Team VISTA

Literature Review

A. Introduction

In-person labs are critical to building scientific knowledge and provide fundamental experience in performing high-level experimentation. However, in-person labs have limitations: the capital and operating costs of in-person science labs can create a barrier to low-income students and underfunded school systems, and physical manipulation may pose an accessibility barrier to individuals with disabilities [24]. Moreover, safety regulations can limit the selection of in-person labs and prevent students from conducting experiments with dangerous materials and equipment [14].

There are also many different solutions to increasing accessibility for individuals with disabilities to provide them with opportunities of performing labs. To accommodate students with physical, visual, or auditory disabilities, we will incorporate customizable features such as voice control, audio descriptions, and visual settings. This tailored approach ensures that students with disabilities have an equal opportunity to learn in a high-quality setting that provides the same learning experience as physical lab settings.

Two main alternatives have been developed to overcome the challenges of in-person labs: remote and virtual labs. Compared to in-person labs, virtual and remote labs have lower equipment and infrastructure costs and partially reduce the financial barrier to STEM education. The risk of bodily injury and exposure to hazardous materials is also eliminated during experiments [21], though additional measures, such as physically present staff, may be needed to mitigate risks of experiments with dangerous elements including high voltage and risky chemicals [4]. In addition to minimizing cost and safety issues, remote and virtual labs are more accessible to the disabled population of students. A virtual laboratory developed by electric engineers Michael Duarte and Brian P. Butz utilized speech recognition to allow the user to manipulate a mouse and input values through their voice [5]. Augmented reality-based remote labs utilize sensors that can track motion and touchscreen displays to enable individuals with physical and cognitive impairments to utilize lab equipment from a distance [29]. Thus, Remote and virtual lab interfaces remove multiple accessibility barriers of in-person labs.

While virtual labs are entirely software-based, remote labs are authentic, physical labs controlled in real-time over the Internet, coupling the engagement and enjoyment of in-person labs with the accessibility of virtual labs. VISTA intends to design an end-to-end system incorporating technology that improves accessibility for students with disabilities, underprivileged students, and students who don't have access to physical labs in general. We will develop a front-end interface that works with the student, a connecting software architecture that receives student input and performs commands on the lab, and an interface that displays a live camera feed of the lab with associated output on the student's screen. Once demonstrated with select labs, this framework can be extended to many STEM labs to tackle physical accessibility concerns, financial constraints, and safety issues in STEM education.

B. In-Person Labs

1. Overview of In-Person Labs

In STEM education, virtual, remote, and traditional in-person labs represent three distinct experiential educational approaches, and each approach has unique strengths and limitations.

Traditional in-person labs are the foundations of hands-on STEM education, providing students with firsthand experience with real-world materials and equipment. The tactile learning experience these labs provide is essential for developing practical skills like utilizing lab equipment and making real-time observations during experiments [1].

In-person labs' immersive nature encourages collaborative learning, allowing students to work together and improve their problem-solving skills. A 2006 study by Singer, et al. found that conventional labs are especially effective at fostering critical thinking and scientific reasoning (Singer et al., 2006). Additionally, using real materials fosters the development of critical motor skills and safety procedures necessary for various STEM subjects, such as biology, chemistry, and engineering [9].

Traditional labs have drawbacks despite their benefits. They are often costly to maintain, with significant expenses for consumables, equipment, and laboratory space (Gardner et al., 2016). Working with hazardous materials raises additional safety issues, which call for close supervision and adherence to regulations. Furthermore, accessibility limitations remain problematic in underfunded school districts that cannot offer a wide range of laboratory experiences, ultimately hindering equitable access to high-quality STEM education [3].

2. Examples of In-Person Labs

In-person labs in the STEM field cover a wide range of disciplines and provide unique, practical experiences that are challenging to replicate remotely or virtually. For instance, biology labs frequently incorporate microscopic analyses and dissections, giving students a firsthand look at biological processes and structures in a controlled setting. These practical experiences reinforce textbook information through physical interaction and offer vital insights into cellular and anatomical complexities.

In-person labs in chemistry enable students to experiment with chemical reactions, such as synthesis reactions and titrations, which require precise material handling and stringent safety protocols. Students can apply their theoretical knowledge to the real world and learn critical lab skills, such as precise measurement and safe handling of chemicals, through these tactile experiences. These lab skills are essential for future employment in chemistry and related fields and are skills that virtual or remote labs cannot fully replicate.

Finally, engineering labs give students the opportunity to interact with tangible components such as circuits, robotics, and equipment. Through the assembly and testing of actual technologies, such as electrical circuits or robotic systems, these laboratories allow students to put their theoretical knowledge into practice. The practical experience that engineering labs provide is vital for developing technical skills because it enables students to work closely with sophisticated equipment and hone their critical thinking and problem-solving skills, which are essential in many engineering disciplines.

C. Virtual Labs

1. Overview of Virtual Labs

Virtual labs are fully simulated environments where students interact with digital representations of scientific equipment and processes. These labs provide a controlled, safe space for experimentation, which is particularly useful in experiments with hazardous materials. For instance, in a virtual chemistry lab, students can safely conduct experiments with hazardous substances without the dangers of working with the actual chemicals ([2]; [10]). Another advantage is their reduced cost to operate and implement compared to traditional in-person labs. Multiple students can use the virtual lab simultaneously, so the platform can be reused and adapted for different STEM labs, reducing implementation costs significantly. Virtual labs also hold a critical advantage over traditional in-person labs in their ability to be more accessible for individuals with physical disabilities [27]. Moreover, they offer unrestricted access, allowing students to revisit and repeat experiments. This helps students learn from their mistakes, better understand the content, and improve in ways traditional labs do not allow [23].

