Will Virtual Reality Transform Online Synchronous Learning? Evidence From a Quality of Experience Subjective Assessment

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***Abstract*—In this article, we preliminarily discuss the limitations of current video conferencing platforms in online synchronous learning. Research has shown that while the involved technologies are appropriate for collaborative video calls, they often fail to replicate the rich nature of face-to-face interactions among students and between students and professors, by constraining them to a grid of faces on screens and limiting the natural flows of conversation and nonverbal communication. We believe that a potential solution to this issue could be adopting virtual reality (VR) technologies in online synchronous teaching. To test our assumption, we developed a novel subjective assessment involving 44 electronics engineering students who attended real lessons on Internet protocols. The taught content was included in the course program and the final exam; the professor made use of slides for teaching and a blackboard to explain some exercises. Two different learning approaches were used: VR-based online synchronous learning and video-based online synchronous learning. While the former consisted in wearing a headset and participating in a virtual classroom in front of the teacher's avatar, the latter involved watching a 2-D video of the streamed lesson through a laptop and communicating through the microphone. The opinions collected from the students included several aspects, namely, overall quality of experience, immersion, interactivity, naturalness, usability, entertainment, comfort, side effects, interaction with the teacher and students, and ease of taking notes. Key findings from Welch's t-test indicate the higher interactivity ($p < 0.05$), naturalness ($p < 0.01$), entertainment ($p < 0.01$), and immersion ($p < 0.001$) perceived by students for the VR-based learning experience than the video-based one. Increased immersion was the most significant aspect, as highlighted by the lowest p-value. On the other hand, the level of comfort was heavily penalized ($p < 0.001$), and students were unable to take notes in the VR classroom environment easily. No significant difference ($p > 0.05$) was achieved for the other considered metrics.**

***Index Terms*—Education, online learning, quality of experience (QoE), subjective assessment, video conferencing, virtual reality (VR).**

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I. Introduction

SOCIAL interaction plays a crucial role in the learning process, fostering collaboration, the exchange of ideas, hearing other points of view, and developing interpersonal skills. The physical classroom is a natural environment for social interactions, where daily face-to-face (F2F) confrontations and nonverbal communication provide the students with a means for establishing social bonds and developing social abilities, such as empathy, conflict resolution, leadership, and teamwork.

The COVID-19 pandemic forced a quick and widespread shift to online synchronous learning, which required the adoption of traditional video conferencing platforms to make education accessible to students worldwide through the Internet. While reasonable for remote communication, these platforms often fail to replicate the rich nature of F2F interactions by constraining people to a grid of faces on screens that limits the natural flows of conversation and nonverbal communication [1]. In particular, some studies have shown that the adoption of video conferencing platforms for educational activities makes it hard for learners to gather and interact with peers and teachers through the screen, leading to indifference, emotional deficiency, and desocialization [2], [3]. Chat- and audiovisual-based communications fail to provide a shared physical space where students can meet to establish the required social relationships and group membership needs, which are provided during F2F classroom learning sessions [4].

The aforementioned limitations of video conferencing platforms for online synchronous learning activities can be lowered with the support of immersive communication technologies, such as virtual reality (VR) and augmented reality (AR). The incorporation of these technologies can be a trigger for transforming the online learning landscape into an immersive and interactive world, allowing distant people to stay and communicate in the same virtual environment. Indeed, there are major theoretical frameworks, such as constructivist learning, experiential learning, cognitive load theory, social learning, and presence and immersion theories, which encourage the introduction of VR and AR technologies in education as these could have key advantages compared to traditional video-based online learning [5].

While immersive multimedia technologies can offer great opportunities and innovations for online education, it is crucial to evaluate students' willingness to accept and engage with them. Quality of experience (QoE) is a standard metric used to

assess people's subjective experience concerning multimedia-based services provided through the Internet. QoE is defined as *"the degree of delight or annoyance of the user of an application or service,"* and subjective assessments are required to quantify the impact of human (e.g., age, experience, and emotion), system (e.g., content quality and end device), and context (e.g., location, duration, and price) influence factors on the QoE [6], [7]. Moreover, as immersive services often rely on real-time data transmission, network-level aspects, such as latency and traffic patterns, also play a key role in shaping QoE and should be carefully modeled and monitored [8]. In the last decade, QoE assessment methodologies have been extended to include further dimensions related to immersive media experiences, such as presence, immersion, and cyber discomfort [9], which are needed to assess the perceived quality of metaverse services [10], [11], 360° videos [12], [13], and VR interactive applications [14].

