Exploiting Extended Reality Technologies for Educational Microscopy

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Abstract. Exploiting extended reality technologies in laboratory training enhances both teaching and learning experiences. It complements the existing traditional learning/teaching methods related to science, technology, engineering, arts and mathematics. In this work, we use extended reality technologies to create an interactive learning environment with dynamic educational content. The proposed learning environment can be used by students of all levels of education, to facilitate laboratory-based understanding of scientific concepts. We introduce a low-cost and user-friendly multi-platform system for mobile devices which, when coupled with edutainment dynamics, simulation, extended reality and natural hand movements sensing technologies such as hand gestures with virtual triggers, is expected to engage users and prepare them efficiently for the actual on-site laboratory experiments. The proposed system is evaluated by a group of experts and the results are analyzed in detail, indicating the positive attitude of the evaluators towards the adoption of the proposed system in laboratory educational procedures. We conclude the paper by highlighting the capabilities of extended reality and dynamic content management in educational microscopy procedures.

Keywords: Extended reality · STEAM education · Interactive technologies · Mobile extended reality · Human-computer interactions

1 Introduction

A key element of teaching content derived from Science, Technology, Engineering, Arts and Mathematics (STEAM), is the availability of laboratory infrastructure as it offers the opportunity to acquire skills and a deeper understanding of natural phenomena [1]. In 1989, Nersessian [2] stressed that, "*practical experience is the heart of science learning*", which indicates the importance of having practical laboratories procedures within the

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educational process. Nonetheless, the installation of laboratory infrastructure requires space, personnel and time, while its operation and maintenance can often raise costs at a prohibitive level [3]. Considering this and the evolution of all disciplines, there has been a growing need for innovative and low-cost methods/techniques/systems to be introduced when teaching STEAM [4–7]. Information and Communication Technology (ICT) has been introducing tools and systems for years now to complement laboratory training. Nowadays, with the introduction of cutting-edge technologies such as Extended Reality (XR), ICT has shown promising future outcomes towards the enhancement of the “hands-on labs” (physically involved in laboratory performed activities) approach, by overcoming obstacles related to budget, distance and availability.

The main contribution of this paper is the introduction of an innovative and interactive educational mobile XR tool/system based on dynamic content for assisting learners in laboratory instrument manipulation. To demonstrate our approaches, we make use of a microscope (and its components) as it composes one of the fundamental instruments of laboratories related to Biology, Physics and Chemistry (Science), which are also known as “wet labs” [8–11]. Within this framework, the proposed system aims to instruct learners about a microscope’s main components and functionalities. Additionally, it enables users to learn about various laboratory procedures by interacting with the microscope using hand gestures over virtual triggers (single camera-based motion sensing technologies). Understanding the need and the importance of the dynamic management of educational content [12], this system introduces a Web based interface based on link data technologies [13]. It must be stressed that the proposed system also aims at the exploitation of edutainment approaches [14–17], setting the standards for increased immersion and presence in the XR environment, stimulating the user’s senses, leading to better understanding of educational material and new skill development [16].

The rest of this paper is organized as follows. The following section covers a brief literature review of related works while indicating the novelties of the proposed system. The third section offers a detailed analysis of the system’s architecture and components. The fourth section provides the educational approaches, while the fifth focuses on the system’s objective evaluation. The paper concludes by summarizing the key points of the proposed system and sets out future directions.

2 Background

The evolution of Virtual Reality (VR) technologies combined with low cost equipment has allowed the emergence of innovative laboratory training solutions [18]. By using simulation techniques, researchers attempt to overcome cost, time and spatial obstacles thus changing the setting of STEAM education through the application of virtual laboratories [19, 20]. Studies have shown that students, who perform experiments in a virtual environment, become familiar with the laboratory instruments and, therefore, can be more actively involved in the physical lab training process [8].

