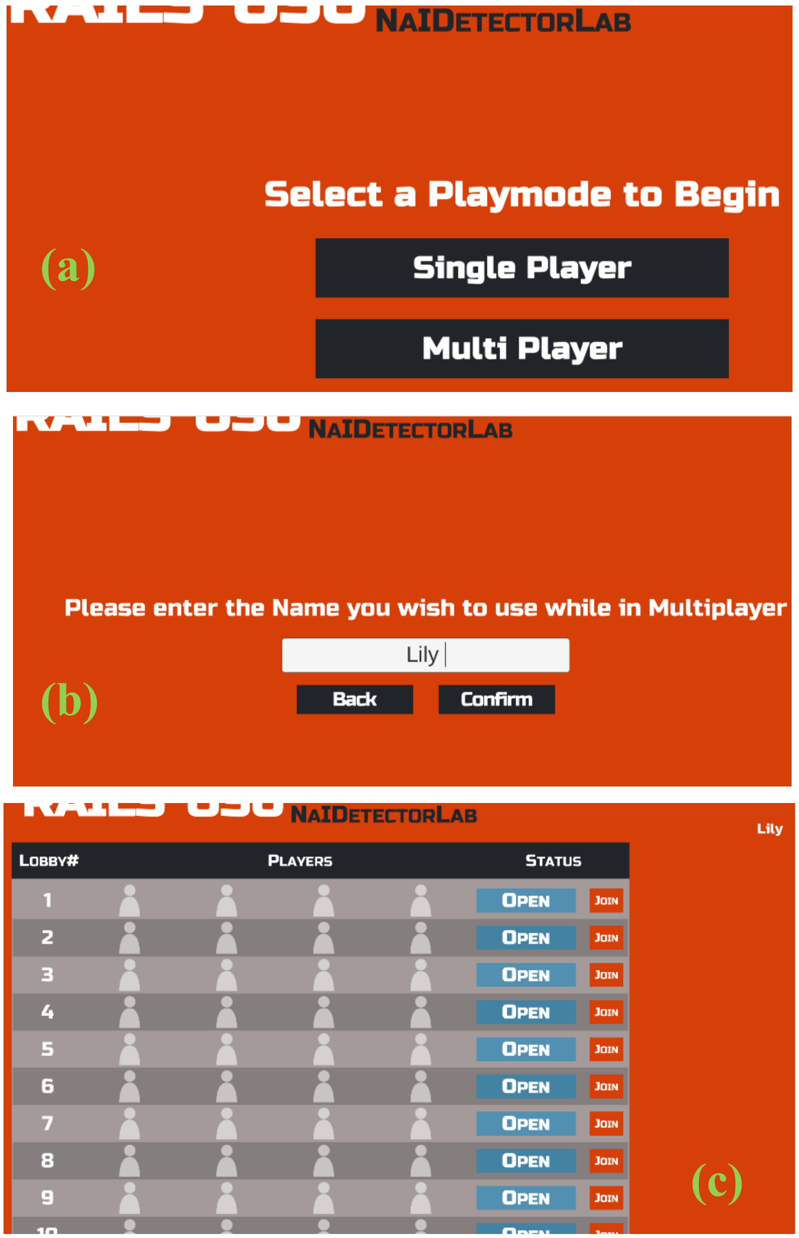

Fig. 3 (a), (b), (c) Snapshots of the NaI Detector Lab's lobby as students select to perform the lab individually, start a new group, or join a group.

In summary, the key features of the virtual labs:

- Five experiments, with two featuring interactive and collaborative elements.
- Group work capability for students.
- Monitoring and feedback provision by instructors/Teaching Assistants (TAs).
- Integration of a chat box to facilitate further student interactions.
- Utilization of external social platforms such as Zoom/Teams/Discord for enhanced collaboration.

