

Framework for Scalable Content Development in Hands-On Virtual and Mixed Reality Science Labs

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Abstract—Authentic hands-on laboratory research is essential for undergraduate STEM education. Yet the tactile authenticity required to impact affective, cognitive, or psychomotor learning outcomes associated with laboratory training remains underexplored. Virtual and mixed reality (VR/MR) have enabled increasingly realistic hands-on STEM training experiences. However, they still lack authenticity with regard to user manipulation of fully functional and realistic laboratory tools, analysis of realistic (i.e. user-acquired) noisy data, and the application of critical thinking skills to draw conclusions from such noisy (and possible faulty) data. Here we present efforts to develop such an approach while also providing faculty content experts tools for code-free customization of VR/MR training experiences via structured spreadsheets. This approach enables nuanced real-time user feedback on laboratory skills such as proper pipetting or sterile technique which are otherwise difficult to provide. It also offers complete safety from chemical, biological, and radiological hazards and is more cost-effective than a traditional lab. This Hands-On Virtual-Reality (HOVR) Lab platform is uniquely enabling and will be valuable in the physical and life sciences for both research and instructional applications.

Index terms—Mixed-reality, virtual-reality, STEM education, science labs, optical tracking, multi-disciplinary uses of XR

I. INTRODUCTION

Active learning is well-suited to meet the wide range of learning needs of modern STEM learners [1]. It reinforces the concepts that students passively absorb from lectures or textbooks by promoting the higher-level critical thinking skills (i.e. application, evaluation, analysis, integration, and ultimately

creation of knowledge) that are central to actually “doing” science. In this context, one-on-one mentored research experiences are the ultimate active learning experience because they are fully authentic and span the full range of higher-level critical thinking skills including the creation and presentation of new knowledge. Students appreciate this, and are highly engaged, motivated, and impacted as a result. Unfortunately, resource limitations make it difficult to provide all students with one-on-one mentored research experiences.

Less resource-intensive alternatives, such as course-based undergraduate research experiences (CUREs) have proven to be a useful lower-cost alternative or complement to one-on-one mentorship [2]. Here we present preliminary data for another alternative which can be scaffolded with both CUREs and one-on-one research mentorship to make achieving desired learning outcomes more scalable and cost-effective. Our novel approach uses virtual and mixed-reality (VR/MR) technology, 3D printing, and high-precision motion tracking of hand-held laboratory tools to enable a highly authentic yet tightly tracked, regulated, and safe STEM laboratory training environment.

In this system, students can practice lab procedures by interacting with virtual content using either VR controllers or optically tracked but otherwise completely authentic hand-held physical lab tools. Student manipulation of these physical lab tools, the acquisition of raw data using them, and the processing and analysis of this raw data is tracked in real-time with millisecond temporal resolution and sub-millimeter spatial resolution. Importantly, complete programmatic control over the signal, noise, and calibration state of all the instruments and

tools in the virtual environment together with the high-resolution tracking of user interactions described above enables the provision of real-time feedback not only on whether users are collecting data correctly, but also on whether they are analyzing and drawing appropriate conclusions from this data.. This approach is cheaper, safer, easier to implement, and can provide more detailed feedback than traditional face-to-face laboratory instruction. With institutional support and

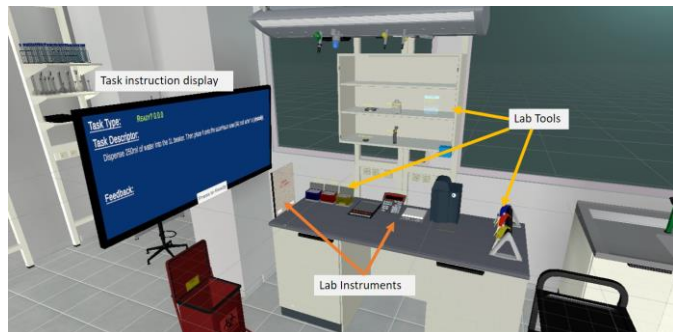


Fig. 1. The Hands-on Virtual Reality Lab system front-end design for student users. The figure shows the lab bench, lab tools (used to manipulate samples), and lab instruments (used to output recordable raw or processed data). Students view the virtual lab bench via a head-mount display (HMD) and interact with the virtual content using either VR controllers or optically-tracked hand-held physical lab tools (see below).

investment, students can use this approach to conduct STEM lab training activities at their own pace and on their own schedules – while still gaining fully authentic hands-on exposure to scientific instruments, tools, and methods.