Several literature studies have investigated and assessed the adoption of VR technology for online learning within immersive environments using subjective questionnaires. The achieved results have shown that immersive technologies can improve engagement and learning outcomes for the students compared to traditional video conferencing online learning approaches [15], [16], [17]. However, these studies only considered immersive VR environments where students can individually learn about a particular topic by interacting with 3-D objects or consuming multimedia content instead of texts. To the best of the authors' knowledge, none of the previous works has considered implementing a VR classroom where students can meet, interact, and attend a lesson together as if they were F2F.

Based on these considerations, in this article, we have organized and conducted a subjective study to assess the learning quality perceived in an immersive VR classroom representing a class with a teacher's desk, students' desks, and a blackboard (we refer to VR-based online learning in the following for this learning scenario). A total of 44 students attended five real lessons (focused on different Internet protocols) provided by the teacher in this VR-based learning environment. Students were divided into two groups, i.e., each lesson was attended by a maximum of ten students within the virtual room (due to the limited number of VR headsets), while the rest of the students simultaneously participated in the lesson watching the 2-D video stream of the virtual room lesson, such as normal video conferencing (we refer to video-based online learning in the following for this learning scenario). At the end of each lesson, students had to complete a subjective questionnaire to rate the experienced lesson under various aspects that are commonly considered in the assessment of QoE for VR-based applications, namely, overall QoE, immersion, interactivity, naturalness, usability, entertainment, comfort, and cyber discomfort. Moreover, due to the learning focus of our case study, we have asked to rate further aspects concerning the quality of interaction with the teacher and between the students, the ease of taking notes, and the willingness to participate in VR-based online learning classes in the future.

The achieved subjective results have been thoroughly analyzed by computing the mean opinion score (MOS) and using statistical analysis (Kruskal–Wallis, Welch's t-test) to assess and compare the quality perceived by the students using the two learning approaches in terms of the considered evaluation aspects. From these results, we mainly obtained that the level of naturalness, entertainment, interactivity, and immersion is significantly higher when using VR-based technologies for learning, whereas the level of comfort is penalized. Moreover, most of the students would only use VR technologies occasionally (68%), whereas an important part (more than 25%) would be open to using it frequently.

The following is the summary of the major contributions of this article.

1) We developed a novel subjective assessment method to evaluate students' QoE when attending a class in a VR-based classroom environment and to compare it with the quality perceived by the students attending the same class with a traditional 2-D online class video streaming tool. The students could join the implemented immersive 3-D virtual classroom with their avatars to attend lessons as if they were attending in person. In this environment, they could interact with both the professor and other students.
2) The subjective assessment was conducted by involving 44 students attending five real lessons (where various Internet protocols were taught). The lessons were simultaneously attended by some students in the virtual classroom and by others through a traditional online 2-D video streaming tool to make a valid comparison. The students were asked to provide both quantitative evaluations and free comments concerning the limitations and advantages of the VR-based online teaching modality.
3) We conducted a thorough statistical analysis to compare the ratings provided by students concerning the two considered learning approaches and identify potential differences. Key findings from Welch's t-test indicate the higher interactivity ($p < 0.05$), naturalness ($p < 0.01$), entertainment ($p < 0.01$), and immersion ($p < 0.001$) perceived by students for the VR-based learning experience than the traditional video-based one. Increased immersion was the most significant aspect, as highlighted by the lowest p-value. On the other hand, the level of comfort was heavily penalized ($p < 0.001$), and students were unable to take notes in the VR environment easily.
4) We provide a discussion highlighting the major findings resulting from the conducted study and the current limitations and challenges that need to be considered in future work. In these conclusions, important lessons have been summarized, which set the path for future important studies to be conducted in the field.

The rest of this article is organized as follows. Section II discusses the related work in this area. Section III describes the experiment design and the learning assessment. In Section IV, we present the achieved results, while Section V discusses the outcomes and limitations of the conducted research. Finally, Section VI concludes this article.