Literature Review

According to the ICAP framework, cognitive processing is most effective when students engage in meaningful conversations about the topic with their peers and instructor [12], [13]. The foundation of collaborative learning is that learning together is better than learning alone [7]. In collaborative environments, students bring unique backgrounds and skills to the group and accomplish something together that they may otherwise be unable or hard to achieve individually. [8]. According to Downing et al. (2007), "the established role of the tutor (and instructor) is important in facilitating a supportive learning environment in the early weeks of establishing an online sense of community. (P.212)"[14]. The (SI) interaction is also essential in determining student engagement and satisfaction [9], [15]. However, more is needed to know how (SS) and (SI/TA) interactions facilitate student learning and performance in virtual advanced laboratories.

While assessments have been developed for in-person classes and laboratories to evaluate student cognitive engagement [16], [17], [18], [19], [20], comparable research has not been carried out to investigate student engagement in advanced graduate-level virtual labs. We aim to evaluate how including collaborative and interactive features in the AVR-DML impacts student cognitive engagement in the lab environment. We will identify which elements of cognitive engagement are present in the lab and how they contribute to student engagement. To achieve this goal, we will use the ICAP framework [12], [21], which allows for a detailed examination of how students engage within the virtual lab environment, providing insights into the nature and quality of their interactions in different experiments within the AVR-DML.
We will analyze (SS) interactions through the built-in chat box, external social platforms such as Discord or Teams, and (SI/TA) interactions during virtual lab activities to assess how they enhance student cognitive engagement. Additionally, we will examine how different experiments vary in promoting interactive, constructive, active, and passive engagement.

Site and Participants:

The study will be conducted within the Online Master of Radiation Health Physics Program at Oregon State University, which is the largest program of its kind in the nation. This fully online program aims to prepare individuals for careers in nuclear energy, ionizing radiation, and handling of radioactive materials, particularly in the fields of security, national defense, medical health, and safety. Through this program, students will acquire the professional skills necessary to positively impact society in areas such as energy security, national defense, medical health,

and industrial competitiveness. The coursework is tailored for those interested in radiation protection, with concentration areas that include arms control technology, nuclear instrumentation and applications, nuclear waste management, and space nuclear power.
Students in the program are required to take an online course in Advanced Radiation Detection and Measurements. This course is divided into two sections: a lecture section delivered asynchronously online and a lab section conducted virtually. After completing certain prerequisite courses, students become eligible to enroll in this advanced class.

Our target population for this research consists of graduate students who are enrolled in this course. They will review the posted online lectures and complete the required labs virtually. Students will complete the first three labs individually, without any collaborative features. After this, we will randomly group them based on a survey that captures their time zones and availability. They will then conduct the final two lab experiments with collaborative features in designated groups with their lab partners.

Methodology and Results

Step 1: Research Design

This study employs a mixed-methods approach to assess cognitive engagement in the virtual environment. Its four measurement tools are quantitative surveys, qualitative interviews, interaction analytics, and learning assessments.

- **Quantitative Surveys**

  To assess cognitive engagement levels across the ICAP categories, we will use the validated Student Course Cognitive Engagement Instrument (SCCEI) developed by Barlow et al. [22]. This tool measures engagement during specific learning activities, including notetaking, processing material, and peer interaction. This instrument will be tailored toward our research to better capture elements of cognitive engagement in the virtual environment. After validation, surveys will be developed in Qualtrics [23] and distributed to students. We will use a standard Likert scale to collect data. Students will complete pre- and post-lab surveys for individual and collaborative labs aligned with the ICAP categories. We will validate the instrument following these three steps:

  <u>1. Content Validation</u>

  We will ensure that each question aligns with the ICAP framework. This involves mapping questions to ICAP categories (Interactive, Constructive, Active, Passive) and verifying that the questions capture the intended engagement behaviors (for example, explaining ideas for Interactive or manipulating for Active). We will also seek feedback from experts with knowledge in cognitive engagement and nuclear science and engineering instructors to confirm the clarity and relevance of questions. We then will conduct cognitive interviews with a small sample of students to ensure the questions are understood as intended.

- **ICAP Alignment in Data Collection**

  The ICAP framework provides guidance for categorizing engagement activities [21].

  - **Passive Engagement**: Listening to instructions and observing simulations without interaction.
  - **Active Engagement**: Copying experimental procedures and performing step-by-step tasks.
  - **Constructive Engagement**: Generating hypotheses, interpreting data, and reflecting on experimental outcomes.
  - **Interactive Engagement**: Engaging in discussions with peers to solve problems and co-construct knowledge.

