Extended Reality for Cleanroom Simulation and Augmentation in Nanotechnology Classroom

Mr. Joshua Stoner, The George Washington University

Joshua Stoner is a first-year Ph.D. student in Computer Engineering at The George Washington University, where he works in Dr. Gina Adam's lab. He has a background and ongoing interest in Extended Reality (XR) and its applications in educational and training environments. His current research focuses on developing augmented reality (AR) and virtual reality (VR) tools for cleanroom training. He holds a B.S. in Computer Engineering from Elizabethtown College.

Zhuolin Yang, The George Washington University

Zhuolin Yang received the B.S. degree in computer science from Laurentian University, Sudbury, ON, Canada, in 2018 and the M.S. degree in computer science from the George Washington University, DC, USA, in 2020. She is currently pursuing a Ph.D. degree in computer engineering at the George Washington University, DC, USA. In 2020, she joined the Adaptive Devices and Microsystems Group at GWU. Her research interests include the development of hardware-mappable algorithms, particularly training methods for distributed memristive circuits and integrated algorithmic solutions for high-resolution cardiac monitoring, as well as the application of extended reality technologies in education and training.

Sean Letavish, The George Washington University

Sean Letavish is a former GWU student, completing his Master's in Electrical Engineering in 2023. He is a former NASA electrical engineer, and is currently a Systems Engineer at Collins Aerospace in Annapolis Maryland.

Lucian Blanks, Gallaudet University

Lucian Blanks is a Hard of Hearing researcher who earned a B.S. in Biology and Public Health from Gallaudet University and a B.A. in Philosophy from St. Catherine University. Their interests include biochemistry, accessibility, and interdisciplinary research.

Dr. Paul S. Sabila, Gallaudet University

"Dr. Sabila is a Professor of Chemistry in the Biology and Chemistry Program within the School for Science, Technology, Accessibility, Mathematics, and Public Health (STAMP) at Gallaudet University.

Dr. Sabila completed a post-doctoral fellowship in 2008 in the Department of Medicinal Chemistry, School of Pharmacy, at the University of Connecticut. He earned his Ph.D. in Organic Chemistry from the University of Connecticut in 2006 and his bachelor's degree, summa cum laude, from the University of Nairobi in Kenya in 1999. His Ph.D. dissertation focused on the synthesis of strained and heterocyclic organic compounds. During his doctoral studies, he completed an internship at Boehringer-Ingelheim Pharmaceuticals, Inc. in Ridgefield, Connecticut.

Additionally, Dr. Sabila has worked as an Assistant Quality Control Manager at Gesto Pharmaceuticals in Kenya and as a Medical Sales Representative at Phillips Pharmaceuticals, also in Kenya. He is a member of the American Chemical Society, Organic Division.

Dr. Gina Adam, The George Washington University

She received a Ph.D. degree in electrical and computer engineering in Dmitri Strukov's group and a M.A. degree in teaching and learning from the University of California, Santa Barbara in 2015. She was a research scientist with the National Institute for R&D in Microtechnologies (IMT Bucharest) and a visiting scholar at École Polytechnique Fédérale de Lausanne (EPFL). Amongst her scientific achievements are the first demonstration of a stacked RRAM crossbar with 4 bit precision, high yield functional integration of stacked RRAM onto foundry CMOS and the first perceptron network implemented in monolithically integrated RRAM crossbars. Her honors include the International Fulbright Science

and Technology Award (2010), the Mirzayan Fellowship at the U.S. National Academy of Engineering (2012), the Marie Sklodowska Curie Individual Fellowship from the European Commission (2016), the AFOSR Young Investigator Program Award (2023), the NSF CAREER Award (2023), and the DOE Early Career Research Program Award (2024). She also received the GW Engineering Outstanding Early Career Teaching Award (2022), the GW-wide Morton A. Bender Teaching Award (2023), the Northeastern Association of Graduate Schools Doctoral-level Teaching Award (2024), and the IEEE HKN C. Holmes MacDonald Outstanding Teaching Award (2024).

Extended Reality for Cleanroom Simulation and Augmentation in Nanotechnology Classroom

Abstract

With the growing reshoring of U.S. semiconductor manufacturing, there is a growing shortage of qualified professionals. However, training future experts in the design, fabrication, and testing of nanoelectronics and semiconductor chips requires adequate cleanroom facilities. Since these facilities are expensive to operate and maintain, previous efforts have explored fully virtual reality (VR)–based training environments. Nevertheless, users of VR simulators can experience challenges such as nausea, motion sickness, discomfort, and reduced sense of physical presence. Hardware limitations that confine training to fully virtual environments exacerbate these issues even further and can be significant barriers to effective learning. To address this workforce development gap and enhance training opportunities, this paper investigates the use of Extended Reality (XR) tools to supplement and integrate lab activities within an academic cleanroom facility.