A study on a blended learning virtual reality (VR) laboratory highlighted several important benefits to virtual laboratories [23]. According to Antonelli et al. (2023), virtual labs can improve conceptual learning by visualizing abstract scientific phenomena in ways that traditional labs may not. The design of VR labs allows students to explore lab scenarios and gain deeper insights by viewing experiments from multiple angles in real-life settings. Furthermore, integrating self-assessment tools enables students to receive immediate feedback and correct mistakes in real-time, enhancing learning outcomes [23].

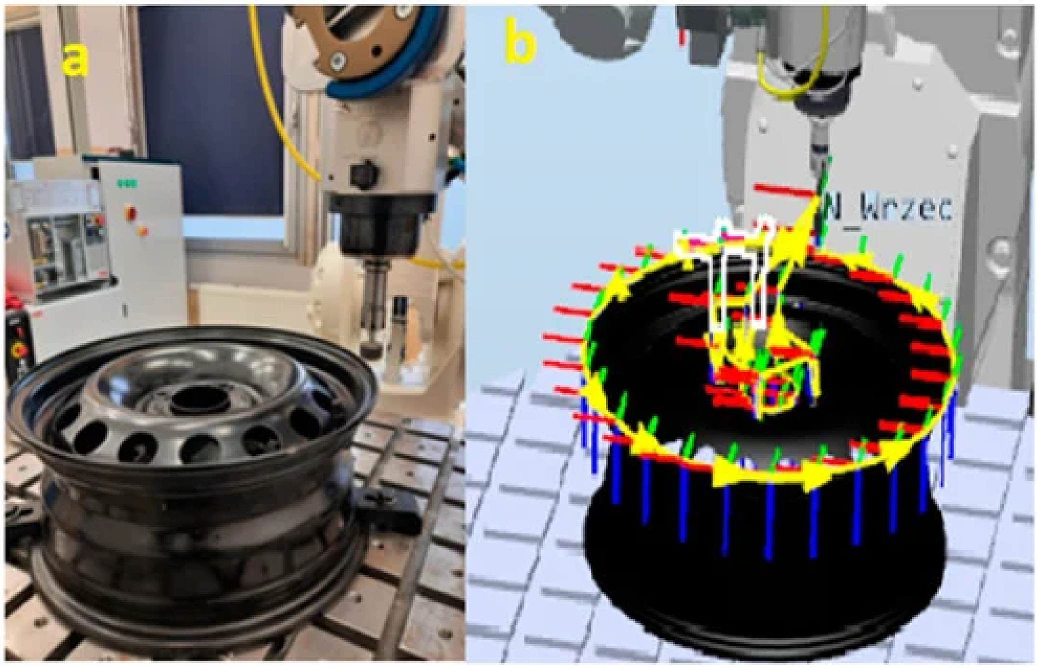

Figure 1. VR replica as a digital twin marking the machining route of the physical machining part and its tool [32].

Despite these benefits, virtual labs have drawbacks. They lack the tactile engagement of in-person labs, hindering the development of practical, hands-on skills necessary in STEM fields (Gardner et al., 2016). Additionally, virtual labs increase the potential for academic dishonesty, as monitoring and enforcing academic integrity is more challenging in entirely online environments [13]. Virtual labs also rely on dependable technology and stable internet access, which can limit accessibility for students in underprivileged settings (Gardner et al., 2016).

2. Examples of Virtual Labs

Numerous well-known platforms offer comprehensive virtual lab experiences for STEM education, each with special characteristics to improve student comprehension and engagement.

Labster allows students to investigate cellular respiration, chemical reactions, and other intricate processes in secure virtual settings. Students can repeat or speed up experiments with Labster's utilization of 3D animations and interactive tests, which helps students fully grasp scientific concepts [33].

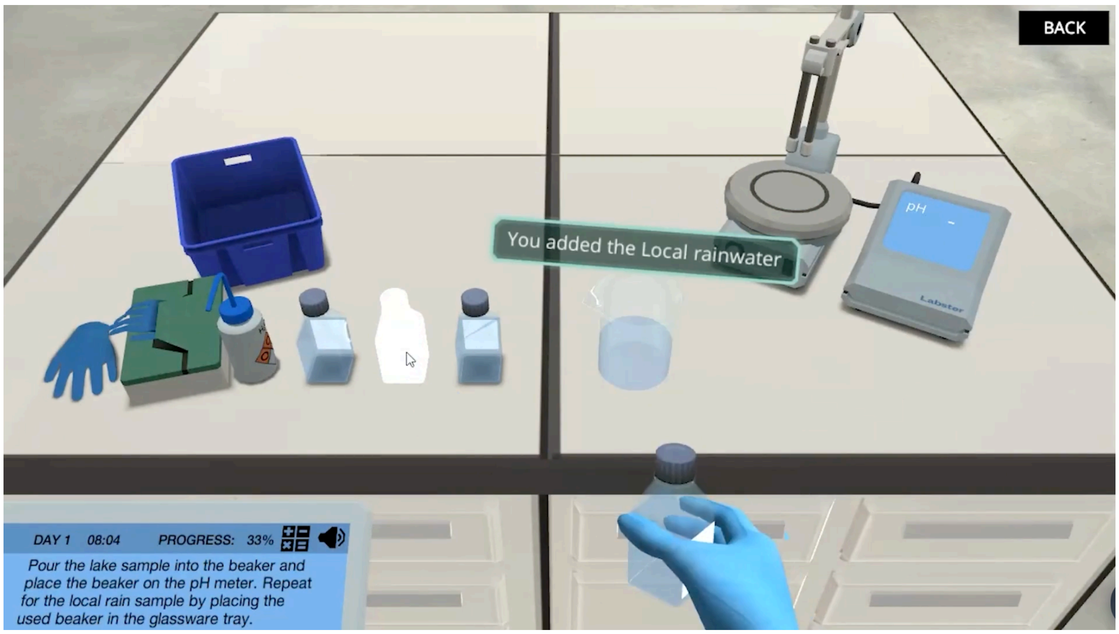

Figure 2. Labster's virtual lab for acids and bases enables students to safely conduct pH measurement experiments in an interactive, digital environment [34].