  Fig. 4 presents preliminary questions to capture ICAP engagement elements within the virtual environment. Subject matter experts in Nuclear Science and Engineering, as well as Engineering Education, will review these questions to ensure that the survey effectively gathers the necessary data to assess cognitive engagement.

  <u>2. Construct Validation</u>

  Construct validation ensures the survey measures the theoretical constructs (ICAP categories) it is designed to evaluate. For this purpose, we will use statistical tools such as factor analysis and correlation analysis. Factor Analysis conducts exploratory and confirmatory factor analyses (EFA/CFA) to determine if the questions are grouped into factors corresponding to ICAP categories. On the other hand, Correlation Analysis tests how well each question correlates with others in the same category (high within-category correlations) and less with other categories (discriminant validity).

  <u>3. Pilot Testing</u>

  We will test the survey in a smaller, controlled sample of students to identify issues before full deployment. We will collect feedback on question clarity, survey length, and technical issues. A finalized version of the survey will then be ready for larger-scale use.

In addition to surveys, we will also conduct qualitative Interviews with students, interaction analytics, and learning assessment.

- **Qualitative Interviews:** are semi-structured interviews that provide more profound insights into student experiences. These questions will focus on how collaborative activities and communication tools designed for the virtual labs shaped their engagement.

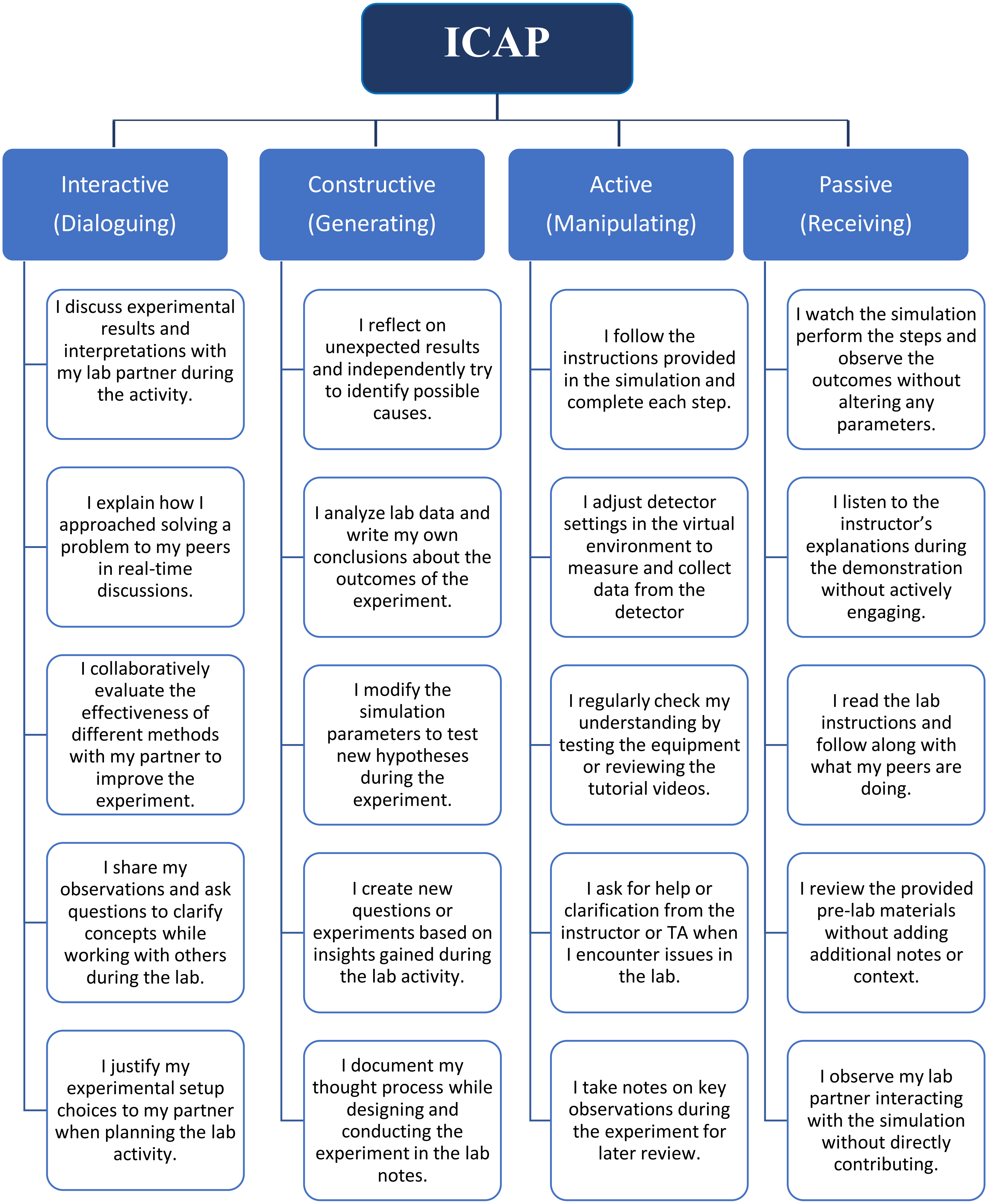

Fig. 4 Preliminary questions to capture ICAP engagement elements within the virtual setting.

- **Interaction Analytics**: Interaction data, such as chat logs and system usage patterns, will be analyzed to identify behaviors corresponding to different ICAP modes. Metrics include student discussions' frequency and depth and ability to apply knowledge collaboratively.

- **Learning Assessments**: Conceptual tests and lab reports will assess students' understanding of radiation detection and measurement principles and their proficiency in virtual experimental tasks. These assessments will be used and be correlated with ICAP-aligned engagement data.

Pilot Study:

Before implementing our study tools on a larger scale, we conducted a pilot study that included four semi-structured interviews with students who participated in the virtual labs. Of the four students, two completed the lab exercises independently, which provided an opportunity to analyze individual cognitive engagement. The other two worked together in groups, providing a different perspective on teamwork dynamics in a virtual setting. Students in the group communicated through Zoom, Teams, and the embedded virtual lab chat box while performing lab experiments.