Two XR methods were developed in line with physical equipment in the cleanroom facility at the George Washington Nanofabrication and Imaging Center (GWNIC). The first method is a VR-style simulation, operating independently of a physical lab space. The second is a headset-based augmented reality (AR) experience, designed to augment existing lab environments with virtual tools and procedures.

A comparative evaluation was conducted to assess user experience across both methods. Although the sample size was relatively small (N = 13) and participants had varying levels of prior cleanroom experience, the results revealed several notable trends. A higher proportion of students reported that movement in the AR-based movement felt "more natural," and slightly fewer students experienced motion sickness in the AR environment. However, many students found the AR interface less intuitive to control compared with the VR simulation.

Based on collected data and user feedback, this paper discusses which XR training tools most effectively support student learning and engagement. It also explores strategies for enhancing classroom and lab environments beyond the scope of this study, aiming to balance resource availability with the quality of the learning experience. While XR training tools may never supplant on-hand education, these results show that such simulation capabilities prove a valuable supplementation for students in the physical space and can substitute when lab equipment is inaccessible.

Introduction

Recent U.S. government policy increasingly encourages domestic semiconductor fabrication to support national defense and supply-chain stability, as exemplified by recent government stakes in companies such as Intel [1]. It is becoming increasingly apparent that the demand for individuals trained and familiar with cleanroom operation and standards will continue to grow. This trend has been widely noted in the context of semiconductor and nanoelectronics education, where access to fabrication facilities is already limited by cost, safety requirements, and capacity constraints [2], [3]. A reasonable expectation from this shift is that existing facilities within the United States may struggle to simultaneously meet expanding production demands while also training the workforce required to staff new or expanded fabrication sites.

One potential solution, and the focus of this paper, is the use of extended reality (XR) environments to supplement early-stage cleanroom familiarization and procedural training. Prior work has demonstrated that immersive XR environments can effectively support laboratory preparation by allowing learners to explore equipment, workflows, and safety protocols in advance of hands-on instruction [4], [5], [6]. As a training approach, particularly under resource constraints, this strategy is not without precedent. XR-based simulators have long been employed in aerospace, defense, and other safety-critical fields to provide exposure to complex systems while reducing cost, risk, and time demands associated with training on physical equipment [7], [8].

The novelty of this paper is its direct comparison of two extended reality (XR) training modalities, fully immersive virtual reality (VR) and headset-based augmented reality (AR), implemented around the same cleanroom sputtering process within a nanotechnology classroom. While prior work has largely examined VR-based cleanroom simulations in isolation, this study evaluates how VR and AR differentially impact student experience, usability, and human factors such as motion sickness, preferred methods of movement, and interaction intuitiveness. By comparing both XR approaches with identical educational objectives, this work provides insight into how each modality can best supplement cleanroom training under real educational constraints and student preferences.

This paper is organized as follows. Section II reviews related work in XR-supported laboratory and cleanroom education. Section III describes the VR and AR system implementations and study methodology. Section IV presents quantitative and qualitative results from student evaluations, followed by a discussion of implications, limitations, and design considerations in Section V. Section VI concludes the paper and outlines directions for future work, emphasizing the role of XR as a complementary tool to hands-on cleanroom instruction.

Prior Work

Early works on virtual laboratories highlighted significant limitations stemming from the technological maturity of the time [7], [9], [10]. While they recognized the potential of virtual labs to expand access to STEM education, they noted that distance learning in science and engineering was still lagging behind other fields due to the limited interactivity, realism, and scalability of early systems. Hardware constraints, network bandwidth, and the lack of immersive interfaces restricted the ability of these platforms to replicate authentic laboratory experiences. As a result, adoption was slow and outcomes were often less effective compared to hands-on labs, underscoring a need for more advanced immersive technologies that later studies began to address [7], [11].

Recent efforts have explored the use of immersive virtual reality (VR) simulations to augment hands-on nanofabrication and cleanroom training [2], [6], [9]. The goal has been to address well-known barriers such as limited physical access, safety concerns, and instructional capacity in hands-on laboratory environments. A prototype VR cleanroom simulation was previously developed at George Washington University for nanoelectronics education [3], embedding a 45-minute interactive module that guides learners through the workflow for fabricating micro-scale resistors, from sample preparation to electrical characterization. A mixed-methods study with five students enrolled in a university-level nanoelectronics course indicated that users found the simulation useful for repeatedly exploring cleanroom spaces and sequence logic in a risk-free, repeatable setting, which contributed to increased confidence in later engagement with an actual cleanroom facility. Participants also provided recommendations for interface and learner-experience improvements [3]. VR simulation has also been used to prepare students for complex equipment operation such as sputter deposition and vacuum systems, where virtual practice increases student familiarity and reduces the likelihood of errors during real equipment use [4]. What is often missed, or even highlighted as a failure, within these papers are the overall "soft factors" that contribute to making these experiences complete educational experiences. Often, selected users are hindered in their learning by the onset of motion sickness, which can prevent them from fully engaging with the learning environment [3], [5], [7].