Researchers pinpointed that the use of XR in STEAM education results in an increase of user achievement [21], engagement and motivation to accept change [22] as well as improved knowledge acquisition while amplifying both pleasure and enjoyment of being involved. The use of XR in laboratory training can provide efficient, safe, convenient, flexible and portable educational tools. Such tools allow users to access them easily, anytime and remotely (from any computer system that access the Web) [23]. Therefore, they can help prepare students for the on-site hands-on laboratory experience. Over the years, several studies have been conducted on the use of VR technology in laboratory training. Onlabs is a standalone 3D virtual reality biology laboratory that provides a high-level realistic environment for higher education students [20]. Becerra et al. [4] developed and evaluated a low-cost VR application for understanding of movement in physics by using gamification techniques. Bogusevschi and Muntean [6] introduced a VR application for experimental laboratory simulations of "Water Cycle in Nature" for primary school students. In the terms of learners' experience and application usability, the results were very encouraging.

Additionally, edutainment is often used, which is the combination of fun and education [16] that can be achieved either by incorporating elements of entertainment into a learning scenario or vice versa. The goal of edutainment is to make learning enjoyable, by enabling an interesting and engaging experience, transforming the learning process into an event, supporting the active participation [17]. Nowadays, technology provides the media that can stimulate learners' senses in order to maximize their engagement and understanding of the educational material, while enables the instructors to easily personalize and communicate the content of their teaching [24]. Aksakal [16], referring to the education expert David Buckingham said that when edutainment is based on visual context, constitutes "*the game of describing with least word*". Edutainment is widely applied through VR technology, with many future promising results through XR applications, since XR technology supports interaction, personalization and fun, through the undoubtfully interesting and engaging ability to simultaneously explore real and virtual elements in the same environment. Nevertheless, Okan [14] aptly states that during the design process of an edutainment application "*the question is how much "edu" and how much "tainment"* [25] *should be included*". Thus, the design of an edutainment software should be focused on the efficient communication of the educational content and the user should not be distracted by the enrichment content.

Nowadays, even though "physical" laboratories are still the fundamental core of STEAM laboratory education, researchers aim to develop systems and tools using XR technologies. However, the creation of a user-friendly enjoyable multilingual system/tool with personalized content which can be used in all levels of education is a challenging task especially when the corresponding effectiveness is required to remain unaffected by geographical, financial and time constraints. The proposed system constitutes a part of the integrated system XRLabs which explores the development of STEAM educational systems/tools based on conventional laboratory training procedures for students of all educational levels [7, 26]. The proposed system aims at allowing users to practice remotely without time and sources restrictions, focusing on skill acquisition and better understanding of laboratory procedures, by using a low-cost, user-friendly mobile XR solution for every education level.

3 User-Centric Extended Reality Based Framework

One of the most essential and frequently used instruments in hard science laboratories is the microscope. In our study we choose to make use of a photonic stereo microscope to exploit the capabilities of XR in STEAM education. The proposed system is structured on three main components (sub-systems): the dynamic management of the educational content, the implementation of AR/MR as part of the XR technology and the use of hand gestures as an interaction method (virtual buttons triggering).

Figure 1 depicts the system's main architecture. It clearly indicates that the educational part of the system appeals to many different user levels. The demonstration of the educational content takes place via the XR sub-system using mobile devices. Moreover, the educational content and the scenarios are managed by expert users (e.g. trainers) through a Web-based Graphical User Interface (GUI). On the other hand, it should be highlighted that users without Internet access may exploit some local content (considered as default).