Likewise, the University of Colorado Vboulder's PhET Interactive Simulations offers more than 150 free physics, chemistry, and biology simulations. With the help of these simulations, students can change parameters and see abstract notions in real-time, which helps them better understand concepts like forces in motion and molecular interactions [35].

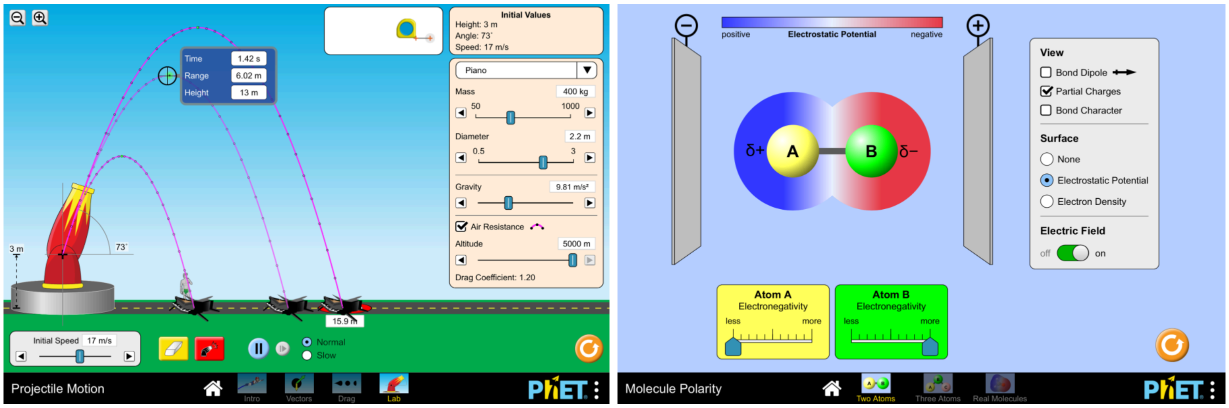

Figure 3. PhET Interactive Simulations allow students to explore concepts like projectile motion (left) and molecule polarity (right) by adjusting variables and observing real-time changes [35].

Finally, another useful and very popular tool is Gizmos from ExploreLearning, which uses "STEM Cases" to immerse students in authentic situations while they investigate subjects like genetics and photosynthesis using inquiry-based learning, Gizmos facilitates critical thinking and experiential learning in a virtual setting by enabling students to carry out virtual experiments with instant feedback [36]. Together, these platforms show how virtual labs can offer easily accessible, interactive STEM education that fosters the development of critical thinking and conceptual understanding in a wide variety of subjects.

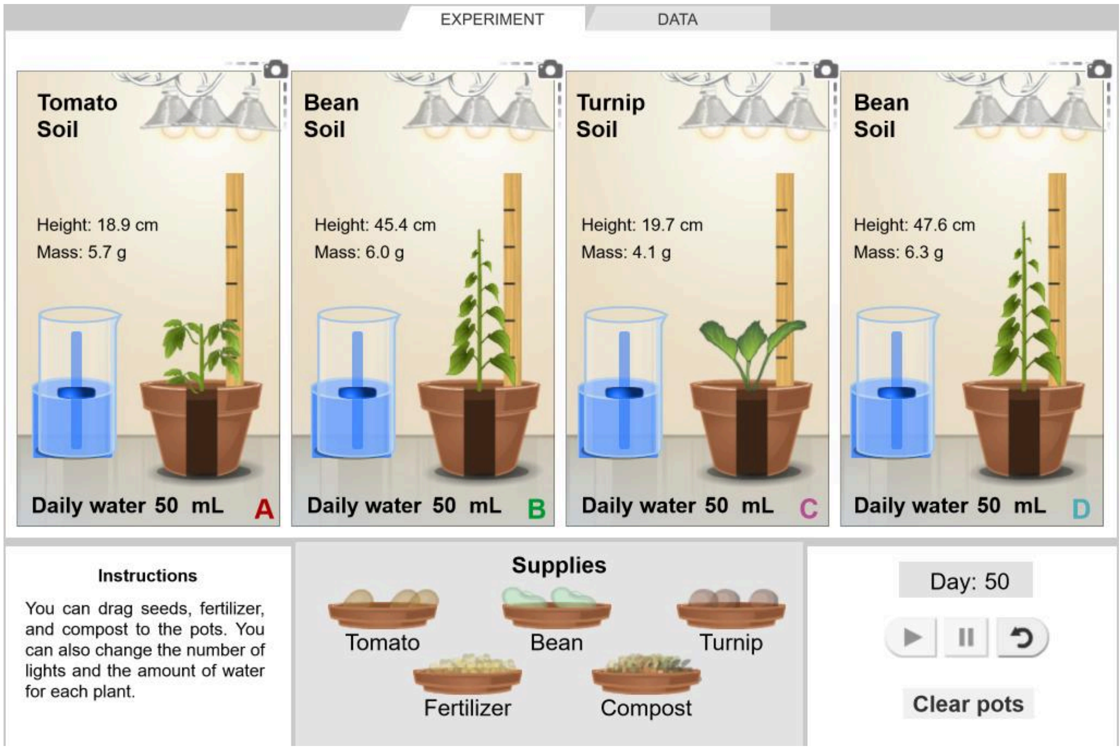

Figure 4. Gizmos simulation enables students to explore plant growth under controlled virtual conditions, fostering inquiry-based learning [36].