The interview questions were developed based on the IQRT framework for qualitative inquiry [24]. We carefully transcribed the interviews and analyzed the data using thematic analysis, guided by the ICAP framework. This framework allowed us to categorize and interpret the participants' varying levels of cognitive engagement and the shared themes in students' experiences and interactions within the virtual labs.

This pilot study enabled us to collect detailed qualitative data about the participants' experiences in the virtual lab environment. It provided valuable feedback on the virtual lab settings, student interactions, and the unique challenges and advantages they encountered during their virtual lab activities. Additionally, it helped us refine our interview techniques to enhance the clarity of our questions, ensure alignment with the learning objectives, and maintain relevance to the virtual lab experience. The results also offered important insights into how the virtual lab functioned as a social agent in the participants' experiences. The next section will cover the results of this study.

Preliminary Results:

- **ICAP-Coded Interviews: Thematic Analysis Findings**

From the qualitative analysis of the ICAP-coded interviews, we found several primary themes that highlight differences between solo and group laboratory experiences:

1. Collaborative Interaction and Shared Problem Solving (Interactive Engagement) Participants in group settings discussed the importance of extensive peer interaction, emphasizing mutual support, collective troubleshooting, problem-solving, and guided discussions. They consistently highlighted the significance of collaborative troubleshooting and peer support. Students shared experiences in which they worked together to validate experimental setups and correct each other's methods. One student stated, "*We were able to help each other realize where we might have gone wrong in the steps*". This statement underscores the importance of immediate error correction and idea sharing, as well as the critical impact of interaction in fostering cognitive engagement and enriching learning. Another participant mentioned, "*I'd say, OK, I'm gonna do this and this now, actually out loud to the group,*" illustrating a metacognitive process expressed within the group. Additionally, one participant highlighted, "*We got together as a group to go through it, so we could help each other kind of go through the process*". This indicates a shared metacognitive reflection during group discussions and suggests that verbalizing steps and seeking clarification significantly improved their learning experience. Furthermore, participants observed that these interactions provided a more authentic lab experience, increasing their sense of involvement and accountability. Overall, these interactions demonstrate a high level of collaborative and interactive engagement.