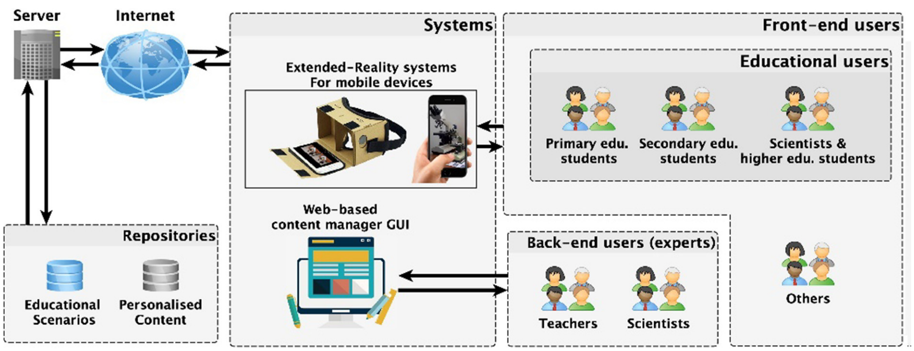

Fig. 1. System's architecture overview

3.1 Dynamic Content Management (DCM)

The first sub-system implements a Dynamic Content Management (DCM) application of the educational content using a Web-based GUI. The ability to add new user groups (different levels) as well as editing existing groups is the first step that experts (trainers etc.) should perform. Furthermore, they can select a list of target groups and assign to them appropriate educational content according to their interests. In addition, a system for registering users and logging in to the platform has been implemented to manage the users of the system (trainers and learners), enabling personalization. All content of the XR systems can be managed through the DCM sub-system in real-time. The application supports multiple languages, but the demonstration has been implemented to support English and Greek. Figure 2 depicts screenshots of the DCM.

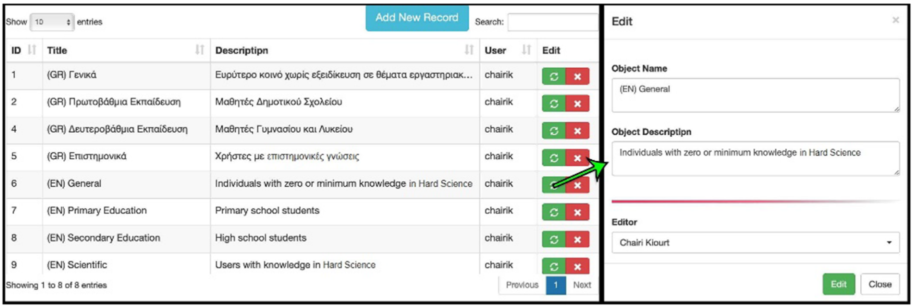

Fig. 2. Web-based dynamic content interface snapshots.

3.2 XR Sub-system

The second sub-system (XR) is aimed for mobile devices, Android and iOS smartphones and tablets, exploiting the advanced capabilities of the Unity game engine and the Vuforia SDK. Two different tracking methods are being exploited serving different purposes. Firstly, we exploit image marker tracking (marker-based methods) [27] to present the virtual laboratory instrument (3D microscope) on a real surface (e.g. table). To be more specific, when the device's camera detects a specially designed image (in our case composed of multiple QR codes) which operates as a marker, it triggers the display of the necessary virtual elements (microscope, virtual buttons) on top of it. This approach constitutes a version of the educational tool that aims to enable distance training when the real instrument is not available to the learner. Secondly, we exploit an advanced object recognition technique, based on model target detection, using the available 3D model of an object, in our case the microscope. In this case the user has the ability to superimpose information on top of the actual instrument. Specifically, when the camera detects the real microscope (physical laboratory instrument) and a pointer (dot) in the center of the screen aims at some component on the real microscope, that component is highlighted, and the relevant educational content appears next to it.

Both approaches can run independently or simultaneously. When applied together, the user has the opportunity to enhance her/his learning skills, by visually matching the focused part of the virtual microscope, with the corresponding part of the real microscope. Additionally, MR features are applied, like virtual triggers being responsive to environment (hand movements) and occlusion handling [28] (the real microscope hides the virtual one when the latter is placed behind the real) as it is expected in the actual reality according to the position of the two objects.

The system also applies in stereoscopic mode, where the user can use special low-cost AR glasses. Therefore, it is important to stress that smartphones have a significant advantage over tablet devices. Because of their size, they can be easily attached on a head-mounted stereo view cardboard (a low-cost solution for VR/AR/MR applications) and improve the immersive attributes of the educational process. Figure 3 depicts snapshots of the XR user experience, illustrating the simultaneous viewing of the two different versions where the user can visualize and understand the real components that correspond to the virtual components of the microscope.