D. Remote Labs

1. Overview of Remote Labs

Remote labs allow students to operate real laboratory equipment physically situated elsewhere and controlled via the Internet. This technique provides an authentic experience, as students interact with physical equipment, often in real-time, while gathering actual data and allowing multiple users to operate the system ([23]; [8]). Remote labs, like virtual labs, negate safety issues and can be more accessible for individuals with disabilities. These labs foster practical skills and bridge the gap between theoretical knowledge and real-world applications [11].

The ScienceVR framework, for instance, contrasts several instructional styles, such as 2D graphical displays, Desktop Virtual Reality (DVR), and Immersive Virtual Reality (IVR). 2D Graphical Displays involve flat, screen-based representations, such as images or videos, that provide visual information without spatial depth. DVR expands this by allowing users to interact with 3D environments on their desktops, offering some immersion but limited sensory engagement. IVR completely immerses the user in a 3D virtual environment through VR headsets, creating a more realistic and engaging experience. As shown in Figure 5, the results demonstrate the educational value of virtual reality in STEM learning with Immersive VR outperforming traditional approaches in both task completion rates and memorability [12].

	2D	**IVR**	**DVR**
Q1 (Ease of use)	*M* = 6 *SD* = 0.6	*M* = 4.8 *SD* = 1.1	*M* = 4.3 *SD* = 1.7
Q2 (Memorability)	*M* = 4.7 *SD* = 0.7	*M* = 5.8 *SD* = 1.5	*M* = 5.7 *SD* = 1
Q3 (Learnability)	*M* = 4.5 *SD* = 0.7	*M* = 5.6 *SD* = 1.6	*M* = 5.6 *SD* = 0.9
Q4 (Pleasantness)	*M* = 4.4 *SD* = 0.8	*M* = 4.7 *SD* = 1.4	*M* = 5.3 *SD* = 1.2
Q5 (Clarity)	*M* = 4.8 *SD* = 0.6	*M* = 5.2 *SD* = 1.6	*M* = 5 *SD* = 1.3
Q6 (Visualization)	*M* = 4.3 *SD* = 0.5	*M* = 5.6 *SD* = 1.3	*M* = 5.9 *SD* = 0.9
Q7 (Overall Satisfaction)	*M* = 4.8 *SD* = 0.6	*M* = 4.8 *SD* = 1.1	*M* = 5.3 *SD* = 1.2

Figure 5. Usability Mean Score and Standard Deviation for 2D, IVR, AND DVR [12].

However, the resource-intensive nature of remote labs is a significant limitation. They often require complex setups, including sophisticated hardware and robust network infrastructures, which may make them difficult to scale for broader educational use [23]. Maintaining and upgrading this equipment can also be costly and labor-intensive, posing challenges for long-term sustainability.

Factors	In-Person Labs	Virtual Labs	Remote Labs
Hands-On Experience	✔	X	✔
Accessibility	X	✔	✔
Safety Concerns	X	✔	✔
Collaborative Learning	✔	X	✔
Skill Development	✔	X	✔
Feedback Mechanisms	X	✔	✔
Real-Time Data	✔	X	✔
Academic Integrity	✔	X	X
Cost	X	✔	X

Figure 6. Labs Comparison Summary.

2. Educational Benefits of Remote Labs

Remote laboratories offer an accessible alternative to in-person labs, allowing students with disabilities or limited resources to gain essential hands-on learning experiences. According to a study conducted on high school students comparing multiple in-person labs with their virtual alternative, students prefer hands-on experiences and find them more enjoyable and informative [26]. Remote labs also offer this advantage by allowing students to interact with a physical laboratory while incorporating the flexibility of virtual labs. This flexibility enables students with disabilities or those without access to physical lab equipment to gain this hands-on experience. The National Science Foundation funded a study that found that students with visual disabilities require audible commentary throughout the experiment [19]. However, different disabilities require different accommodations, which must be accounted for.

Moreover, remote labs have the potential to be a superior alternative to physical and remote labs in terms of quality. A review of 23 studies on remote labs found that remote labs were at least as effective, if not more so, than hands-on labs in key areas including interactivity, reported student satisfaction, and better student learning outcomes [22]. Additionally, remote labs provide a specific experience that is lacking with virtual labs: failure [28]. Although virtual labs inform the user when they complete tasks incorrectly, their lack of engagement limits students' true comprehension of their mistakes, a crucial aspect of STEM education [28].

Beyond engagement challenges, a potential drawback of remote labs is the lack of flexibility for teachers to select or personalize their labs, as designers and the free market often dictate the availability of remote versions of specific labs [30]. As such, for remote labs to become a handy tool to support online experimentation at all levels, they must address teachers' diverse needs by incorporating flexibility, interactivity, and open-endedness [30].

3. Access to Different Types of Labs

Remote labs can offer a wider variety of labs, from the types of labs offered to the level of difficulty of the lab. Types of labs refers to the subjects that labs can cover, such as chemistry, physics, or circuit labs. Difficulty of labs refers to the levels that the labs can cater to. For example, labs can be conducted at a high school level, college level, or just be a dangerous lab in general.

Remote labs could provide access to learning experiences not previously available to students in person, namely dangerous or risky experiments [2]. The frequency of safety incidents in academic laboratories is higher than in industrial laboratories, and the inherent safety and liability concerns that accompany in-person labs continue to hinder and restrict STEM education ([2]; [16]). Despite improvements in instructional methods, equipment safety, and personal protective equipment, safety issues have continued to be identified as one of the top focuses in STEM education [16]. Yet, inquiry-based learning incorporates the advantages of laboratory experiences and is essential to student learning; therefore, safer systems are needed to address liability concerns without sacrificing educational quality (Zirkel & Barnes, 2011).

So far, virtual labs incorporating VR and/or AR technology have provided access to dangerous experiments, particularly chemistry labs. These attempts include a mixed reality-based chemistry experiment learning system (MRCELS) and virtual simulation experiments (VSEs) ([2]; [10]).