2. Knowledge Construction through Inference and Adaptation (Constructive Engagement)

Solo learners highlighted the necessity of drawing on their previous experiences and theoretical knowledge to address the instructional gaps present in the virtual lab environment. Participants often engaged in trial-and-error processes. One student mentioned, "*The lab instructions sometimes weren't super clear, so I had to figure out what it probably meant.*" Another noted the need for "*deep mental processing to interpret ambiguous guidance.*" Additionally, one participant noted, "*I mean, like, some of the lab instructions are written for, like, in-person labs... so it's trial and error trying to get it to figure out what you're supposed to do.*" This engagement illustrates constructive learning, which involves formulating hypotheses and interpreting contexts. Solo learners frequently expressed a need to bridge gaps in instructions through inference and reflection. For example, one participant stated that the lab design "*Reinforced the theory*" when speaking about how the lab design prompted them to rely on previous knowledge. This theme embodies constructive engagement, where learners build upon incomplete information to develop new understanding.

On the other hand, group learners demonstrated constructive engagement through a slightly different lens, often leveraging peer dialogue to validate or refine individual interpretations. Instead of only relying on personal inference, students in collaborative settings participated in shared meaning-making. One participant reflected, *"When I wasn't sure what to do next, talking it through with my partner helped clarify what the instruction might actually mean."* Another noted, *"Even though the directions were vague, bouncing ideas off each other helped us make better sense of it."* These interactions illustrate that group learners also engaged in hypothesis generation and contextual interpretation, but with the added benefit of externalizing their thought processes and receiving immediate peer feedback. Group settings facilitated deeper construction of knowledge by encouraging learners to articulate reasoning, challenge assumptions, and synthesize multiple viewpoints, reinforcing the core tenets of constructive engagement.

3. Active Engagement in Navigating the Virtual Labs and Integrating Knowledge Autonomously (Constructive and Active Engagement)

Our interview results indicate that engaging in virtual labs enhanced students' autonomy and active learning. Students reported a notable sense of intent in navigating their tasks, which led to improved understanding and retention of materials. For instance, one student highlighted, "*You could sometimes click through the steps before the narration finished, so I got into a rhythm and could predict what came next*." This shows how students can develop predictive skills and confidence through self-paced learning. However, software constraints can also play a role in the learning process; one student mentioned, "*The only thing that it did was force me to go through those steps again*," emphasizing that these limitations prompted them to revisit and reinforce their understanding.

Collaboration in group settings also fostered deeper engagement. A participant reflected on the dynamics of their group, stating, "*One person would manipulate the detector, while another would read the instructions out loud, and a third individual entered the data.*" This active switching of roles not only kept all members engaged but also enriched the learning experience through teamwork.

Throughout the virtual lab experience, both individual and group participants described navigating the virtual lab with intent and autonomy. Examples included adapting to software limitations, completing tasks without direct instruction, and using online resources. Phrases like "*adjusting lab setup*" and "*I usually went online and went on to these discussion groups when I had a question*" illustrate Active engagement and resourcefulness that characterize successful learning in virtual environments.

4. Observational Learning and Occasional Detachment (Minimal Passive Engagement)

Passive engagement was infrequent and generally brief and transient throughout all interviews. Even when there were moments of passivity, such as briefly listening to instructional audio segments or waiting for their turn to perform a task in the lab, participants quickly returned to more actively engaging behaviors. One group participant described passivity not as disengagement but rather as waiting for their turns, especially when task roles were divided, and some members were observing: "*I'd just watch them go through it, and then it would be my turn next round*." One participant stated, "*Sometimes, team members were just watching unless it was their turn*," suggesting temporary disengagement during group work. Additionally, one participant reflected, "*It was easy to zone out a bit when you weren't the one actively doing the task*," highlighting moments of lower cognitive investment due to the pacing of the group. This finding suggests that the design of the virtual labs effectively promotes active engagement, fostering a more dynamic experience and minimizing passive engagement.