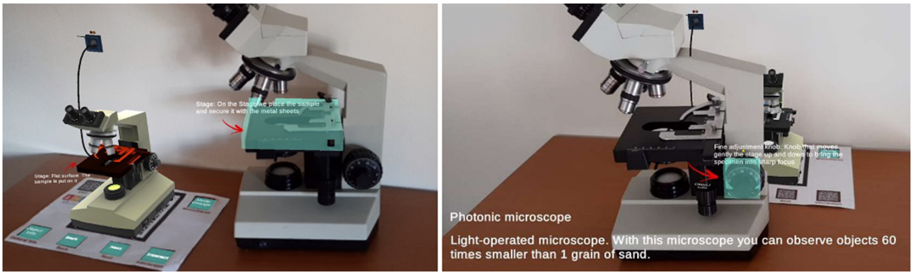

Fig. 3. Simultaneous display of both detection methods showing MR features

Given the fact that many studies have highlighted the problem of motion sickness in virtual environments [29, 30], the deployment of the XR sub-system in two different view modes: stereoscopic view and full-screen view, enables the user to personalize his/her experience according to his/her needs, preferences and possible physical discomforts.

3.3 Interaction Sub-system

For the implementation of the interaction sub-system, we exploit motion sensing technologies, single camera-based hand-tracking method via the emerging technology of marker based Virtual Triggering (VT). Simply put, the latter technology allows users to move their hand over a specific marker in the camera's field-of-view and the system returns the corresponding action. Figure 4 acts as a representation of the hand motion tracking mechanism over the area of a virtual button (small QR codes) in the camera's field-of-view. The red ray indicates the connection between virtual microscope and the mobile device camera. The yellow and green rays refer to exiting/entering system and view modes, while blue rays refer to the interactions with the virtual microscope and its components (training material). The right image of Fig. 4 depicts an example where the user interrupts the communication between the camera and the most bottom-right QR code, resulting in a real-time interaction with the light of the microscope.

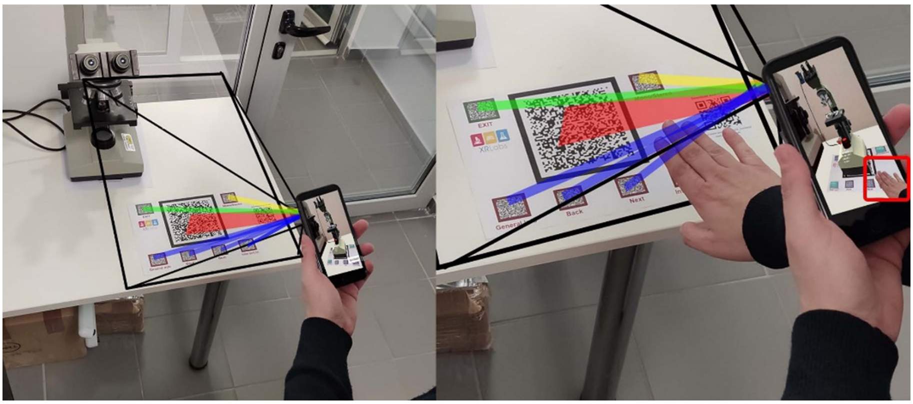

Fig. 4. Single camera based virtual buttons triggering methods

It is important to stress that we choose to use the marker-based AR technology, to take advantage of VT approaches, in order to create a unified system that will exploit the same interaction method in both stereoscopic and full screen mode, enhancing the application's user friendliness. Thus, the trainee will not be obliged to become familiar with different interaction methods depending the view mode they choose.

The proposed method, composes a natural low-cost way of interacting with the virtual object by exploiting hand moves, aiming to increase immersion and improve the educational experience without the need of expensive equipment. For example, in the "Microscopy" mode, when the user moves his/her hand over the virtual button "Interaction", the user simultaneously can interact (rotate, press, etc.) with the targeted microscope component, thus simulating its real functionality.

Table 1 summarizes the functionality of each virtual button placed on the image marker in addition to the mode and view being activated.