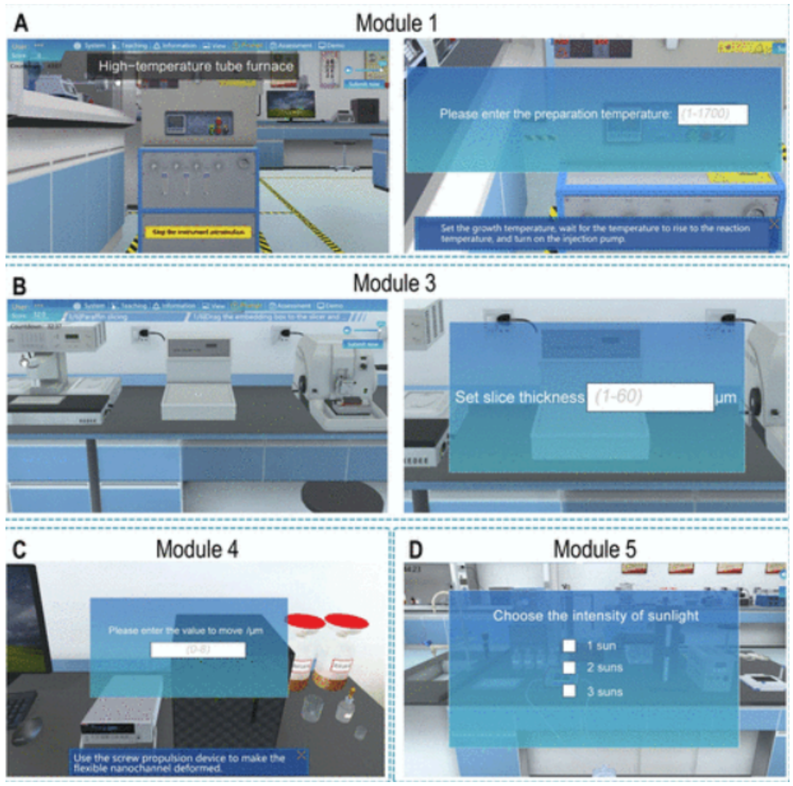

Figure 7. Figure of VSE modules showing sample of student view of the lab [10].

These systems allow students to experiment with different parameter settings (multi-experiential paths) that may be difficult or dangerous to perform in-person while avoiding irreversible dangerous consequences. This new approach also fosters creativity and independence among students by allowing them to explore multi-experimental paths that may not be feasible to do in-person, all at great cost reductions ([10]; [2]). Essentially, these flexible lab environments allow students to safely engage in experiential learning, make and correct mistakes in real time, which fosters critical thinking and problem-solving skills that are crucial to a STEM education.

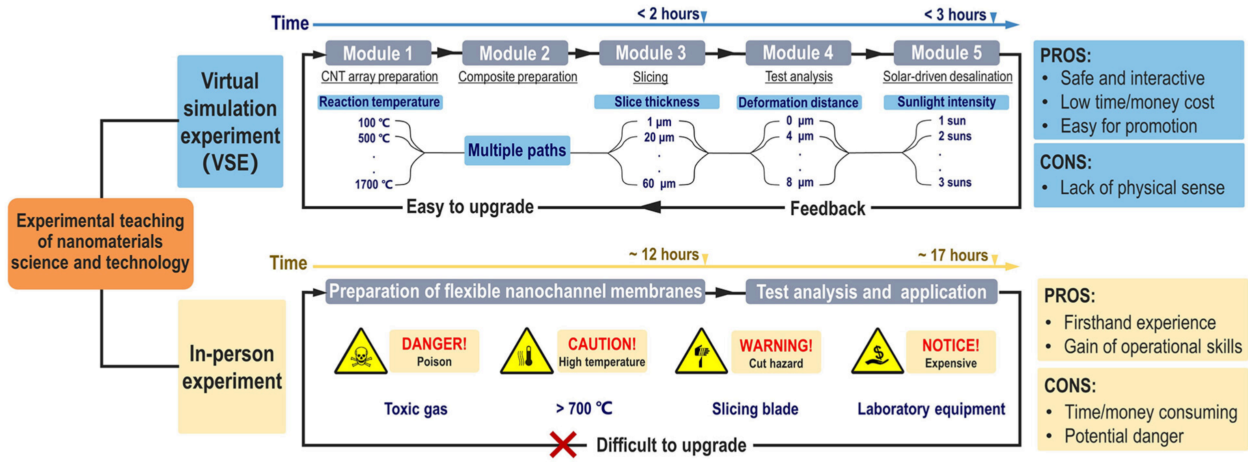

Figure 8. Figure of VSE vs In-Person experiment risks and decision-making process [10].

So far, only virtual platforms have been created to provide students worldwide access to complex and hazardous chemistry experiments while accounting for potential safety risks [16]. Therefore, there is an opportunity for remote labs to improve upon the engagement, enjoyment, and accessibility of these types of labs.

4. Remote Lab Examples

The remote labs most applicable to what Team VISTA is researching are VISIR (Virtual Instrument Systems In Reality) and netCIRCUITlabs. Based in Europe and Australia, respectively, both remote labs are commercial educational products.

VISIR's primary purpose is to enable remote access with circuits and electricity. When students connect circuits virtually, the system builds the circuit, allowing the multimeter to measure the results [7]. VISIR works with a framework of three basic points: components, implementation, and instrumentation, as demonstrated in Figure 9 [7].