Previous works have explored the use of AR as a tool for simulating cleanrooms, with some finding the technology either too immature or too expensive to develop, thereby limiting the potential benefits the platform could offer [12]. Others have investigated mobile devices as a potential AR medium, leveraging the ubiquity of cellphone cameras and processing power [13]. One user expressed frustration with the implementation of AR, stating, “I found this app unnecessarily complex.” In contrast, another team applying AR in chemistry education found that most users agreed their app could serve as a substitute for in-class exercises, particularly in situations where hands-on experience is less feasible [11], [14], [15]. While these studies often take a comparative approach, evaluating multiple learning methods beyond hands-on training

[12], [13], they typically examine only one implementation method at a time, using other studies as a point of comparison. To address this limitation, this paper aims to evaluate multiple XR simulators using the same participants, thereby controlling for participant variability and enabling more direct comparisons across platforms.

Methodology

This paper looks at both VR and AR simulation environments, towards developing future digital twins and supportive assistants that the students can utilize comfortably in a training environment. Two XR training environments were developed for this study: a Virtual Reality (VR) Simulation and an Augmented Reality (AR) simulation based on microfabrication facilities in real cleanroom space (Figure 1). The Virtual Reality (VR) Simulation provides a fully virtual, headset-based VR cleanroom environment that replicates the sputtering process performed in the physical laboratory (Figure 1a-b). This virtual environment operated independently of any physical lab spaces and included a full tutorial section. The virtual setting modeled both the full university cleanroom facility and the adjacent instructional classroom, with a dedicated virtual room that housed the sputtering system used for training. The augmented reality simulator allows virtual tools and procedural guidance to be overlaid directly onto the physical laboratory environment to guide the students' hands-on experimentation (Figure 1c-d).

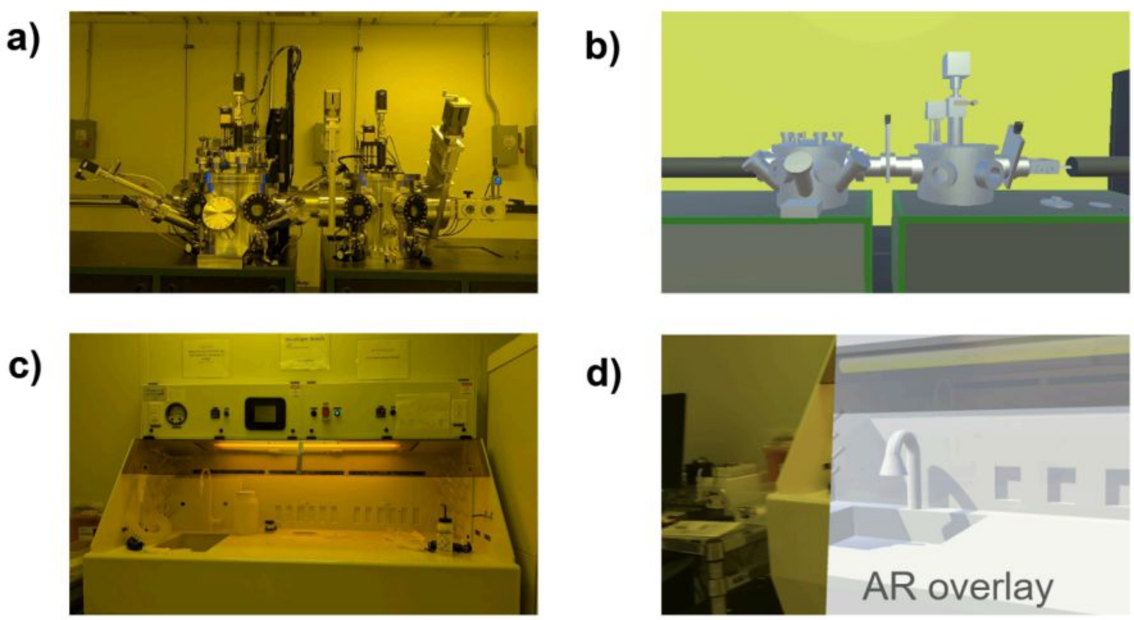

Fig 1: A comparison of the real vs. simulated facilities. A sputtering system in a) the physical laboratory space vs. b) in VR. A lab bench in c) the cleanroom vs. d) with overlayed AR capabilities.