Table 1. Virtual buttons functionality summarize

Virtual button functionality		Mode*	View**
EXIT	Exit stereoscopic view	Both	Stereo
Mono/Stereo	Toggle Full screen/Stereoscopic view	Both	Both
General info	Enable/Disable startup general information	Both	Both
Back	Return to the previous step of the microscopy process	Microscopy	Both
Next	Go to the next step of the microscopy process	Microscopy	Both
Interaction	Interact with the targeted microscope component	Microscopy	Both

*Microscope Exploration or Microscopy or Both
**Full Screen or Stereo or Both

For the clarity of the experience, the elements being selected (components of the microscope) are highlighted with Red color, while in the "Microscopy" mode, the elements that the user interacts with, are highlighted in green. Figure 5 presents snapshots of the system. In particular, it illustrates the 3D model of the microscope, which with the use of the image marker, spawns on the real surface next to the real microscope. Furthermore, the top right image shows the appropriate highlighting while individual components are in focus (red color) or being interacted with (green color). All text content is obtained dynamically from the repositories. Additionally, the bottom image of Fig. 5 depicts the stereoscopic view mode.

Fig. 5. Extended Reality based training in microscope manipulation. (Color figure online)

4 Educational Approach

In laboratory training, it is of great importance that the learner is familiar in advance with the basic functions of the laboratory instrument, in order to avoid unnecessary costs, wasted time and resources due to misuse and lack of experience [8]. Additionally, simulation in education, increases student engagement and motivation utilizing an Edutainment environment. Moreover, with the outbreak of the pandemic (Coronavirus disease 2019, COVID-19)[1], many countries around the world were forced to impose quarantine, thus highlighting the necessity of the existence of infrastructure for distance work and education. As a result, the possibility of developing systems that enhance the remote laboratory training for educational science programs where the performance of hands-on activities is crucial, is very promising and welcomed.

The system we propose is a low-cost solution which can supplement or be an alternative to real skills training, exploiting edutainment mechanisms. First of all, the trainers can intervene in the education procedure by introducing the educational material dynamically and enable the learners to self-practice remotely as many times as needed to understand the subject. As mentioned in the previous session, one of the fundamental principles of edutainment is personalization, which allows trainees to acquire knowledge for the same subject at their own pace [17]. The main purpose of the proposed system is to: (i) provide general technical information about a laboratory instrument, (ii) focus on

[1] Covid-19 of the SARS-CoV-2 virus, which was first detected in the Chinese city of Wuhan at the end of 2019.

the components of a microscope and their functionalities and (iii) interactively demonstrate the basic steps of a complete microscopy procedure. System usage flowchart for learners is depicted in Fig. 6.

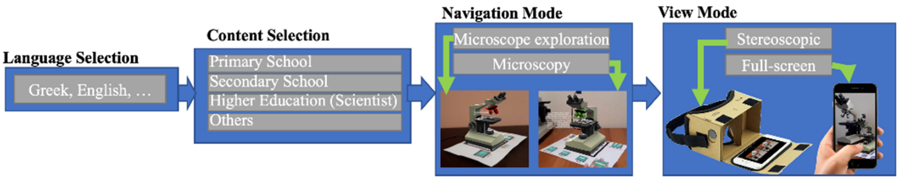

Fig. 6. The main flowchart of system usage

When the application is launched, the user is prompted to login to the system using credentials acquired by their trainer. Next, the user selects the appropriate language followed by the selection of the appropriate educational content based on his/her skill level. Thus, we have created different educational content for different target groups, such as (i) Primary education, (ii) Secondary education, (iii) Higher education and scientists, and (iv) others. At this point, it should be highlighted that the trainer may create specific content for a given user group. As a next step, the user selects the preferred training mode ("Microscope Exploration" or "Microscopy"), based on the needs of the educational course. The last step involves the selection of view mode (Stereoscopic or Full-screen). Users without head-mounting or users with tablet-based devices are recommended to use the full-screen mode.