II. RELATED WORK

Many STEM virtual lab simulations use low-immersion web-based 2D displays and highly inauthentic user interaction (UI) mechanisms (e.g. computer keyboards and mice) [3]–[5]. The relatively few high-immersion (i.e. 3D) STEM virtual learning systems that do exist are generally fully VR with three or six degree-of-freedom (3dof or 6dof) universal hand-held controllers mediating UIs with all objects in the digital environment [6]–[8]. The generality of these controllers unfortunately, makes them ill-suited to serve as authentic surrogates for all actual hand-held lab tools. Because AR systems overlay digital content over the real world, they are similarly limited by their dependence on actual physical instruments that are not subject to programmatic control. In addition, generating authentic hands-on STEM lab experiences in such systems requires tracking real-life lab tools with computer vision methods – which are both expensive and limited with respect to tracking resolution. Finally, in such systems the reagents used must be real (a safety concern) and detectable by the computer vision cameras employed (a significant challenge). Together these limitations make AR less well suited for STEM laboratory training applications. No existing platform offers the essential tactile/kinesthetic force feedback and level of authenticity required for college-level physical and life science laboratory instruction.

To meet this need, we have developed the Hands-on Virtual Reality Lab (HOVR Lab) mixed reality system. We have applied it here to chemistry and biochemistry lab training situations and outline a discipline independent framework for scalable content development that will enable rapid creation of

customized training experiences for diverse student populations by faculty content experts with little to no coding experience.

III. HANDS-ON VIRTUAL REALITY LAB SYSTEM DESCRIPTION

The HOVR LAB mixed reality system consists of three major components. First, it employs a dual-mode lab tool UI framework which enables fluid and customizable switching between VR-mode (i.e. controller-mediated) and MR-mode (i.e. physical lab tool-mediated) control of each lab tool that is deemed critical to psychomotor skills acquisition. Second, it employs a scalable Unity3D back-end software system which 1). detects the 3D poses of all VR controllers and physical lab tools being manipulated during data acquisition as well as any other standard user interactions, 2). outputs simulated raw data to the user via virtual instruments in the lab environment, and 3). assesses the user's performance in recording, analyzing, and interpreting this data. Third, the HOVR Labs system has a faculty content-developer front-end consisting of a customizable

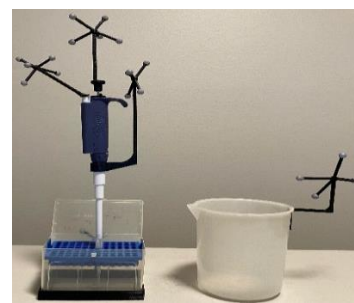


Fig. 2. Physical lab tools are optically tracked using 5-point IR retroreflective bead marker sets mounted onto lab tools in a non-perturbative manner via 3D printed adapters. The adapters are designed to minimize marker occlusion and interference with lab tool use.

and highly structured Lab Module Generator spreadsheet which is read by the back-end software to generate the laboratory module that the student user will experience.

Lab tool tracking in MR-mode is achieved via optical tracking of uniquely identifiable markers that are rigidly mounted onto the lab tools via 3D printed marker mounting adapters. The marker adapters are designed to minimize interference of the markers with standard lab tool usage while maximizing marker visibility to the tracking cameras. In VR-mode, students interact with the completely virtual lab tools using standard VR controllers. Voice-activated control of various features of the simulated environment also facilitates UIs and streamlines the experience. The system is designed to allow STEM learners to practice hands-on lab skills in an MR environment with completely authentic tactile/kinesthetic UI for lab tool manipulation. Although we've explored various alternatives, our system currently uses Unity3D for back-end program execution, an HTC Vive Pro head-mount display (HMD) to render and display the virtual world to the user, two HTC Vive controllers for VR-mode UI, and Optitrack Motive for passive optical tracking of lab tools in MR-mode.

A. Overview and User Experience Design

As shown in Fig. 1, the student-facing front-end design of our virtual lab bench includes three main classes of objects – lab tools, lab instruments, and a display for presenting instructions and feedback to the user.