5. Differentiated Experiences Based on Learning Mode

Group members often highlighted the value of collaboration, with one student saying, "*It was great to have people with different strengths. One person might be good with calculations, another with navigating the software*." In contrast, solo participants appreciated the flexibility of working alone: "*I could take as long as I needed to figure something out without feeling like I was holding others back*." Both perspectives emphasize how group and solo dynamics uniquely influence engagement and learning.

A significant theme across the interviews was the difference in cognitive engagement between solo and group modalities. Group work facilitated more frequent transitions into interactive and constructive modes of thinking and engagement, whereas solo participation relied more heavily on constructive and active behaviors. These differences highlight the importance of collaborative structures in fostering higher-order cognitive processes.

- **ICAP Engagement Analysis**

The interview transcripts underwent careful analysis using the ICAP framework, which enabled us to identify various modes of cognitive engagement based on explicit student statements and the contextual behaviors observed during virtual lab activities. In total, we identified 36 coded instances across four semi-structured interviews. A comparative analysis of these interviews clearly revealed distinct patterns of engagement between the group and solo laboratory formats, as in Table 1.

- **Group Interviews (Interviews #1 & #3):**

  Group participants showed significantly higher interactive engagement, accounting for 43% in Interview #1 and 57% in Interview #3. Active engagement was also notable (43% in Interview #1 and 21% in Interview #3), indicative of dynamic peer collaboration and demonstrating task-oriented student behaviors. Minimal Passive engagement was observed in group interactions, underscoring effective collaborative interaction dynamics.

- **Solo Interviews (Interviews #2 & #4):**

  In contrast, solo participants predominantly exhibited Active engagement (60% for interview #2 and 40% for Interview #4), demonstrating strong individual task management and interaction with virtual lab resources. Interview #2 showed some constructive engagement at 20%, while Interview #4 demonstrated 40%, indicating analytical thinking and hypothesis generation based on prior knowledge. Minimal Passive engagement was also observed in solo participants associated with brief moments of observational inactivity. Neither solo interview displayed significant Interactive behavior.

Table 1. Summary of ICAP-Coded Instances by Interview

Interview #	Mode	Count	Representative Behaviors/Quotes
1 (Group)	Interactive	3	"Make a consensus before the next step"; group troubleshooting
	Constructive	1	"Trial and error trying to figure out what to do"
	Active	3	Assigning tasks: clicking, reading, recording
	Passive	0	Avoided by skipping passive lectures
2 (Solo)	Interactive	1	Recounting shared class discussions and instructor feedback loops
	Constructive	2	"Hands on experience reinforced the theory"
	Active	6	Adjusting lab setup, dealing with software limits
	Passive	1	Skipping video lectures to reduce disengagement
3 (Group)	Interactive	8	"Help each other through the process", guiding peers instead of giving answers
	Constructive	2	"trying to figure out why the readings didn't match what we expected", group discussion
	Active	3	Asking for help during challenges
	Passive	1	Observing during others' tasks
4 (Solo)	Interactive	1	Noted industry relevance of lab discussions
	Constructive	2	Recalled prior knowledge and field-specific application
	Active	2	Using online forums and lab videos to troubleshoot
	Passive	0	No evidence of passive engagement; student remained task-focused

Discussion:

The preliminary results of this study highlight meaningful distinctions between collaborative and individual virtual lab experiences through the lens of the ICAP framework and thematic analysis. Group-based interactions consistently prompted higher-order cognitive engagement, particularly Interactive behaviors, aligning with theoretical predictions and previous research on the benefits of peer-mediated learning within social constructivist frameworks [25], [26]. In group settings, students described moments of joint decision-making and collaborative troubleshooting that pushed them to think more deeply and clarify their reasoning out loud.

Solo learners, on the other hand, demonstrated strong Active and Constructive engagement. They approached the lab as a puzzle, one student said, *"It felt like a puzzle. I had to remember what I learned last term and try a few different ways to get the right results".* These moments of inference and reflection highlight the cognitive demands of working independently and show that solo learners are capable of rich engagement. However, without peer interactions, opportunities for Interactive engagement, like co-constructing knowledge or challenging assumptions, were understandably limited.

