Adaptive Virtual Reality Learning Environment with a Reinforcement Learning-driven Pedagogical Agent

Sai Shreya Nuguri[†], Anirudh Kambhampati[†], Noah Glaser[†], Prasad Calyam[†],
Shangman Li[†], Cassidy Bates[+], Alia Stevens[*], Sanjana Nuguri[‡]
[†]*University of Missouri-Columbia,* [+]*Drury University,* [*]*University of North Georgia,* [‡]*University of North Texas*
Email: [†]{*snuguri, akwg7, sli, noah.glaser, calyamp*}*@missouri.edu*,
[+]*cbates06@drury.edu*, [*]*ajstev9584@ung.edu*, [‡]*sanjananuguri@my.unt.edu*

***Abstract*—With the fast evolving advances in technology to create immersive learner experiences in Virtual Reality (VR), there are significant opportunities for developing immersive and engaging VR Learning Environments (VRLEs) to train neurodiverse individuals. Integrating Pedagogical Agents (PAs) in these VRLEs has the potential for supporting neurodiverse learners by providing personalized, adaptive guidance tailored to their unique needs. However, a key challenge lies in ensuring the PAs can adapt effectively to the diverse circumstances of the learners. In this paper, we present a novel VRLE viz., uSucceed that leverages a Reinforcement Learning (RL)-driven PA to provide adaptive, personalized support to enhance the training experiences by tailoring the VRLE to the needs of neurodiverse learners. By designing the RL-driven PA algorithm to use Deep Q-Network, we study its capability in guiding the actions of the student in an ongoing learning basis. Simulation experiment results of the speed, accuracy and efficiency of the RL-driven PA in a VRLE demonstrate the benefits of our approach. These results build a strong base for future dynamic VRLE research that can be programmed to adapt based on the learners' experience.**

***Index Terms*—Virtual Reality, CyberSecurity, Reinforcement Learning, Pedagogical Agent, OpenAI, Neurodiverse Learners**

I. Introduction

Recent advancements in Virtual Reality (VR) technology are fostering the creation of immersive and engaging learning environments. These learning environments are particularly beneficial for neurodiverse learners, who often require tailored educational approaches to thrive. By adapting VR environments to individual needs, the learning experience can be enhanced to improve outcomes [1], [2]. Virtual Reality Learning Environments (VRLEs) can thus offer a transformative opportunity by delivering immersive and engaging experiences [3], making them a potent medium for addressing the challenges of neurodiverse student education.

Achieving a high level of engagement in VRLEs requires careful design that is tailored to the needs of the end users, ensuring that the environment adapts to their unique learning styles [4]. VRLEs are designed to promote game-based learning with cutting-edge technology, revolutionizing education for diverse learning needs [5]. These environments can be designed to dynamically adjust challenges and scenarios in real-time by continuously generating new VR experiences tailored to individual learning preferences and situational factors, thereby sustaining engagement and enhancing outcomes [6].

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In this paper, we present a novel VRLE viz., uSucceed to train neurodiverse learners on CyberSecurity concepts through hands-on tasks. uSucceed utilizes Unity [7] to develop immersive environments with game-like tasks and Photon Unity Networking [8] to facilitate multiplayer gameplay. The novelty of our uSucceed approach lies in the design of an OpenAI-based RL-driven Pedagogical Agent (PA) that implements Deep Q-Network (DQN) methods to guide the learners through the tasks, promoting hands-on experience and skill retention [9]. The use of VR in conjunction with advanced artificial intelligence (AI) technologies not only facilitates a more inclusive learning environment but also empowers neurodiverse individuals by providing them the tools and skills needed to succeed in cybersecurity [10].

The remainder of this paper is organized as follows: Section II reviews related work in VRLEs and identifies our research questions associated with integrating advanced technologies into VR training for neurodiverse learners. Section III describes our uSucceed solution approach and the design of the content, design of the PA and RL-methods guiding the PA. Section IV presents the results of performance evaluation on the RL-method and Section V concludes with a summary of salient findings and outlines future work.