Lab “tools” are visible on the shelf and on the lab bench. These include pipettes, beakers, tip racks, reagent bottles, and many other hand-held objects. Students use the lab tools to transfer reagents (which are never touched and thus completely virtual) and perform chemistry experiments by following the step-by-step instructions defined by the faculty content developer in the Lab Module Generator and presented to the student user on the display. The precision and accuracy of each lab tool can be controlled programmatically but is also dependent on the user’s (proper or improper) manipulation of the lab tool. Lab “instruments” are defined as lab tools that also serve as sources or sinks of raw or processed data that the user can/must eventually record in their lab notebook. Examples of lab instruments include a scale, a desktop computer running an instance of Microsoft Excel, and a calculator.

Objective #	Task Descriptor	Objective Type	Objective Level	Tool	Tool Type	Variable	Target Value
0	Dispense 500ml of water from the ultrapure water dispenser into a 1L Beaker. Place that beaker in the submission area, and press the "submit" button to make a physical submission.	Physical	Introductory	1L Beaker	Container	Total_Volume (mL)	500
1	Place the weighing boat onto the scale.	Use-Scale	Introductory	Scale	Instrument	Contained_Tools	Weighing Boat
2	Now tare the scale.	Use-Scale	Introductory	Scale	Instrument	Displayed Mass (g)	0
0	Pick up the P20 pipette and set it to 20.0 uL using the "Set Pipette" menu on your left hand's wrist.	Use-Pipette	Introductory	P20 Pipette	Pipette	Set_Volume (mL)	0.02

Fig. 3. Example of a section of a Lab Module Generator spreadsheet. Each row defines one snapshot of the virtual world during the lab procedure where the selected variable on the selected lab tool has a particular target value. The task description, logical criteria to be met, and feedback are parsed into the Unity3D simulation software on start-up. When students submit results, the corresponding tool and target value of its variable will be used to check if the student performed the task correctly. Data validation logic is programmed in the Excel which allows the chemistry and bio-chemistry content developers to efficiently make a lesson plan by selecting from a predefined list of task types, lab tools, and variables (Only a small part of the Excel is shown in the above picture due to limited space).

The overall lab experience is broken down into a set of “milestones” each originating from a separate row of the Lab Module Generator spreadsheet. Each milestone defines one or more conditions that must be met in order for the student to progress through the lab experience. At each milestone, the student user reads the instructions on the display, performs the specified task, indicates their readiness to be assessed on their performance of the task, receives positive or negative feedback, and then either proceeds to the next milestone or is invited to either re-attempt the task or – if necessary - re-acquire their data. Throughout the experience, the student user records raw or analyzed data into a virtual lab notebook at milestones pre-specified in the Lab Module Generator spreadsheet. Acquired and recorded datapoints can be used in subsequent data analysis milestones in order to assess the user’s analysis of their data. Data entry into the notebook is done using menus that are specific for the data required for that milestone (e.g. a numeric keypad, multiple choice selections from pre-defined options defined within the Lab Module Generator spreadsheet by the faculty content developer, etc.). In some milestones, data analysis is done using Microsoft Excel running on the GPU computer that is also running the experience.

Each lab tool, instrument, or derivative “datapoint” has associated with it an accuracy (i.e. systematic error), a precision (i.e. standard error), a measurement type (i.e. mass, length, volume, temperature, etc.), and a unit of measure (e.g. liter for

volume measurements). Instrumental errors are propagated to saved raw datapoints and ultimately to processed data using standard numerical error propagation methods in order to define the acceptable tolerances for any raw or processed values submitted by the student for assessment in a given milestone.

As a simple example, a student might be told to measure 250 mL of water using a 1 L beaker. To complete this task, the student would grab a virtual 1L beaker using a VR controller (in VR mode) or a physical 1L beaker (in MR-mode); add water from the water dispenser; read the water level using the gradations on the virtual 1L beaker rendered in their HMD; place the 1L beaker onto a “submission area” for assessment; and then say “submit” or “ready” to indicate they are ready to be

assessed. The software would then: check how much water is in the beaker; determine whether this value is within the tolerance limits required given the precision of the 1L beaker; and then display the appropriate feedback (e.g. “nice work” or “try again and be sure to look out for...”) as defined in the Lab Module Generator spreadsheet. If incorrect, the student would be invited to repeat this milestone until the correct volume of water is submitted in the 1L beaker.

B. Dual-Mode Lab Tool User Interaction Design Elements

There are many motion tracking solutions which could be used for mixed reality applications. However, the precise tracking of multiple scientific lab tools and instruments simultaneously in real-time without interference with lab tool function is a significant challenge. Notably, some lab tools must be tracked with greater precision than others in order to enable proper functionality. For example, the top of a pipetteman requires sub-millimeter tracking resolution relative to the shaft in order to enable precise tracking of liquid transfers, while the transfers made using a beaker can be tracked well enough even with a tracking resolution of ± 1 cm.