II. Related Work

In Sections II-A and II-B, we provide an analysis of the works that study the use of video streaming and VR technologies in online learning. Video streaming technologies can be considered the traditional ones as they have been used since more than a decade ago with a sudden diffusion during the COVID-19 pandemic period. The VR technologies appeared only recently, and their usage and role in the learning domain still need to be explored. In Section II-C, we provide a brief comparative analysis of the two technologies and present the objective of this article in light of the past works' analysis.

A. Video Conferencing Systems for Online Learning

The last 20 years have seen a growing utilization of video conferencing systems for online learning, first in higher education and later in mainstream education [18]. Several research studies have investigated the appropriateness of these tools for learning. The quality of four widely used video conferencing platforms, namely, Zoom, Skype, Microsoft Teams, and WhatsApp, was evaluated in [19] in terms of the systems' general characteristics, learning-related features, and usability. The analysis found that Zoom offers the most learning-related features and best supports the four experiential learning modes: concrete experience, reflective observation, abstract conceptualization, and active experimentation. Skype ranked highest in overall usability, while Teams and WhatsApp had some limitations in features and usability for educational purposes. However, the authors conclude that video conferencing systems still need to develop more comprehensive and human-centered functionalities. In [20], instructional effects of the teaching, social, and cognitive presence were investigated by setting a blended learning activity where some students synchronously attended the same class sessions at a remote site, while the instructor taught the F2F student group. The findings revealed that the attainment of the intended learning outcomes relied more on the teaching presence than on the social and cognitive presence of the approach. The transition from F2F to online education in Georgia due to COVID-19 is considered in [21], where the effects of using Google's G Suite for online education were investigated involving 950 students. The results highlighted students' successful adaptation to online learning with high attendance rates and the effective use of digital tools for teaching. However, the quality of online lessons perceived by the students was not considered by this study. The data collected from 31 university students in [22] reported flexibility as the main advantage of using Zoom for online learning during the COVID-19 pandemic. On the other hand, students had a negative attitude toward the use of Zoom because they perceived it as harming their learning experience and motivation by increasing episodes of distractions and reducing the quality of interaction.

Besides the technical limitations of video conferencing platforms, Rapanta et al. [4] argued that the shift to online teaching due to the pandemic revealed that many university teachers lacked the necessary pedagogical content knowledge for this format, providing unacceptable quality levels of teaching. Thus, they suggest three important key aspects to be considered while setting up an online teaching environment: social presence (creating a supportive, inclusive, and collaborative learning environment), cognitive presence (facilitating critical thinking and understanding through interaction and reflection), and facilitatory presence (guiding and supporting students in their learning process). Moreover, the study in [23] identified interactive multimedia, appropriate technological devices, content accessibility, and usability as positively correlated with overall satisfaction with the online learning experience. VR-based systems have the potential to include all of these aspects to improve the effectiveness of online learning.

B. VR-Based Systems for Online Learning

The previous section highlighted the capabilities of video conferencing technology to support students in remote learning activities. However, important negative effects (such as decreased motivation and lack of teaching and social presence) have also been identified, which make it difficult to assume that these technologies can worthily substitute F2F learning [2], [4]. VR technology has the potential to address these video conferencing limitations by providing an immersive learning environment where teachers and students can interact as if they were in person [5].

The expected effectiveness of VR in education can be explained through various theoretical frameworks, including constructivist learning, experiential learning, cognitive load theory, social learning, and presence and immersion theories. According to constructivist theories, learning is an active process where individuals construct knowledge through experiences [24]. VR aligns well with this approach by allowing learners to explore virtual environments, manipulate digital objects, and engage in problem-based learning. This is the case, for example, of virtual science labs that enable students to conduct experiments [25]. Closely related to this, VR supports experiential learning by immersing students in realistic scenarios, enabling them to practice skills in context before applying them in real life [5]. In addition, VR can reduce extraneous cognitive load by presenting information in spatial and interactive ways that align with human cognitive architecture. However, it is important to highlight that poorly designed VR environments can increase cognitive load, leading to reduced learning efficiency [26]. Indeed, effective VR design should balance immersion with cognitive simplicity to enhance retention and comprehension.