Both simulators were based on a dual-chamber sputtering system in the university cleanroom facility. The sputtering system was modeled using a computer-aided design (CAD) program and imported into a Unity-based development framework. Custom interaction logic was implemented using Unity in conjunction with OpenXR and Microsoft XR toolkits to make the simulator experience and support multi-platform functionalities. The VR version of the simulator was deployed on a Meta Quest headset tethered to a laptop (Figure 2a), while the AR version of the simulator was deployed on a Microsoft HoloLens headset running independently (Figure 2b).

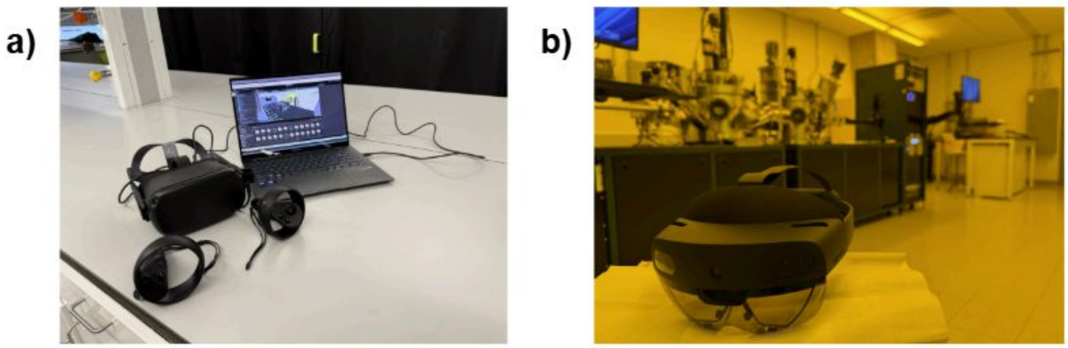

Figure 2: Equipment used for the simulators. a) An example of the Quest device and laptop used, and b) a HoloLens with an AJA sputtering system in the background

The simulator guides students through a structured, step-by-step representation of the sputtering process, beginning with entry into the virtual cleanroom environment, where the student will be met with the AJA sputtering system as seen in Figure 3a. Students first attach the substrate to the holder using a pair of tweezers and load it into the load-lock chamber as pictured in Figure 3b, after which the load-lock is sealed. Using a paddle mechanism, the substrate is transferred from the load-lock into the main chamber and secured in place. Once the substrate is in position, the paddle is retracted and the connection between the load-lock and main chamber is closed, as seen in Figure 3c. The main chamber is then pumped down to the required vacuum conditions, after which students initiate the sputtering process using the controls in Figure 3d.

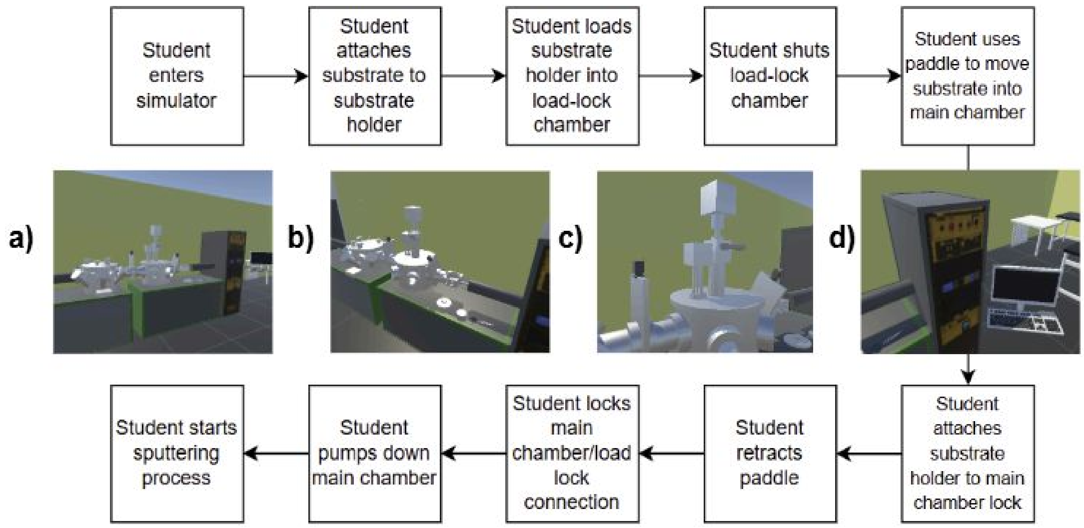

Figure 3: A general step-by-step of the simulator experience. a) Overview of on-axis portion of sputtering machine; b) Loading area of sputtering machine; c) Load-lock and main chamber connection; d) Computer and cabinet controls for sputtering machine