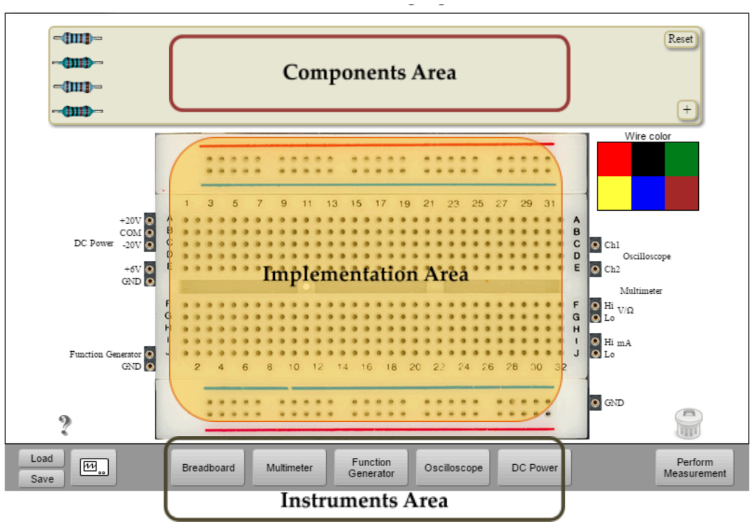

Figure 9. Figure of VISIR labs framework [7].

These parts allow students to perform the experiments while building an understanding of what the real equipment actually looks like. While this is the interface of the remote lab, the lab has three additional parts: the equipment server, the measurement matrix, and the switching relay matrix [17]. Figure 10 demonstrates what the components look like and how they communicate.

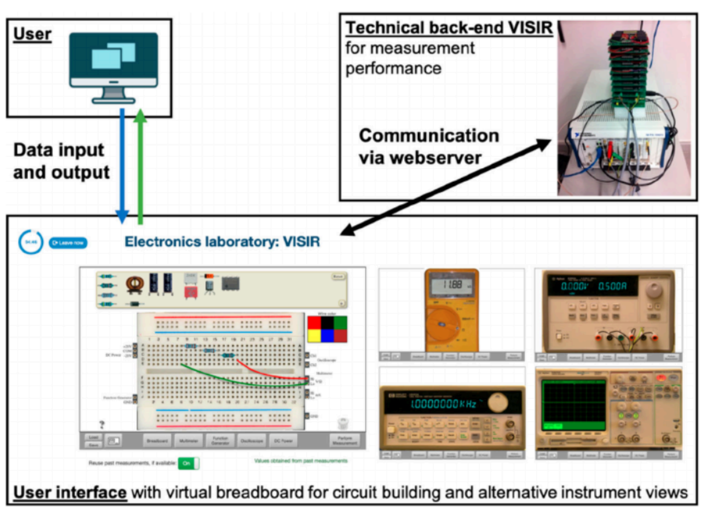

Figure 10. Structural overview of the VISIR remote lab [18].

These components work together to process student input, replicate the student's actions, and return the corresponding output or result. However, while VISIR now supports student use, its early research focused more on developing the technology than integrating it effectively into the education system [17].

From 2009-2019, there were over 80,000 VISIR sessions and over 2,000,000 actions in those sessions performed by students [6]. While VISIR represents elements similar to what Team VISTA seeks to achieve, some aspects and goals differ from those of this commercial remote lab. The first difference lies in the types of labs that VISTA aims to target; while VISIR works with circuits and electricity, which VISTA may also work with, VISTA aims to work with other types of labs that are more high school level, working with chemistry, physics, or electricity. Additionally, as previously noted, VISTA also seeks to work with dangerous labs that may spark interest in students to pursue, yet may be too risky to perform in-person or by the student. Secondly, VISTA aims to work with more physical components instead of just a matrix and an equipment server, VISTA wants to work with movement, playing around with ways to experiment with different types of formats, like robotic arms, wheels, and other components. The similarity grasped from this remote lab includes the elements that connect the parts to make them remote. VISTA seeks to develop a front-end interface that works with the student, find a way to get student input from one location to another, and finally return the output through a camera screen that the student may view. These are elements demonstrated by VISIR that VISTA may implement.

Another remote lab, netCIRCUITlabs, was similarly developed for commercial use. One of the main differences between VISIR and netCIRCUITlabs is the skill level involved in using the labs. Of the two, netCIRCUITlabs contains more sophisticated capabilities [6]. The format of netCIRCUITlabs looks similar to VISIR in that there are three components to the remote lab. Figure 11 demonstrates parts of netCIRCUITlabs and how they communicate.