From the social dimension point of view, VR enables social learning by creating collaborative virtual spaces where learners can engage in peer-to-peer interactions. Virtual classrooms, language immersion environments, and teamwork-based VR applications enhance learning through social engagement [27]. Finally, the presence theory [28] defines presence as the psychological sense of "being there" in a virtual environment. According to this theory, higher presence levels, which can be provided by VR technologies, lead to greater engagement and motivation, improving learning outcomes [25]. Immersion theory suggests that deeper immersion enhances focus and emotional investment, making learning experiences more impactful. For example, history students exploring ancient Rome

in VR report higher engagement and better retention compared to traditional textbook learning [29]. Accordingly, VR has significant potential to enhance education by leveraging multiple theoretical perspectives. Some of these expected advantages of VR technologies in learning have been explored by specific experimental studies, as discussed in the following.

The majority of the studies exploiting VR technologies for learning concern the science, technology, engineering, and mathematics (STEM) field because VR-based laboratories enable students for safe hands-on experiential learning sessions. The study in [30] compares learning chemistry-related concepts using traditional text and 2-D images or participating in a VR lab, including interactive 3-D models of molecules. A total of 30 participants were involved in the study, and the results have shown that VR enhanced the learning outcomes of the students, who also found the experience very engaging and helpful. An experimental assessment was conducted in [31], where 32 students had to construct a human skeleton using both an ad-hoc-designed VR application and a desktop 2-D interactive application. Higher engagement and learning were rated for the VR application, whereas the 2-D one was perceived as more usable. However, the authors only selected individuals with a strong IT background, potentially biasing the results. The effects on learning outcomes of a VR chemistry lab and a VR human anatomy experiment lab, compared with the traditional method of teaching, were also studied in [32]. Again, the results from 105 students indicate positive impacts of VR-based experiences on student satisfaction and learning performance. An immersive 3-D environment was developed in [15] to compare traditional and VR approaches in teaching engineering students how different parameters can influence solar-power panel efficiency. In this case, while the VR experience increased student engagement, no reliable evidence suggests that VR provides increased learning over traditional methods. VR technologies have also been demonstrated to teach science subjects more effectively to primary school students in [17], where a digital talking Parrot guided the young students into immersive colorful virtual game scenes concerning electricity and electric circuits. It was observed from the quiz performance and survey feedback that students gained knowledge more effectively through the VR learning experience compared to conventional paper-based learning.

VR has also been used to implement virtual classrooms where students can meet and collaborate. The study in [33] considered using either a VR room or Skype to meet online. Test participants were asked to complete a media experience survey along with a questionnaire asking them which tool they preferred. The results pointed to improved feelings of presence, closeness, and arousal in the VR environment. The VR classroom system proposed in [16] is compared with the video conferencing tool Zoom to solve a collaborative task (compile a list of words related to a keyword) involving two or three participants at a time. The VR system outperformed Zoom in terms of presence, performance, collaboration, and engagement.

As a summary, the literature review highlights a common positive impact on student engagement and learning outcomes observed when using VR for learning activities. However, major issues and challenges have also been identified related to the incorporation of VR in education, which regard the higher demands of student digital literacy, the high cost and unpredictable usability of VR devices, and the lack of teacher proficiency in the use of VR [34], [35].

C. Video Conferencing Versus VR-Based Systems for Online Learning

There is a debate on media-comparison studies, which is aimed at investigating whether changing media alone is meaningful for the user experience. Some of the studies discussed in the previous section performed experimental tests to compare the impact of video conferencing and VR-based media technologies within the domain of online learning, resulting in common increased engagement provided by the VR environment [15], [16], while in some cases, increased sense of presence [33] and learning outcome [16], [17] were also observed. However, the main limitation of most of these literature studies is that they focused on the implementation of an immersive VR environment where students can individually learn about a particular topic by interacting with 3-D objects or consuming immersive multimedia content instead of texts [17], [30], [31], [32]. Only two studies have proposed a virtual classroom where people can meet and collaborate. Nonetheless, in [33], a peer-to-peer communication is considered, whereas in [16], a maximum of three people could meet simultaneously in the VR room to complete a collaborative task. To the best of the authors' knowledge, none of the previous works has considered a virtual classroom where students can meet and attend a real lesson together as if they were in person. This feature is expected to make the experience more interactive and engaging. We aim to contribute to the state of the art in this sense by assessing the learning experience of students in a virtual classroom and comparing it with that of students using a video conference system.