We explored various optical tracking solutions which meet the above requirements for the totality of lab tools we sought to use in our system (~30 which need to be simultaneously tracked). Currently, we use SteamVR tracking to track the HMD (and the user’s perspective of the VR environment) and the VR controllers. For tracking lab tools in MR-mode, we currently use

Optitrack Motive passive tracking of IR-retroreflective markers mounted onto custom-made 3D-printed adapters. Most lab tools are simple and require only 6dof tracking (e.g. beakers or reagent bottles) and thus only a single rigid body marker set. However, some lab tools (e.g. pipetteman) have multiple mobile elements and thus require additional markers which can report on the additional internal degrees of freedom (e.g. the top and tip ejector of the pipette). Fig. 2 illustrates examples of our patent-pending lab tool optical tracking solution in which passive tracking markers are designed and mounted onto a pipette (8dof lab tool) and a beaker (6dof lab tool).

One potential complication of our approach in MR-mode is that in order to avoid having a physical lab bench cluttered with physical lab tools containing adapters, students need to be able to use a single optically tracked physical lab tool to manipulate all virtual instances of that class of lab tool. To resolve this issue, we designed a specialized UI system which we termed the handler-activator-activated tool system. In this system, instead of having three different physical pipetteman for the 20 microliter, 200 microliter, and 1000 microliter pipettes used in a traditional biochemistry lab, we have only one physical pipetteman which can control any instance of all three pipettes. When in VR-mode, the VR controllers are used as a completely generic “handler” which picks up, drops off, and manipulates all lab tools regardless of their class. In contrast, when MR-mode is activated for a particular class of lab tool, a single tracked physical lab tool “handler” is used to manipulate all virtual instances of that class of lab tool. In MR-mode, the physical lab tool “handlers” have a distinctive grey color. Students can load colored and functional instances of lab tools (i.e. “activated tools”) onto their handlers by moving the handler onto lab tool “activators” located at fixed points on the benchtop or on the lab shelf. The activated lab tools contain the scripts that provide functionality. Students can release instances of activated lab tools onto the lab bench using special gestures such as tapping the handler onto the benchtop. This approach enables user interaction with numerous instances of virtual lab tools using a small number of tracked physical lab tool handlers and thus reduces table clutter and improves tracking performance.

C. Scalable Content Development via Structured Spreadsheets

A major barrier to the broader dissemination of VR/MR STEM learning experiences is the high cost of developing, testing, and iteratively optimizing such experiences for different target student populations. To address this issue, we designed our system to be scalable and easily customizable by chemistry and biochemistry content experts that have limited programming experience. For this purpose we designed a highly structured spreadsheet which functions as middleware to help chemistry and biochemistry content experts define and iteratively refine the logical milestones or steps that students should pass through during their VR/MR experience. Drop down lists and data validation logic ensure adherence to the formatting and syntax requirements of our back-end software which reads the formatted Lab Module Generator spreadsheet and actually creates the VR/MR lab experience. Fig. 3 shows example rows/milestones of such a Lab Module Generator. In this example, the student is first tasked with getting 500mL of water using a 1 Liter beaker (row/objective/milestone 1). Next,

they are asked to place a weighting boat onto the scale. Next, they must tare/zero the scale. Finally, they must set a P20 pipette to pick up 20 microliters. Roughly 100 rows and about 20 columns are required to define a standard pipette calibration lab experience in which the user pipette is either randomly miscalibrated or not and the user must carry out experiments to determine whether and by how much the pipette is miscalibrated..

Milestones or objectives can be any one of a few pre-defined types. “Physical” submissions involve the placement of a lab tool on a “submission area” to check the value of one of its many variables (e.g. total volume, solute type/concentration, pH, etc.). For example, in milestone/objective 0 from Fig. 3, the “total volume” variable of a 1L beaker is checked to see if it is within a pre-specified tolerance from 500 ml (the “target value”). “Data acquisition” milestones require the user to record a “datapoint” into their lab notebook. “Data analysis” milestones require the user to use the raw datapoints acquired and recorded in previous milestones to calculate parameters (e.g. average, standard deviation, percent systematic error, etc.) which are checked against target values in order to assess the student’s data analysis skills. “Conclusion” milestones require the user to examine the analyzed data and draw logical conclusions which are then also assessed using Boolean logical operators that are implemented at the level of the Lab Module Generator spreadsheet by the content developer. This system supports expansion of the number and types of lab tools, variables, calculations, and Boolean logical operations available to content developers. By having content developers select from predefined milestone types, lab tools, variables, etc. they can create or modify lab experiences quickly, efficiently, and at low cost (i.e. without having to write or modify the source code).