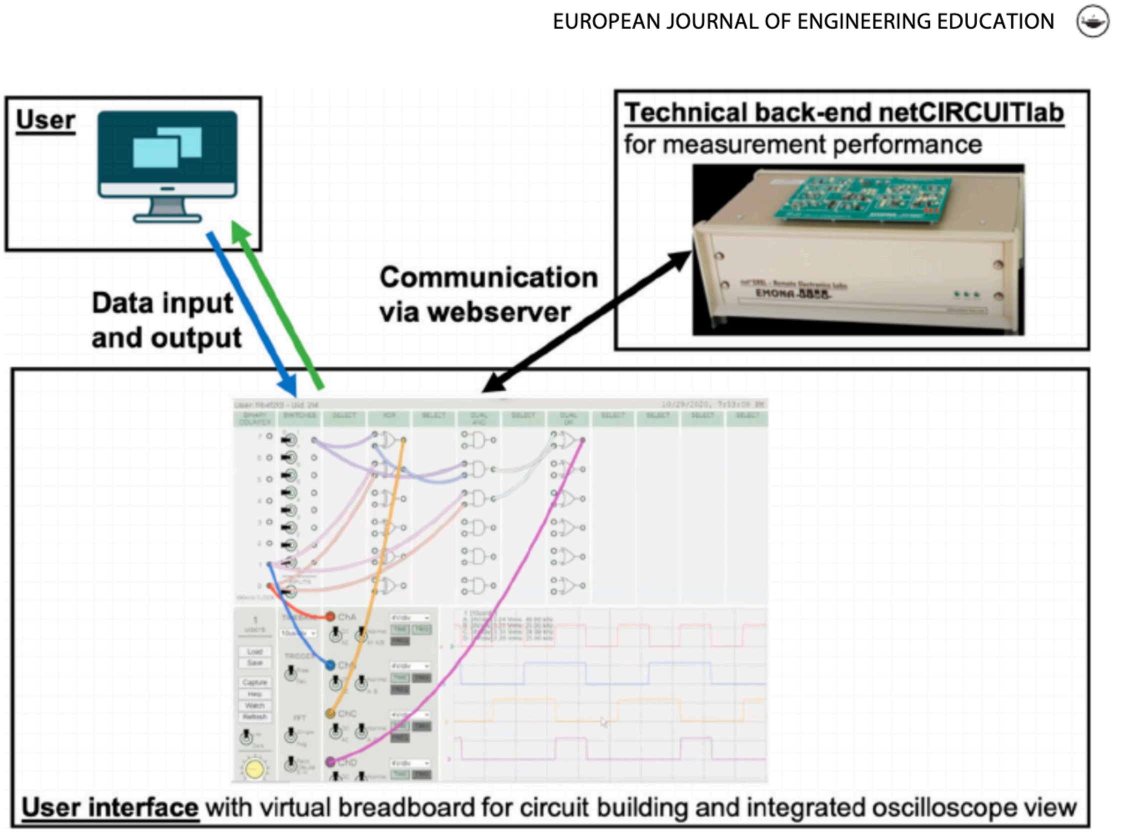

Figure 11. Structural overview of netCIRCUITlabs remote lab with user interface and technical back-end [18].

The main difference between netCIRCUITlabs and VISTA is the complexity and types of labs available due to the sophistication of netCIRCUITlabs. Both VISIR and netCIRCUITlabs work primarily with experimentation, with different functions and their results. While there are apparent differences between the goals that VISTA has and those currently available, there are many similarities that may be implemented to reach the goals that VISTA sets out to achieve.

References

[1] Ambusaidi, A., Al Musawi, A., Al-Balushi, S., & Al-Balushi, K. (2018). The Impact of Virtual Lab Learning Experiences on 9th Grade Students' Achievement and Their Attitudes Towards Science and Learning by Virtual Lab. Journal of TURKISH SCIENCE EDUCATION, 15(2), 3–23. https://doi.org/10.12973/tused.10227a

[2] Chen, CM., Li, MC. & Tu, CC. (2024) A Mixed Reality-Based Chemistry Experiment Learning System to Facilitate Chemical Laboratory Safety Education. J Sci Educ Technol 33, 505–525 . https://doi.org/10.1007/s10956-024-10101-3

[3] de Jong, T., Linn, M. C., & Zacharia, Z. C. (2013). Physical and Virtual Laboratories in Science and Engineering Education. Science, 340(6130), 305–308. https://doi.org/10.1126/science.1230579

[4] de la Torre, Pedro, J., & Sebastián Dormido. (2016). What remote labs can do for you. *Physics Today*, *69*(4), 48–53. https://doi.org/10.1063/pt.3.3139

[5] Duarte, M. & Butz, B. P. (2002). The virtual laboratory for the disabled. 31st Annual Frontiers in Education Conference. Impact on Engineering and Science Education. Conference Proceedings (Cat. No.01CH37193), 3(1), https://doi.org/10.1109/FIE.2001.963989

[6] Garcia-Zubia, J. Cuadros, J., Hernandez-Jayo, U., Romero, S., Serrano, V., Angulo, I., Alves, G., Fidalgo, A., Orduña, P., Rodriguez-Gil, L. (2021). Using VISIR Remote Lab in the Classroom: Case of Study of the University of Deusto 2009–2019. In: Auer, M., May, D. (eds) Cross Reality and Data Science in Engineering. REV 2020. Advances in Intelligent Systems and Computing, vol 1231. Springer, Cham. https://doi.org/10.1007/978-3-030-52575-0_7

[7] Hernández, U., García-Zubia, J. (2020). VISIR. LabsLand. https://labsland.com/pub/docs/experiments/electronics/en/use_this_laboratory.html#what-is-visir.

[8] Heradio, R., Torre, L., & Dormido, S. (2016). Virtual and remote labs in control education: a survey. Annual Reviews in Control, 42, 1-10. https://doi.org/10.1016/j.arcontrol.2016.08.001

[9] Hofstein, A., & Lunetta, V. N. (2003). The laboratory in science education: Foundations for the twenty‐first century. Science Education, 88(1), 28–54. https://doi.org/10.1002/sce.10106

[10] Hou, Y., Wang, M., He W., Ling Y., Zheng J., Hou, X. (2023). "Virtual Simulation Experiments: A Teaching Option for Complex and Hazardous Chemistry Experiments." Journal of Chemical Education 2023 100 (4), 1437-1445. DOI: 10.1021/acs.jchemed.2c00594.

[11] Kazmierkowski, M. P. (2013). Using remote labs in Education (Zubia, J.G. and Alves, G.R.; 2011) [Book News]. IEEE Industrial Electronics Magazine, 7(1), 67–68. https://doi.org/10.1109/mie.2012.2236487

[12] Labster. (2021). Labster's ScienceVR framework for STEM education. *ScienceDirect.* https://doi.org/10.1016/j.compedu.2021

[13] Liang, J. G., Watson, G. R., Sottile, J., & Behrend, B. (2023). Academic Cheating in Online and Live College Courses During the COVID Pandemic. ERIC Institute of Education Sciences. https://files.eric.ed.gov/fulltext/EJ997467.pdf

[14] Love, T. S. (2013). Addressing safety and liability in STEM Education: A review of important legal issues and case law. Journal of Technology Studies, 39(1), 28–41. https://doi.org/10.21061/jots.v39i1.a.3