The deployment[2] provides two different training scenarios to learners. In the first mode ("Microscope exploration") the user can turn the camera around the virtual or/and (or if available) the real microscope, pointing it at individual components of the instrument and get information about its functionalities (see footnote 2). The second mode ("Microscopy") is the sequential demonstration of the microscopy process in a step by step manner. In this mode, the user can interact with the components of the virtual microscope by using the necessary virtual triggers to manipulate it in real-time. Individual steps need to be followed to complete the microscopy procedure (see footnote 2). The design of the use of virtual buttons that trigger the sequence of microscopy steps (Next, Back), does not allow user errors (the interaction with the microscope through the virtual button is enabled only if the previous step is successfully completed), which enhances the user-friendliness of the application.

When the real microscope is available, the learner can use the acquired knowledge to perform the microscopy using the real instrument, having real-time empirical knowledge thus minimizing the possibility of mishandling it. Therefore, knowledge is better communicated through imitation and repetition. In the classroom where material, time and laboratory instruments availability are important, the system allows all students to simultaneously practice using the virtual version on their mobile device, while the teacher demonstrates the microscopy process on the real microscope. Hence, the learner

[2] Deployment as well as all the additional support material: http://www.ceti.gr/chairiq/xrlabs/.

takes an active role in her/his learning, acquiring knowledge and having fun through empiric learning.

In developing the system for training different target groups on microscopy, the learning theories of how knowledge is constructed, were taken into consideration. With the Microscope Exploration Mode and based on the behaviorism [31], the system teaches facts and gives essential information for understanding the new concept of microscopy and acquiring the knowledge through repetition. In the Microscopy Mode, we considered the Cognitive Load Theory [32] and as we acknowledged that the microscopy experiment has an inherent difficulty, we divided this experiment into 14 steps in order to lower the high intrinsic cognitive load [33]. The extraneous load was also limited to a minimum, by avoiding unnecessary information and confusing instructions [34]. Finally, as constructivism declares, we designed an application that engages actively the learner as it includes observation, reflection, data collection and interaction. Aiming to increase enjoyment through learning, we combine personalization, interaction and simulation technology, thus the system stimulates the student's instinctive curiosity to learn through experience. Providing the opportunity for distance training, we enable students to practice continuously, thus increasing their confidence in understanding the process, enjoying the satisfaction of good student performance.

The combination of XR technologies and hand gestures based interactive methods provides a pleasant and interesting educational environment for the users. The entertaining aspects of the proposed system (interactive educational scenarios, simulation, graphical, visual and personalized content) are offered to attract and engage learners to enjoy the laboratory training process. However, the incorporation of the graphical elements into the system (information pointers, highlight shapes, colors) are used carefully, without unnecessary effects, aiming to emphasize to the educational content, without distracting the learner. Thus, combined with personalization and interaction, the system motivates the learners to get in touch and understand the subject through stimulating their curiosity and their senses, aiming at learning and not just having fun with the application [14]. The development of educational scenarios through the DCM is controlled by the trainers, providing them the important capability of customization of the educational scenarios/procedures or the development of new ones. For example, instructors through DCM can change the educational text content that want to communicate each time or select samples for microscopy that will be available to the trainee as images, depending on the actual experiment they want to present to him/her. Additionally, trainers may exploit the proposed system as a laboratory procedure demonstration that offers enhanced experience through a screen sharing plugin of the mobile device. This leads to a worldwide real-time connection among trainers and learners. To sum up, the exploitation of the proposed system by the learner in educational processes focuses on three different aspects:

– Home practicing: as a preparation tool before the interaction with the physical laboratory instruments, which allows learners to repeat the experiment without constraints.
– Instrument guide: the learner may exploit the XR systems during the real experiment in the physical laboratory for further information or to recall some elements of the instrument.

– Continuous knowledge update/lifelong learning: without any restrictions, out of courses or training sessions and available for anyone.

5 System Evaluation

In order to study the effectiveness of the proposed system, eleven laboratory (Hard Science) experts (Researchers/University Teachers) and computer graphics (Computer Science) experts (Researchers/University Teachers) are employed to evaluate it, based on a short questionnaire in accordance with evaluation rules pointed out by Guimaraes and Martins [35]. The evaluation procedure was as follows: first the experts watched an instruction video, then they had the opportunity to test the system by themselves and at the end they answered the questionnaire. The analysis of the results confirms the positive impression of scientists in combining XR technologies with educational content. Overall, the system was well-rated and judged as very useful supplementary tool for demonstrating and teaching laboratory instrument functionalities.