II. Background and Related Work

For neurodivergent learners, especially autistic individuals, VR provides valuable support tailored to their learning needs [11]. Early work in [12] identified VR's potential in training neurodivergent learners, and recent studies continue to explore its use in educational and therapeutic settings [13], [14]. VR has been used to teach skills such as public transportation [15], social skills [3], and emotion recognition through facial expression systems [16]. While research has focused on social interactions, there is a growing need for VR applications in workforce development and daily living skills [17]. Another challenge is customizing VR scenarios for diverse neurodivergent learner preferences [18].

Recent advancements in AI technologies offer promising solutions for creating tailored and adaptable VR experiences that address the unique needs of learners [18]. VRLEs facilitate environments designed to dynamically adjust task difficulty and challenges in real-time based on learner performance and environmental context [5], as seen in [19] where the authors use a neural network to monitor performance and a fuzzy inference system to map performance deficits to instructional techniques.

A Pedagogical Agent (PA) is an AI-powered conversational agent, often represented as a virtual character, that supports students' learning processes by employing various instructional strategies in interactive learning environments [9]. The use of PAs in VR environments has shown promise in enhancing educational experiences for neurodiverse individuals by offering tailored feedback and interaction strategies to improve engagement and attention [20]. Despite challenges such as sensory overload, AI-driven monitoring systems provide additional support, enabling real-time, adaptive guidance that fosters inclusivity and enhances learning outcomes for neurodiverse students [6], ultimately creating more conducive learning environments [21] and enriching overall educational experiences [22].

Our uSucceed work builds on the need for innovative approaches that combine theoretical knowledge with practical skills [23] and the need for immersive, tailored and engaging learning environments that are beneficial for neurodiverse learners to enhance the learning experience and improve outcomes [1]. With the backdrop of cybersecurity education with hands-on tasks in a VRLE, our work with uSucceed uniquely features the design and implementation of an OpenAI-based PA implementing DQN methods to adaptively guide the learner through the tasks, we study the factors that enhance the learning experience and improve skill retention. Specifically, our study is guided by the Research Question (RQ): ***How can RL-driven PAs, using DQN methods, be effectively designed and integrated within VRLEs to provide adaptive guidance tailored to learners?***

In this paper, we aim to address RQ with the integration of Dialogflow [24], Unity, OpenAI [25], and Amazon Web Services [26], alongside the implementation of DQN methods [27] and focus on assessing improvements in learning by comparing PA performance with- and without- DQN methods.

III. uSucceed Solution Design

In this section, we outline the system architecture of uSucceed and focus on three key aspects: Design of the Content for Cybersecurity Education, Design of the PA, and Design of the RL-method guiding the PA.

A. System Architecture

The system architecture of uSucceed, as illustrated in Figure 1, is designed to provide an adaptive VRLE for educating neurodiverse individuals on skills to defend against cyber attacks. Built with Unity 2022.3.9f1, it utilizes assets like Photon Unity Networking (PUN2) [8], UltimateXR [28], and Meta XR All-in-one SDK [29]. These tools enable multiplayer interactions in an immersive VR environment where learners participate in simulated cyber attacks and engage in hands-on cybersecurity training, guided by a PA.

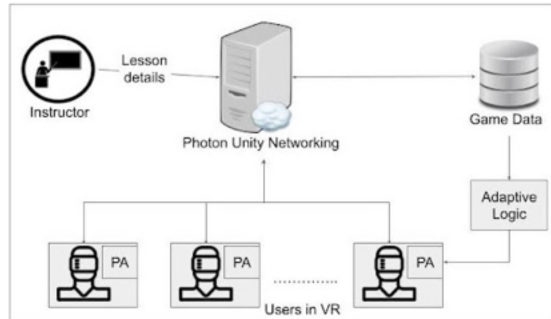

Figure 1. Overview of uSucceed Multiplayer System Architecture using Photon Unity Networking.