A total of 13 undergraduate and graduate students enrolled in a George Washington University ECE 4160/6260 Introduction to Nanoelectronics course participated in the study. Participants had varying levels of prior experience with XR technologies and differing backgrounds in nanoelectronics. Participants had varying levels of prior experience with XR technologies and differing backgrounds in nanoelectronics. All participants possessed a baseline understanding of the relevant context provided by the courses in which they were enrolled. Participants were randomly assigned to groups to determine their scheduled time slots for use of the AR or VR experience. All participants had the opportunity to utilize both the AR and VR experiences, with the AR experience limited to 15 minutes per student, while the VR experience could be used by each student for up to 45 minutes. Instructions were given within the VR and AR experience; however, instructors were also available to assist students when they had additional questions.

Data Collection

Data was collected using a pre- and post-simulation questionnaire to capture participants' prior experience, perceptions, and learning outcomes associated with both the AR and VR training environments. Participants completed a pre-simulation questionnaire to assess baseline familiarity with cleanroom equipment and protocols, prior experience with gaming and XR devices, and previous use of the vFabLab simulator in class. Demographic information was collected, including academic year and program of study. Susceptibility to motion sickness or nausea was also a particular focus during this portion of the questionnaire.

After completing the XR training, participants completed a post-simulation questionnaire that evaluated multiple aspects of the AR and VR experiences. Quantitative items included: Frequency of motion sickness or nausea experienced during AR and VR. Preference for VR movement methods (real-world motion vs. game controls) and posture (sitting vs. standing). Perceived naturalness of movement in AR and VR. Clarity of instructions, visual quality of virtual elements, and engagement compared with hands-on training. Self-reported improvement in cleanroom procedures and sputtering machine operation. Identification of areas requiring improvement (visuals, instructions, controls)

Qualitative responses were collected through open-ended questions asking participants to explain their experiences with AR and VR, suggest improvements, and reflect on how each training modality supported their learning.

Results

Figure 4 shows the proportion of participants who report experiencing motion sickness in real life, the VR simulator and the AR simulator. Almost half the participants experience some level of motion sickness in real life. A similar percentage of participants experience motion sickness in the simulators, with the severity increasing in the simulators. In the VR environment, the participants experienced slightly more motion sickness on average, with ~46% reporting some motion sickness, more often and more severe than the AR experience. For the AR environment, ~38% of users experienced some form of motion sickness, which limited prolonged interaction for a select few of those individuals. However, it is important to point out that the participants experience less motion sickness in the augmented reality environment. Overall, there is a high level of correspondence when comparing those who report motion sickness and real life vs. those who reported motion sickness in the simulator. Improvements have to take into consideration ways of reducing motion sickness, particularly for participants more predisposed to it.

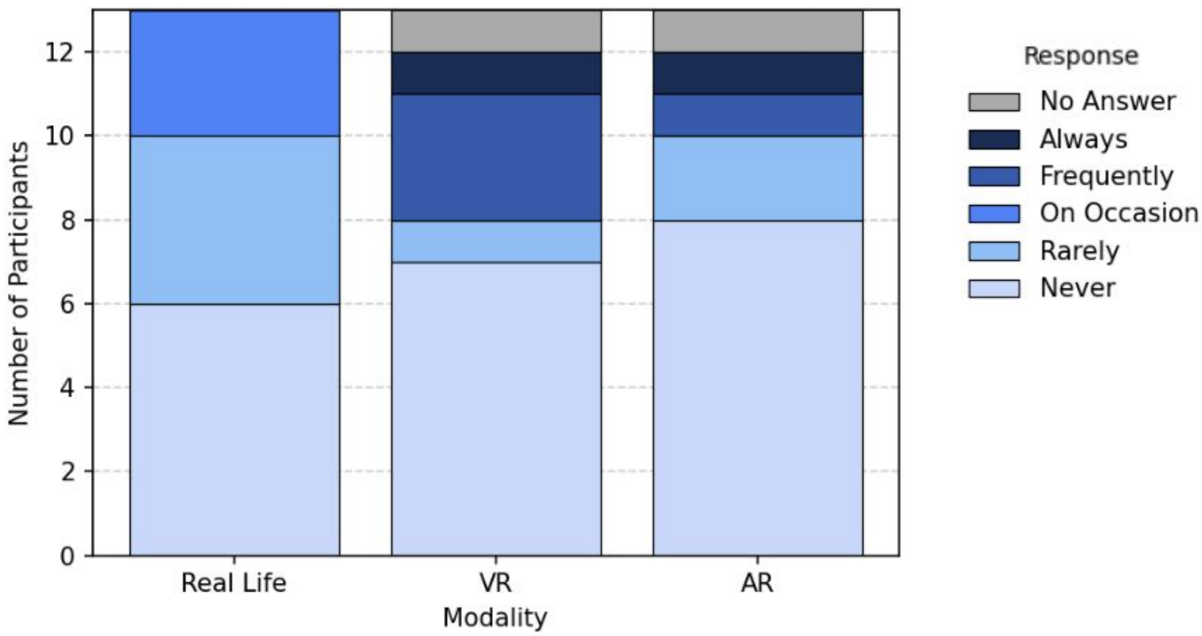

Figure 4: User self-reported degree of motion sickness in real life vs. proposed VR/AR experiences