IV. ASSESSMENTS AND PILOT STUDY DATA

In Fall of 2021, we tested a simple pipette calibration HOVR Lab module in two upper-division biochemistry lab courses containing a total of about 25 students. In this module, a pipette is randomly miscalibrated and the user is asked to acquire and analyze data in order to determine whether and by how much it is miscalibrated. Our pilot study focused primarily on assessing the usability of the system. However, we also assessed the importance of the tactile authenticity of lab tool manipulation on cognitive, affective, and psychomotor skills acquisition. Our mixed-methods study was based on previous studies which have also explored the impact of physical versus virtual lab experiences in other STEM fields [9], [10]. We used a pre-mid-post design with two interventions for our pilot studies. Students were randomly assigned into control or experimental groups in which the sequence of the two interventions (VR-mode version or an MR-mode version of the module) was altered. At the beginning and end of the study we used the Chemical Concepts Inventory [11] to gauge students’ incoming (pre) and outgoing (post) general understanding of chemistry. The Meaningful Learning in the Laboratory Instrument [12] was used to assess the expected and perceived cognitive and affective impact of the students’ traditional laboratory class as well as each of the two interventions from our study. Targeted cognitive assessments directly related to the subject matter covered in the pipette calibration module were also used immediately before and after each intervention. These consisted of both multiple choice

questions identified by faculty content experts as well as standardized and validated multiple choice items taken from American Chemical Society Exams [13] and aligned to the Anchoring Concepts Content Map [14]. In addition, we also assessed the impact of the VR/MR experience on students' intrinsic motivation and self-efficacy using other established inventories [15], [16]. Finally, to assess student user experience (UX) with the VR/MR environment in the VR and MR-modes of the module, we employed a previously-validated UX in immersive virtual environments instrument [17].

Briefly, the qualitative results of our various assessments on the pipette calibration module indicate the following: 1). the system was particularly uncomfortable for students with glasses; 2). the large majority of students enjoyed both the VR and MR interventions and considered them valuable and innovative learning experiences; 3). our initial version of the module – which involved calibrating three different pipettes at two different volumes- was too long and needed to be shortened in order to ensure that students would be able to complete the VR/MR activity within a reasonable timeframe; 4). the excel spreadsheet-based method for iterative refinement of each module/experience makes iterative refinement of the VR/MR experience very easy; and 5). students found the feedback on their data analysis and calculations to be very helpful. A detailed and more quantitative analysis of our preliminary pilot test results as well as the results of our ongoing larger-scale trials is currently in progress.

V. DISCUSSION AND FUTURE WORK

VR and MR systems are very likely to play a valuable role in the future of science laboratory education. While they may never fully replace traditional wet lab experiments, they will almost certainly bridge critical learning gaps by providing detailed and real-time feedback on performance metrics which often escape instructors in traditional settings. MR systems are far less expensive to purchase, maintain, and implement when compared to traditional wet labs and they also offer reduced safety concerns/liability, greater freedom for students to learn on their own time, improved engagement, greater focus, and more opportunities to make mistakes and learn in a less stressful and more game-like environment.

In this paper, we present a novel framework for scalable and cost-effective development of fully customizable VR/MR science labs across the physical and life sciences. We briefly introduce the general methods we use for enabling MR-mode tracking of physical lab tools. We apply our approach to the simplest (yet arguably most important) of chemistry/biochemistry lab procedures – pipette calibration. We demonstrate proof-of-principle and examine the feasibility of our general approach and present preliminary results from a pilot user study examining efficacy and impact on both cognitive and affective outcomes in the fields of chemistry and biochemistry.

In the future, we hope to target more advanced concepts/procedures and more detailed characterization of the impact of authentic hands-on (i.e. MR-mode) versus inauthentic controller-based (VR-mode) lab tool UI on student psychomotor skills acquisition, conceptual understanding, and affective outcomes (self-efficacy and intrinsic motivation). The complete technical details (including the tracking performance metrics of

our system) will be published in a more technical journal. Our system empowers content developers to tailor their students' HOVR lab experience without having to code, and we are very hopeful that more faculty will be able to harness the power of spatial computing to enhance teaching and learning at the bench using this approach.