B. Design of Content

The VRLE supports collaborative learning by simulating cyber attacks such as DDoS, where learners take on roles like User, Attacker, and Defender — each with unique tasks and interactions tailored to their role within the simulated DDoS attack. For instance, learners in the "Defender" role perform security checks on servers while receiving guidance and support from their PA, as seen in Figure 2. PUN2 synchronizes player actions and game states in real-time, ensuring seamless interaction. The user interface, designed with clear fonts, color-coded buttons, and relevant imagery, enhances user experience while promoting collaborative problem-solving. Dynamic synchronization of player actions further enriches the immersive learning experience.

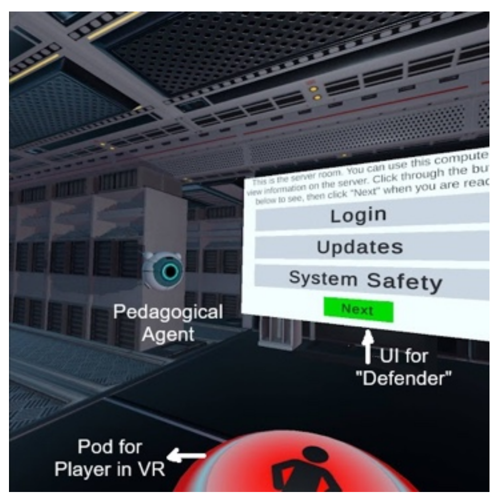

Figure 2. A snippet of the prototype UI design for the gameplay in uSucceed VRLE and the PA assigned to the learner role.

C. Pedagogical Agent Implementation

The RL-driven PA plays a key role in answering RQ1 by offering personalized, real-time feedback that adapts to the learner's pace. The PA combines Unity, Google Dialogflow [24], AWS [26], and the OpenAI Plugin for Unity [30], creating an immersive VR world for cybersecurity learning.

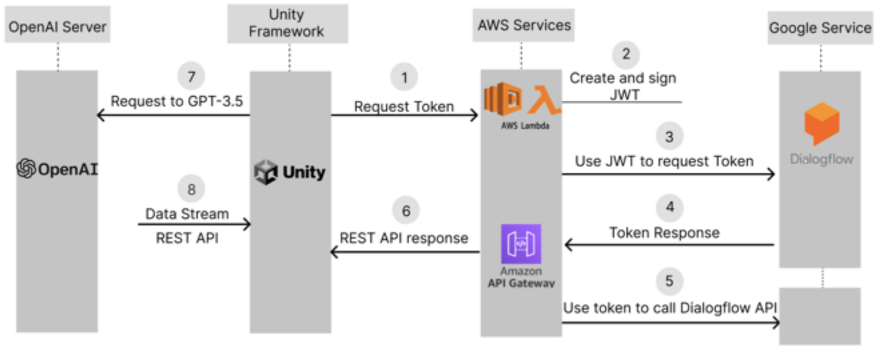

Figure 3. API communication between Dialogflow, OpenAI and Unity enabling users to interact with the PA to learn cybersecurity skills.

Dialogflow manages user queries for personalized interactions, while AWS Lambda automates access token generation. ChatGPT handles cyber attack queries, and Whisper [25] provides multilingual support. Amazon Polly [31] manages speech interactions. The PA uses DQN-based deep RL methods to adapt guidance based on performance, offering targeted support, especially for neurodiverse learners.

The environment simulates a multi-level setting where the agent encounters various cyber attacks, each represented by a distinct state. The agent selects actions corresponding to mitigation strategies, with rewards for effective actions and penalties for delays. The state, action, and reward spaces are defined as follows:

- State Space: Represents the current attack scenario the agent faces, defined by the number of possible attacks in a level.
- Action Space: Consists of recommended mitigation strategies to counteract cyber attacks.
- Transition Dynamics: Govern progression through levels based on task completion.
- Reward Function: Positive rewards are given for correct mitigation actions, and negative rewards for inaction or delay.

The goal is for the agent to learn a policy that maximizes cumulative rewards over time. Algorithm 1 details the training process using DQN with experience replay.

IV. Performance Evaluation

In this section, we provide a comprehensive analysis of the performance of our RL-based PA algorithm. We address the RQ by evaluating the RL-driven PA's performance through reward trajectories across episodes, demonstrating its effectiveness in enhancing cybersecurity learning.