A key part of the issue with motion sickness and overall usability seems to be related to issues of controls and visuals. As shown in Figure 5, the majority of the participants provided feedback that controls should be improved. It was a major problem for both the simulators, but overall the participants found the AR controls harder to handle. Minor feedback was offered for visuals and instructions. Participants provided more detailed feedback in open-ended questions.

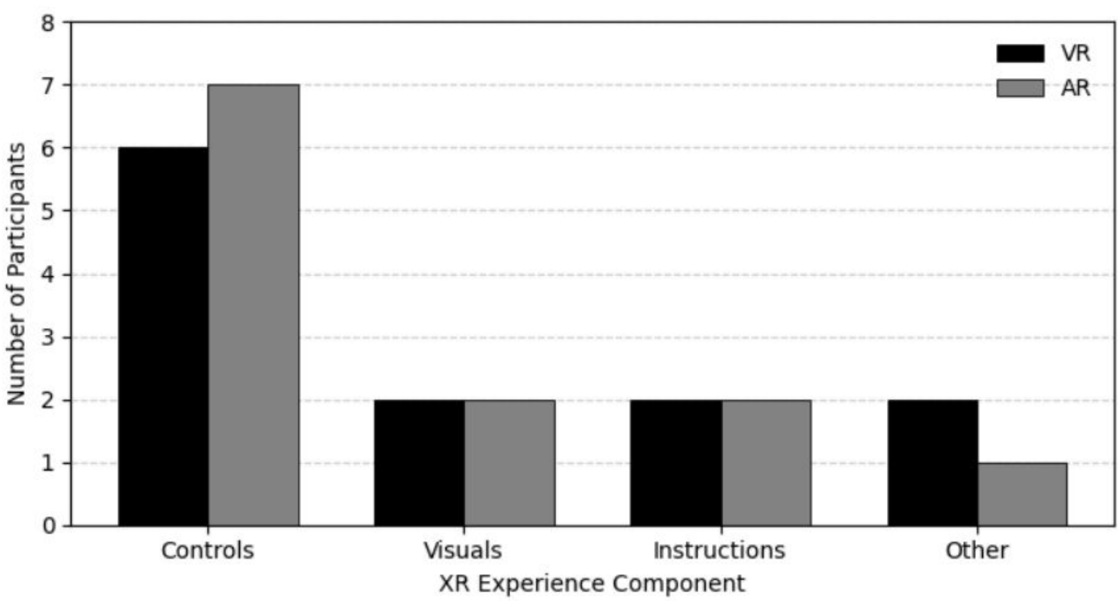

Figure 5: Participant feedback on which portion of the simulator they felt needed improvement

In the open-ended portion of the survey, the participants reported generally positive experiences with both the AR and VR cleanroom simulations, although each modality exhibited distinct advantages and limitations. The VR experience was broadly well-received. Participants emphasized the value of the one-to-one replication of the physical lab, which allowed safe, repeated practice of cleanroom procedures. Controls relying on button presses were intuitive, though minor usability issues were reported, including difficulty with door operations and object placement. Visual fidelity was generally higher than in AR, although occasional blurriness was observed. Several participants experienced motion sickness. Recommendations for improvement included more explicit instructional cues, enhanced visual feedback, and integrated task tracking.

The participants highlighted the immersive nature of the AR environment, particularly the hand-tracking interactions, which facilitated engagement with procedural tasks. Instructor guidance was noted as important for effectively navigating the simulation. Participants identified challenges related to visual clarity and fine motor control, especially when manipulating wafers with tweezers. Suggestions for improvement included implementing a virtual floor or recovery mechanism for dropped objects, as well as a task checklist to monitor procedural progress.

Across all participants, several recurrent themes emerged: the importance of instructor support, e.g., "*Having someone along with us to explain the process was very helpful.*", the need for task monitoring and error recovery mechanisms, and the trade-off between immersion and usability. Motion sickness and occasional control difficulties were identified as limiting factors as users reported in their feedback, e.g., "*Very cool but got too dizzy*!", but overall, XR simulations offered practical hands-on learning opportunities that were not feasible with traditional computer-based simulations alone.