In the proposed study, we have organized and conducted a subjective quality assessment to evaluate the quality of a VR-based online learning experience as perceived by bachelor's students. As a control group, we have also assessed the quality of conventional video-based learning experiences (video conferencing). To assess the perceived student quality from the QoE perspective, we followed the guidelines provided in the QUALINET White Paper on immersive media experience [9] and in [10], [11], and [14], which identify the main influence factors that may affect the QoE of interactive and immersive VR applications. These factors specifically include immersion and sense of presence as well as usability, engagement, and interactivity provided by immersive applications. This research study aims to identify and quantify how VR can address the limitations of video conferencing in terms of these metrics.

III. Methodology

A. Experimental Design

This study aimed to assess and compare two different learning environments: video-based and VR-based online synchronous learning. The platform we have chosen to teach the lessons is

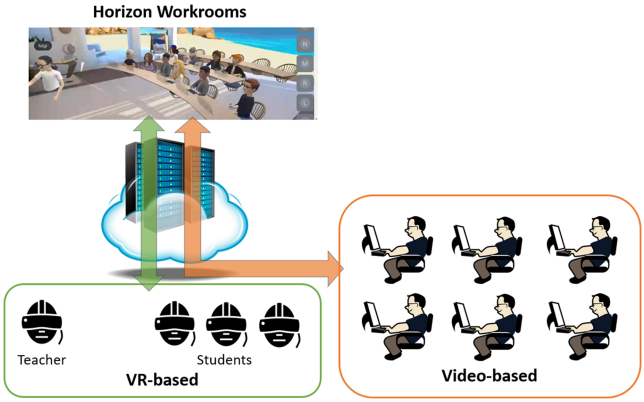


Fig. 1. Framework of the conducted experiment.

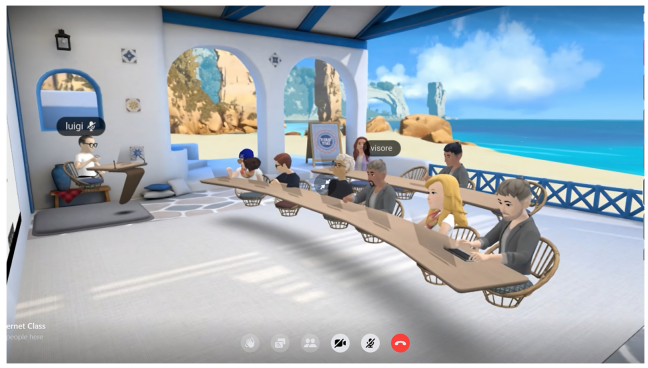


Fig. 2. Teacher's avatar is seated at the teacher's desk and shows the lesson's slides on a virtual screen in front of the students.

TABLE I
NUMBER OF STUDENTS PER LEARNING EXPERIENCE AND TEST SESSION

Online learning experience	Test1	Test2	Test3	Test4	Test5
Video-based	33	32	31	33	34
VR-based	10	10	10	8	6

the virtual room provided by Horizon Workrooms,[1] which is a collaboration platform developed by Meta that uses virtual spaces for meetings and collaborative online activities. This virtual room can be joined simultaneously in VR, through a Meta Quest headset, and on a traditional 2-D video stream, through a PC Web browser.

Fig. 1 illustrates the framework of the conducted experiment. Concerning VR-based learning, students wore the Meta Quest 2 headsets to attend the class in the immersive 3-D Horizon Workrooms environment. They could use their laptops virtualized in the virtual room (it is a functionality provided by Workrooms) to take notes about the lesson. At the same time, the students assigned to video-based learning could join and watch the 2-D video stream of the virtual room lesson, talk with the teacher and students in the virtual room using the microphone, and use their laptops to take notes about the lesson. In this case, the students participated in the lesson using their laptops and wearing headphones.

The experiment involved a total of 44 bachelor's students (39 males and 5 females) enrolled in the Internet course of the bachelor's degree in electrical and electronic engineering of the University of Cagliari, who also provided written informed consent before participating in the study. All participants had prior experience with video-based online learning, whereas only nine students had sporadic prior experience with VR headsets, which did not allow them to gain significant experience and skills in using the VR devices. Thus, we have considered all students having the same level of experience with VR applications.