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REFERENCES

- [1] C. Bonwell and J. Eison, *Active Learning: Creating Excitement in the Classroom*. 1991 ASHE-ERIC Higher Education Reports. 1991.
- [2] J. Awong-Taylor, *et al.* (2016). Undergraduate research for all: addressing the elephant in the room" *Council on Undergraduate Research*. 37(1), p. 2022. DOI:10.18833/CURQ/37/1/4
- [3] M. T. Bonde, *et al.* (2014). Improving biotech education through gamified laboratory simulations. *Nature Biotechnology*. 32(7), pp. 694–697. DOI:10.1038/nbt.2955
- [4] C. Tüysüz. (2010). The effect of the virtual laboratory on students' achievement and attitude in chemistry," *International Online Journal of Educational Sciences*. 2(1), pp. 37–53. <https://doi.org/10.21891/jeseh.837243>
- [5] B. F. Woodfield *et al.* (2005). The Virtual ChemLab project: A realistic and sophisticated simulation of organic synthesis and organic qualitative analysis, *Journal of Chemical Education*. 82(11), pp. 1728–1735. DOI:10.1021/ED082P1728
- [6] C. H. S. Wong, K. C. K. Tsang, and W. K. Chiu., (2021). Using augmented reality as a powerful and innovative technology to increase enthusiasm and enhance student lin higher education chemistry courses. *Journal of Chemical Education*. 98(11), pp. 3476–3485. <https://doi.org/10.1021/acs.jchemed.0c01029>
- [7] M. Abdinejad, C. Ferrag, H. S. Qorbani, *et al.* (2021). Developing a simple and cost-effective markerless augmented reality tool for chemistry education," *Journal of Chemical Education*. 98(5), pp. 1783–1788. <https://doi.org/10.1021/acs.jchemed.1c00173>
- [8] T. Barkatsas, N. Carr, and G. Cooper, "Implementing Virtual Reality in the Classroom: Envisaging Possibilities in stem Education," *STEM Educ. An Emerg. F. Inq.*, pp. 61–73, 2018.
- [9] T. De Jong, M. C. Linn, and Z. C. Zacharia, "Physical and virtual laboratories in science and engineering education," *Science (80-.)*, vol. 340, no. 6130, pp. 305–308, 2013.
- [10] J. J. Chini, A. Madsen, E. Gire, *et al.*, "Exploration of factors that affect the comparative effectiveness of physical and virtual manipulatives in an undergraduate laboratory," *Phys. Rev. Spec. Top. - Phys. Educ. Res.*, vol. 8, no. 1, pp. 1–12, 2012.
- [11] J. Barbera. (2013). A psychometric analysis of the chemical concepts inventory. *Journal of Chemical Education*. 90(5), pp. 546–553. DOI:10.1021/ed3004353
- [12] K. R. Galloway and S. L. Bretz. (2015). Measuring Meaningful Learning in the Undergraduate Chemistry Laboratory: A National, Cross-Sectional Study. *Journal of Chemical Education*. 92(12), pp. 2006–2018. <https://doi.org/10.1021/acs.jchemed.5b00538>
- [13] American Chemical Society Examinations Institute, "ACS Exams," <https://uwm.edu/acs-exams/instructors/assessment-materials/exams/>.

- [14] T. Holme, C. Luxford, K. Murphy. (2015). Updating the general chemistry anchoring concepts content map. *Journal of Chemical Education*. 92(6), p.1115. <https://doi.org/10.1021/ed500712k>
- [15] R. M. Ryan. (1982). Control and information in the intrapersonal sphere: an extension of cognitive evaluation theory," *Journal of Personality and Social Psychology*. 43(3), pp. 450–461. <https://doi.org/10.1037/0022-3514.43.3.450>
- [16] A. O. Pintrich et al. (2015). Motivated strategies for learning questionnaire (MSLQ). *Mediterranean Journal of Social Science*. 6(1), pp. 156–164. <https://eric.ed.gov/?id=ED338122>
- [17] K. Tcha-Tokey, O. Christmann, E. Loup-Escande, et al. (2016). Proposition and validation of a questionnaire to measure the users experience in immersive virtual environments. *International Journal of Virtual Reality*. 16(1), pp. 33–48. <https://doi.org/10.20870/IJVR.2016.16.1.2880>