While the in-person training was consistently regarded as the most effective modality for learning, the VR and AR were perceived as valuable supplements. According to users, VR closely approximated the in-person experience, allowing procedural practice in a controlled environment, while AR primarily supported spatial orientation and interactive engagement. Participants indicated that combining in-person instruction with XR simulations provided the most comprehensive learning experience. Repetition across modalities was frequently cited as critical for reinforcing procedural knowledge and building confidence. 75% of participants indicated that they would be interested in future cleanroom/nanofabrication learning experiences in VR/AR.

Discussion

The findings of this study reinforce prior work suggesting that extended reality (XR) technologies function most effectively as complementary tools rather than replacements for hands-on laboratory training in nanoelectronics and cleanroom education[2], [3], [7]. While in-person instruction remains essential for developing fine motor skills and procedural precision, the results indicate that XR environments, particularly virtual reality (VR), can meaningfully support pre-laboratory preparation by familiarizing students with equipment layouts, process sequences, and safety protocols. This aligns with earlier studies demonstrating that VR-based rehearsal can improve learner readiness and confidence before entering physical cleanroom environments [4], [5], [6].

The stronger association between VR use and perceived procedural understanding may be explained by the modality's capacity for high-fidelity spatial replication and repeatable practice. Prior research has shown that one-to-one virtual reconstructions of laboratory spaces allow learners to mentally map procedures onto real-world environments, reducing cognitive load during subsequent physical execution [5], [6]. Additionally, the ability to repeat tasks without risk or resource constraints has been identified as a key advantage of VR-based cleanroom training, particularly in settings where access to fabrication facilities is limited or tightly scheduled [2], [3]. These characteristics position VR as a particularly effective tool for procedural familiarization and early-stage skill development.

In contrast, augmented reality (AR) appears to offer strengths that are more closely aligned with guided instruction and conceptual reinforcement. Previous studies have shown that AR can enhance spatial understanding and learner engagement when layered onto physical contexts, especially when paired with instructor-led activities [9], [11]. However, limitations in visual resolution and interaction precision have been noted in the literature as ongoing challenges for AR in laboratory environments, particularly for tasks requiring fine motor control [9]. These findings help contextualize the observed need for instructor support and suggest that AR may be most effective when integrated into structured, supervised learning scenarios rather than as a standalone training modality.

Human factors such as motion sickness, usability friction, and interaction fatigue continue to play a critical role in shaping learner experience across XR platforms. Prior work consistently identifies simulator sickness as a limiting factor in immersive environments, with implications for both session length and learning effectiveness [5], [7], [10]. These challenges underscore the importance of prioritizing ergonomic design, adjustable locomotion schemes, and clear feedback mechanisms in educational XR systems. Design features such as task checklists, error recovery options, and object reset mechanisms, frequently recommended in the literature, may help mitigate these issues and improve overall usability [2], [6].

Several limitations should be considered when interpreting these findings. The study involved a relatively small sample size (N=13) and relied primarily on self-reported data, which may limit the generalizability of the results. Additionally, differences in exposure time between AR and VR experiences may have influenced participant perceptions. Future work will aim to address these limitations by expanding participant cohorts, incorporating an easy-to-access XR experience, and developing more personalized, guided XR systems to better support individual learning needs.

Taken together, these findings support a multimodal instructional model in which XR-based rehearsal complements traditional instruction rather than attempting to replace it. Previous research indicates that combining virtual practice with in-person laboratory experiences can enhance knowledge retention, reduce learner anxiety, and promote smoother transitions to real-world environments [3], [6], [7]. Within the context of cleanroom education, this blended approach offers a scalable pathway for addressing training bottlenecks while preserving the experiential learning benefits of physical laboratories.

Conclusions

This work demonstrates that, when appropriately designed and implemented, a varied selection of XR simulated environments can provide a meaningful enhancement to common usability issues found in the nanotechnology classroom. The varied XR approach is a more accessible experience for a wider body of students, as well as offering mitigations to motion sickness of up to ~7.7% compared with a single XR experience solution. While XR-based instruction is not positioned as a replacement for traditional hands-on laboratory experiences, the results support its effectiveness as a supplementary instructional tool, particularly in situations where access to physical facilities is limited by cost, safety, or availability. The immersive and repeatable nature of XR simulations enables students to engage with complex nanofabrication concepts in a structured and low-risk environment. Future work will focus on improving accessibility and further integrating personalized, guided instructional elements to better support individual learning needs and strengthen the connection between virtual experiences and physical laboratory practice.

Acknowledgements

The authors acknowledge funding from the National Science Foundation (grant 2239951) and the DoD DEPSCoR program (grant FA9550-23-1-0497). They also thank the team at the George Washington Nanofabrication and Imaging Center (GWNIC) for their expertise and guidance.