[15] Love, T. S., Roy, K. R., Gill, M., & Harrell, M. (2022). Examining the influence that safety training format has on educators' perceptions of safer practices in makerspaces and integrated STEM Labs. Journal of Safety Research, 82, 112–123. https://doi.org/10.1016/j.jsr.2022.05.003

[16] Love, T. S., Roy, K. R., & Sirinides, P. (2023). A national study examining safety factors and training associated with STEM education and CTE laboratory accidents in the United States. Safety Science, 160, 106058. https://doi.org/10.1016/j.ssci.2022.106058

[17] May, D., Reeves, B., Trudgen, M., Alweshah, A. (2020). "The remote laboratory VISIR - Introducing online laboratory equipment in electrical engineering classes," 2020 IEEE Frontiers in Education Conference (FIE), Uppsala, Sweden, pp. 1-9, doi: 10.1109/FIE44824.2020.9274121.

[18] May, D., Morkos, B., Jackson, A., Hunsu, N. J., Ingalls, A., & Beyette, F. (2022). Rapid transition of traditionally hands-on labs to online instruction in engineering courses. European Journal of Engineering Education, 48(5), 842–860. https://doi.org/10.1080/03043797.2022.2046707

[19] Moon, N. W., Todd, R. L., Morton, D. L., & Ivey, E. (2012). Accommodating Students with Disabilities in Science, Technology, Engineering, and Mathematics (STEM). National Science Foundation. https://hourofcode.com/files/accommodating-students-with-disabilities.pdf

[20] Odeh, S., Shanab, S. A., Anabtawi, M., & Hodrob, R. (2012). Remote augmented reality engineering labs. Proceedings of the 2012 IEEE Global Engineering Education Conference (EDUCON), 1-6. https://doi.org/10.1109/EDUCON.2012.6201162

[21] Poo, M. C., Lau, Y., & Chen, Q. (2023). Are virtual laboratories and remote laboratories enhancing the quality of sustainability education? Innovation and Digital Transformation in Teaching Practice in Higher Education, 13(11), https://doi.org/10.3390/educsci13111110

[22] Post, L. S., Guo, P., Saab, N., & Admiraal, W. (2019). Effects of remote labs on cognitive, behavioral, and Affective Learning Outcomes in higher education. Computers & Education, 140, 103596. https://doi.org/10.1016/j.compedu.2019.103596

[23] Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V. M., & Jovanović, K. (2016). Virtual laboratories for education in science, technology, and engineering: A review. Computers & Education, 95, 309–327. https://doi.org/10.1016/j.compedu.2016.02.002

[24] Pyatt, K., & Sims, R. (2011). Virtual and physical experimentation in inquiry-based science labs: Attitudes, performance and access. Journal of Science Education and Technology, 21(1), 133–147. https://doi.org/10.1007/s10956-011-9291-6

[25] Rose, M.A., Shumway, S., Carter, V., Brown, J. (2015) Identifying characteristics of technology and engineering teachers striving for excellence using a modified Delphi J. Technol. Educ., 26 (2), pp. 2-21

[26] Rytting, M., Wright, G., Shumway, S., & Jensen, J. (2019). Comparison of simulation and hands-on labs in helping high school students learn physics concepts. International Journal of Education, 11(1), 18. https://doi.org/10.5296/ije.v11i1.14017

[27] Saenz, J., Chacon, J., De La Torre, L., Visioli, A., & Dormido, S. (2015). Open and Low-Cost Virtual and Remote Labs on Control Engineering. IEEE Access, 3, 805–814. https://doi.org/10.1109/ACCESS.2015.2442613

[28] Simpson, A., & Maltese, A. (2016). “failure is a major component of learning anything”: The role of failure in the development of STEM Professionals. Journal of Science Education and Technology, 26(2), 223–237. https://doi.org/10.1007/s10956-016-9674-9

[29] Sobata, B., Korečko, Š., Pastornický, P., & Jacho, L. (2017). Virtual-reality technologies in the process of handicapped school children education. 2016 International Conference on Emerging eLearning Technologies and Applications (ICETA), https://doi.org/10.1109/ICETA.2016.7802077

[30] Xie, C., Li, C., Sung, S., & Jiang, R. (2022). Engaging students in distance learning of science with remote labs 2.0. IEEE Transactions on Learning Technologies, 15(1), 15–31. https://doi.org/10.1109/tlt.2022.3153005

[31] Yap, W. H., Teoh, M. L., Tang, Y. Q., & Goh, B. H. (2021). Exploring the use of virtual laboratory simulations before, during, and post COVID-19 recovery phase: An Animal Biotechnology case study. Biochemistry and molecular biology education : a bimonthly publication of the International Union of Biochemistry and Molecular Biology, 49(5), 685–691. https://doi.org/10.1002/bmb.21562

[32] Antonelli, D., Christopoulos, A., Laakso, M., Dagienė, V., Juškevičienė, A., Masiulionytė-Dagienė, V., Mądziel, M., Stadnicka, D., & Stylios, C. (2023). A Virtual Reality Laboratory for Blended Learning Education: design, Implementation and evaluation. Education Sciences, 13(5), 528. https://doi.org/10.3390/educsci13050528

[33] Education, R. (2020, October 22). HOW VIRTUAL LABS ARE REVOLUTIONIZING SCIENCE EDUCATION [Video]. Reimagine Education Awards & Conference. https://www.reimagine-education.com/28-virtual-labs-revolutionizing-science-education/#

[34] Virtual Lab Simulation Catalog | Labster. (n.d.). https://www.labster.com/simulations

[35] PHET Interactive Simulations. (n.d.). PhET. https://phet.colorado.edu/

[36] Gizmos. (n.d.). Interactive STEM Simulations & Virtual Labs | Gizmos. https://gizmos.explorelearning.com/