Therefore, before participating in the experiment, all students participated in the same training sessions to learn how to use the Meta Quest 2 VR headset and controllers. Specifically, each student was introduced to controlling the Meta Quest environment using both controllers and hands. They learned how to move inside the VR environment, set up the pass-through mode, manage the audio and microphone settings, and personalize their avatars. Moreover, to ensure that all the participants had the same VR skills, the training was organized to familiarize them with all the functionalities provided by the Horizon Workrooms application. For instance, they learned how to activate the Workrooms pass-through setting to visualize the real desk. During the training, they were also explained about the meaning of the evaluation metrics included in the subjective questionnaire.

The experiment included five test sessions, and a different lesson was taught during each session. Note that these real lessons were part of the course program and the final exam, so the students had to attend carefully. Each lesson was attended simultaneously by some students joining the VR-based online learning environment and participating with their avatars within the 3-D class environment (as illustrated in Fig. 4), whereas the rest of the students joined the video-based online learning and participated in the lesson like a typical remote video conference (as illustrated in Fig. 2). Moreover, the system allowed the professor to take part in the VR-based learning environment and the traditional video-based system. Among the five test sessions, each student participated once in VR-based learning and one or more times in video-based learning. The exact number of students using the two learning environments during the five test sessions is summarized in Table I.

For each test session, a different 20-min-long lesson was taught by the professor, who was in the 3-D environment through his avatar. Fig. 2 shows a capture of the Workrooms environment, where the teacher's avatar is seated at the teacher's desk in front of the students' avatars, who are watching the projected slides of the class. As shown in Fig. 3, the teacher (and even the students when necessary) can also move to the blackboard to provide explanations and/or do exercises. The letters on the right of Fig. 3 identify the students who joined the lesson using the video-based online learning method. Finally, Fig. 4 shows the particular point of view of a student seated at the school desk in the VR-based online learning environment. During the 20-min-long lesson, the students may experience some difficulties, such as cybersickness and headaches. They were then warned to stop the session in this case and to provide relevant feedback by answering a specific

[1] [Online]. Available: https://forwork.meta.com/horizon-workrooms/

Fig. 3. Teacher's avatar can move to the blackboard, where he can write and draw to deepen the lesson's concepts.

Fig. 4. Point of view of a student in the VR-based online learning environment.

question on this and by providing relevant comments in the open questions.

B. Learning Assessment

At the end of each test session, all the students had to complete a subjective questionnaire, including 15 questions aimed at evaluating different aspects of the attended lesson. The first seven questions concerned the assessment of different factors impacting the QoE for interactive VR applications, which were identified in [14]. Questions 8–11 were specifically focused on the interaction between the teacher and students, and taking notes. All of these questions (except for Q10) could be rated using a five-point Likert scale, where 1 indicated the lowest quality level and 5 the highest one. Finally, questions 12–16 were only directed at students participating in the VR-based online learning to investigate their acceptability and impressions towards this learning approach and the occurrence of side effects. Questions Q12 and Q13 and Q14 and Q15 were multiple-response and open-ended questions, respectively.

In the following, we provide a summary of the asked questions and investigated assessment metrics.

(Q1): *Quality of experience:* "How do you rate the overall level of QoE perceived during the class session?" The QoE is defined as *"the degree of delight or annoyance of the user of an application or service"* [6]. This question was meant to evaluate the overall level of satisfaction of the students with the attended lesson. The meaning of this question was carefully explained to the subjects during the preliminary training for the test.

(Q2): *Immersion (IMM):* "How do you rate the level of immersion perceived during the class session?" Immersion is defined as *"a psychological state in which a person perceives themselves as being inside of a virtual environment and interacting with it"* [36]. We wanted to understand if the students positively perceived themselves in the class environment as if they were F2F.

(Q3): *Usability (USA):* "How do you rate the level of usability of the platform perceived during the class session?" The usability concerns the overall platform's ease of use.

(Q4): *Naturalness (NAT):* "How do you rate the level of naturalness of interaction with the platform controls perceived during the class session?" This question was meant to investigate whether the usage of the control tools and devices provided by the learning platform was intuitive (i.e., easy to understand in their usage) and natural (i.e., the way these had to be used was instinctive and did not require weird actions) for the students. Specifically, these features were related to the usage of the VR controls for the VR-based platform and of the PC controls for the video-based one.