The performance evaluation of the RL algorithm is essential to assess its effectiveness in learning and decision-making tasks. Initially, when the RL algorithm operated without employing DQN, the rewards obtained over episodes displayed a fluctuating pattern, suggesting suboptimal learning. This observation highlights the necessity of enhancing the learning process. By incorporating DQN, our PA became more proficient at learning from its interactions with the environment. The iterative refinement of Q-values through experience replay and neural network updates allowed the PA to make more optimal decisions in diverse scenarios. Figures 4 and 5 illustrate this improvement, showing an upward trend in rewards, which signifies enhanced decision-making and policy development by the RL-based PA. The exploration rate (ϵ) was initially set high to encourage broad exploration, and then gradually reduced as the PA became more confident in its decisions. This balanced exploration and exploitation

Algorithm 1 Deep Q-Network with experience replay

Initialize replay memory to fit the model
Initialize a random action based on level
For each episode in range(num_episodes):
  Reset state & observation and reshape state size
  For each time in range(num_epochs):
    Append state, observation, reward(R), done flag to memory
    If random $\leq \epsilon$:
      Return random action
    Else:
      $q\_values \leftarrow$ predict state from the model
      Return $\max q\_values$
    State $\leftarrow$ next_state
    If done $\leftarrow$ True: Break
If agent memory exceeds buffer:

$$\text{target} = \begin{cases} \text{R} + \gamma \cdot \max(\text{model.predict(next\_state)[0]}) \\ \text{R} \end{cases}$$

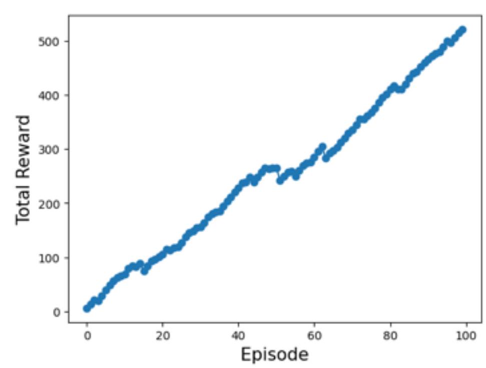

Figure 4. Training progress as seen in the Reward space *with* DQN.

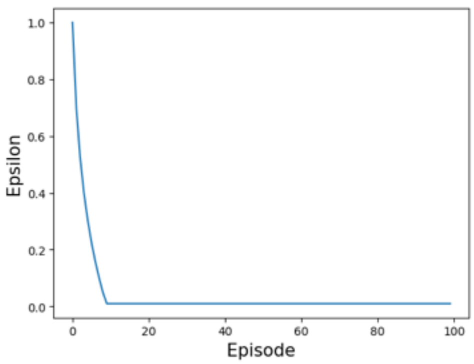

Figure 5. Epsilon decay showing exploration-exploitation trade-off.

approach led to better decision-making, with the PA eventually relying more on its learned policy to maximize rewards. The simultaneous increase in rewards and decrease in epsilon highlighted the PA's learning trajectory and its effectiveness in guiding learners toward better outcomes.

V. Conclusion

In this paper, we introduced uSucceed, a novel VRLE for cybersecurity education, designed to enhance learning outcomes for neurodiverse learners through the integration of PAs and an RL-driven method to adaptively guide the students. We demonstrated how pedagogy guidance, powered by an OpenAI-based RL-driven PA integrated with technologies like Google Dialogflow, AWS, and OpenAI, can enhance a VRLE by providing tailored guidance, thus, improving learning experiences and engagement. Future work will focus on refining uSucceed's adaptability and personalization, by the design and implementation of an RL-driven adaptive logic. By conducting usability tests with neurodiverse learners, and the integration of experience-driven and context-driven procedural content generation in the VRLE, building on recent research, we aim to enable a more nuanced adaptation to both user interaction and external conditions. Consequently, it can lead to future VRLE designs that offer a highly personalized learning experience where content evolves in real-time to meet each learner's unique needs.

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