References

[1] George (Yiorgos) Allayannis and Aldo Sesia, "Investment Decisions: Geopolitical Risks Face Off," *Case Study UVA-F-2110*, 2024, doi: doi:%2010.2139/ssrn.5331829.

[2] D. R. Parnell, A. N. Irving, C. S. Smith, A. G. Buhler, and J. A. Magruder Waisome, "Features of Extended Reality Environments in Semiconductor Fabrication Process Education: A Scoping Review," *IEEE Access*, vol. 13, pp. 80576–80586, 2025, doi: 10.1109/ACCESS.2025.3566609.

[3] S. Letavish, A. Meliksetyan, V. Ravel, H. Ok, N. Milman, and G. Adam, "Using Virtual Reality Cleanroom Simulation in a Mixed Nanoelectronics Classroom," in *2023 ASEE Annual Conference & Exposition Proceedings*, Baltimore, Maryland: ASEE Conferences, Jun. 2023, p. 44588. doi: 10.18260/1-2--44588.
[4] P. Weber, A. Minaic, and A. Phan, "Virtual Reality Simulation and Experiment for Sputter Deposition and Vacuum Training," in *2020 ASEE Virtual Annual Conference Content Access Proceedings*, Virtual Online: ASEE Conferences, Jun. 2020, p. 35488. doi: 10.18260/1-2--35488.
[5] M. El Helbawy and P. Clark, "Revolutionizing Semiconductor Education: An Immersive Virtual Cleanroom for Enhanced Nanofabrication Training," in *2025 ASEE Annual Conference & Exposition Proceedings*, Montreal, Quebec, Canada: ASEE Conferences, Jun. 2025, p. 57145. doi: 10.18260/1-2--57145.
[6] F. Wang, X. Xu, S. Li, W. Feng, and M. Almasri, "Learning cleanroom microfabrication operations in virtual reality – An immersive and guided learning experience," *Computers & Education: X Reality*, vol. 5, p. 100073, Dec. 2024, doi: 10.1016/j.cexr.2024.100073.
[7] V. Potkonjak *et al.*, "Virtual laboratories for education in science, technology, and engineering: A review," *Computers & Education*, vol. 95, pp. 309–327, Apr. 2016, doi: 10.1016/j.compedu.2016.02.002.
[8] R. Kamali-Sarvestani, P. Weber, M. Clayton, M. Meyers, and S. Slade, "Virtual Reality to Improve Nanotechnology Education: Development Methods and Example Applications," *IEEE Nanotechnology Mag.*, vol. 14, no. 4, pp. 29–38, Aug. 2020, doi: 10.1109/MNANO.2020.2994802.
[9] M. Akçayır, G. Akçayır, H. M. Pektaş, and M. A. Ocak, "Augmented reality in science laboratories: The effects of augmented reality on university students' laboratory skills and attitudes toward science laboratories," *Computers in Human Behavior*, vol. 57, pp. 334–342, Apr. 2016, doi: 10.1016/j.chb.2015.12.054.
[10] J. J. A. Nuako, S. A. Adjei, and M. Kozhevnikov, "COMPARISON BETWEEN 360-DEGREE AND DIGITAL IMMERSIVE VR-BASED TRAINING ENVIRONMENTS FOR CLEANROOM SAFETY AND FABRICATION PROCEDURES," 2025.
[11] Bruno Rogérioda Silva *et al.*, "AR Lab: Augmented Reality App for Chemistry Education," in *ACM SIGGRAPH 2019 Talks*, Los Angeles California: ACM, Jul. 2019, pp. 71–77. doi: 10.1145/3306307.3328180.
[12] Järvinen, Tero, "Virtual Reality Models in Cleanroom Design," *49th R3 Nordic Symposium. Cleanroom Technology, Contamination Control and Cleaning*, pp. 11–16, 2018.
[13] P. Arjunamahanthi *et al.*, "Interactive Learning in Microelectronics Education: Comparing PC and Mixed Reality Approaches for Student Engagement and Visual-Spatial Memory," in *Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems*, Yokohama, Japan: ACM, Apr. 2025, pp. 1–8. doi: 10.1145/3706599.3721269.
[14] S. Contaifer, B. J. Exum, D. Wijesinghe, and L. M. Caldas, "A Virtual Reality 360 Video to Introduce Second-Year Student Pharmacists to Sterile Compounding Prior to Course Activity," *Journal of Pharmacy Technology*, vol. 40, no. 2, pp. 59–65, Apr. 2024, doi: 10.1177/87551225231220214.
[15] J. Georgiou, K. Dimitropoulos, and A. Manitsaris, "A Virtual Reality Laboratory for Distance Education in Chemistry," 2007.