Notably, both solo and group moved between different ICAP engagement modes during their lab experience. Students often began with Active behaviors such as clicking through procedural steps or collecting data, and then shifted into Constructive engagement when faced with unexpected outcomes or ambiguous instructions. In collaborative settings, these moments frequently escalated into Interactive engagement as students expressed their reasoning, negotiated interpretations, and resolved conflicting ideas through discussion. These transitions, especially from Active to Constructive or Interactive engagement, seemed to occur most naturally when the lab's challenges were just complex enough to require deeper thinking, but not so hard as to feel frustrating or inaccessible.

Motivation and emotion also played a role in the virtual environment. Students in group settings more often reported feeling focused, supported, and even energized by the social dynamic. One participant said, *"Knowing someone else was counting on me made me focus more, and honestly, it made the lab more fun."* In contrast, solo learners described the experience as "rewarding but isolating," suggesting that while they appreciated the flexibility and autonomy, they also missed the sense of connection and shared accountability that collaboration can bring.

Encouragingly, Passive engagement levels were consistently low in both solo and group settings, highlighting the effectiveness of the virtual lab's design in promoting active participation. This indicates that the lab's interactive tasks and focus on active problem-solving successfully kept students engaged. However, the lack of interactive engagement among solo learners suggests an opportunity for improvement. Incorporating features such as structured peer feedback, optional discussion boards, or AI-guided reflection tools could help solo learners gain some of the benefits of collaboration, even when working independently.

While these insights offer valuable guidance, they should be interpreted cautiously due to the study's limited sample size. Only two interviews were conducted for each learning condition, limiting the generalizability of the findings. In our future research, we aim to expand the participant pool, integrate longitudinal tracking, and examine correlations between engagement patterns, affective responses, and academic performance. Such efforts will build a more robust and comprehensive understanding of cognitive engagement in virtual STEM laboratory settings.

Conclusion and Future Work

This work-in-progress study employs a mixed-methods approach to assess student cognitive engagement in a novel virtual radiation detection and measurement lab for nuclear science and engineering education. The ICAP framework was used as a central analytical lens to examine engagement patterns across both group-based and solo-based experiences. The findings demonstrate that structured collaboration significantly enhances higher-order engagement, particularly within the Interactive mode. Group participants engaged in collaborative problem-solving, consensus-building, and shared reflection behaviors consistent with social constructivist theories, indicating that peer-mediated learning plays a critical role in deepening conceptual understanding.

Conversely, solo learners showed strong Active and Constructive engagement, primarily through inference-based reasoning, problem-solving, and drawing upon prior knowledge. While the absence of peer interaction limited their access to Interactive engagement, solo learning environments fostered individual autonomy, resilience, and metacognitive processing. These findings support the idea that both collaborative and individual learning pathways hold unique strengths in virtual environments and can be strategically optimized through thoughtful instructional design.

In addition, this study highlights how students dynamically transition between ICAP modes and how virtual lab design features such as realistic simulation tools, embedded feedback mechanisms, and instructional clarity influence those transitions. The consistently low levels of Passive engagement across all learning modes underscore the effectiveness of the lab in promoting active cognitive involvement, supporting the potential of virtual labs to replicate and even enrich aspects of traditional hands-on STEM learning.

However, given the small sample size and exploratory scope, these findings should be interpreted cautiously. Building on these results, we will explore several avenues to continue this research. We will expand our sample size and use quantitative analysis to incorporate a larger and more diverse population of learners to better understand engagement patterns in varied virtual lab environments. We will also track students from the first experiment in the virtual lab until the last experiment to investigate how student engagement evolves over multiple virtual lab sessions. This will help us to track the development of higher-order cognitive skills and familiarity with collaborative technologies. We will also explore how targeted instructional enhancement supports transitions from Active and Constructive to Interactive engagement, particularly for solo learners. Examples include guided reflective prompts, peer-review tasks, and AI-driven feedback.

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