Some statistical results of the experts' evaluation are depicted in Fig. 7 where the top-left graph presents the experience of the experts in AR/MR systems, from very low to very high [1, 5]. It should be highlighted that moderate to low experience experts are laboratory experts, while the rest are computer graphics experts. Considering that the system mainly focuses on educating learners, it is critical to exploit XR technology and create an interesting and fun learning tool without distracting the user from the educational process. The evaluation process gave satisfactory results with 81,9% of the respondents ("agree" and "strongly agree", columns 4 and 5) that they were not distracted from the educational subject (Fig. 7 graph b). On the other hand, the interaction system (Fig. 7 graph c) and the user instructions (Fig. 7 graph d) were accepted quite widely. Furthermore, 72,7% of the experts, preferred the full-screen mode instead of stereoscopic mode. Nevertheless, exploring these results, we have set as one of our future goals to focus on improving the usability of stereo mode.

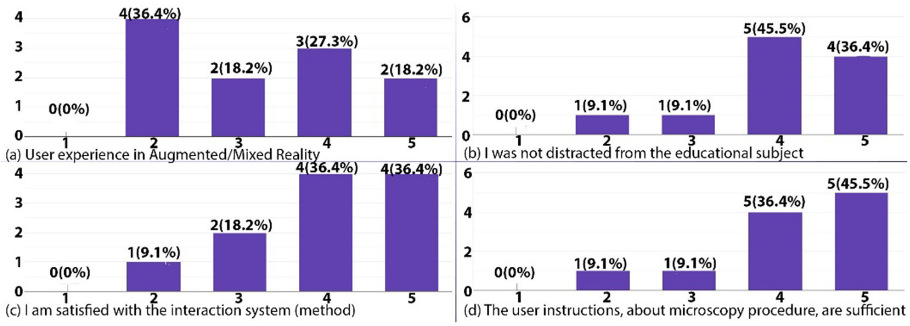

Fig. 7. Statistical results of the experts' evaluation.

6 Conclusions

The main scope of the proposed system is to introduce a low-cost, innovative, dynamic and interactive educational XR based tool, for assisting users in laboratory training (both in handling equipment and carrying out experimental processes). The tool is considered as a part of the STEAM education toolkit and it is addressed to all educational levels. Thus, we aim to attempt an approach to laboratory instruction, utilizing simulation and XR technology, combined with dynamic data management and interaction techniques, that can exploit ideally all user senses. Unlike the traditional science lab, this system does not require a specific physical space or dedicated room and simply assumes the availability of a mobile device (smartphone or tablet), thus solving problems of laboratory equipment availability, cost, maintenance, possible instrument's misuse and user safety. Additionally, learners are given the opportunity to practice as much as they want without restrictions such as time, cost, availability, distance as well as safety issues. In addition, using this system reduces the repair costs and the risks of misusing the laboratory facilities, as misuse can cause considerable damage to expensive and sensitive equipment. Similarly, students' safety can be improved as they become aware of the possible laboratory hazards (equipment and consumables) at a virtual while inexpensive level. Furthermore, the adoption of a dynamic management system of the educational content allows flexibility and enhances the creation of a multilingual educational system.

In the future, we aim to develop an upgraded system, exploiting marker-less XR techniques to eliminate the need of special printed image markers. Moreover, we will explore cutting-edge interaction methods such as the use of special sensor devices to achieve higher levels of gesture estimation accuracy in order to engage the learner in a more realistic and natural experience. Furthermore, we will approach the enrichment of the enjoyment of the system using gamified elements. Finally, we will focus on assessing the effectiveness of the system by assessing the learners experience, with pretests and post-test based on learning analytics methodologies. In general, the main goal will be to succeed in creating an educational playful platform that attracts both trainers and learners and engage them in utilizing entertainment and rewarding motives.

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