(Q5): *Interactivity (INT):* "How do you rate the level of interactivity provided by the platform during the class session?" Interactivity is defined as *"the extent to which users can participate in modifying the form and content of a mediated environment in real-time"* [37]. This question was meant to understand if the learning platform responded adequately to the commands given by the students to perceive an interactive and engaging experience.

(Q6): *Entertainment (ENT):* "How do you rate the level of entertainment and fun perceived during the class session?" This question was meant to investigate whether the learning experience was engaging and provided amusement or enjoyment to the students.

(Q7): *Comfort (COM):* "How do you rate the level of comfort perceived during the class session?" This includes how comfortable (physical fatigue, etc.) it was to attend the lesson with the used platform.

(Q8): *Interaction with the teacher (IntT):* "How do you rate the level of interaction quality between the student

and the teacher?" This includes lesson understanding, asking questions to the teacher, etc.

(Q9): *Interaction with students (IntS):* "How do you rate the level of interaction quality between the students?" This includes engagement with the other students.

(Q10): "Did you take notes during the class session? If so, how?" Possibilities were paper and pen or PC for video-based, and just the PC for VR-based, since students were wearing the VR headset.

(Q11): *Ease of taking notes (NOT):* "How do you rate the ease of taking notes during the class session?" This question was asked only to students who replied "Yes" to question 10.

(Q12): "How frequently would you be willing to participate in VR-based online learning classes?" Four possible answers: "Never"; "Occasionally"; "Frequently"; "All lessons."

(Q13): "Have you perceived side effects during the VR-based online learning experience (e.g., headache, sickness)?" Three possible answers: "No"; "Yes, but it was bearable"; "Yes, very disturbing."

(Q14): "Can you indicate the most positive aspect you have encountered during the VR-based online experience?"

(Q15): "Can you indicate the most negative aspect you have encountered during the VR-based online experience?"

IV. Results

A. Statistical Analysis

We have collected a total of 207 questionnaires: 44 and 163 for the VR-based and video-based online learning approaches, respectively. The number of questionnaires completed for the two learning experiences in each test session is reported in Table I. Note that we had to divide the experiment into multiple sessions because of the limited number of head mounted display (HMDs). Thus, only ten students could participate in the VR-based online learning for each session, while the others were connected as a traditional video conference. However, we carefully designed the lessons not to influence the students. In particular, each lesson (test session) followed a similar approach in terms of content (slides and exercises), but it was focused on a diverse Internet protocol (e.g., transmission control protocol and user datagram protocol), explained with slides and some practical examples.

To verify that the content lesson was not significant, we computed the Kruskal–Wallis test among the subjective scores provided by the test participants for the different test sessions. This test can identify whether one or some test session(s) were rated significantly different from the other sessions. Three assumptions must be respected to use the Kruskal–Wallis test: 1) ordinal or continuous response variables, such as survey responses measured on a Likert scale; 2) independence of individual scores in each group; and 3) similar distribution shape in each group. Moreover, this test does not require the assumption of normality. These assumptions were all respected by the collected data.

First, we have analyzed the responses to the ten quantitative metrics corresponding to questions Q1–Q9 and Q11, introduced in the previous section. The results in Table II show that the null hypothesis was never rejected (p-value > 0.05) for both the learning experiences and all the evaluation metrics. Thus, we can consider all ratings collected during the five test sessions to be consistent as if they were provided during a single session.

To determine if there is a significant difference between the means of the two groups of quantitative subjective feedback (VR-based and video-based), we have computed the Welch's t-test for each of the ten considered evaluation metrics. To increase the statistical significance, we have also computed the Welch's t-test between the two sets of ratings provided for all five sessions. The Welch's t-test does not assume an equal sample size and equal variance for the data to be analyzed; thus, it can be used on the collected data. Table III summarizes the results achieved by the Welch's t-test. It can be seen that for some evaluation metrics (i.e., QoE, IntT, IntS, USA, and COM), no differences are highlighted from the ratings provided by the students. So, for these metrics, no benefits or drawbacks were perceived for VR-based online learning compared to video-based learning.

On the other hand, the differences between the two learning experiences were perceived for the rest of the metrics, although with different significance levels. The students perceived higher interactivity for the VR-based learning experience than the video-based one with $p < 0.05$. A higher naturalness and entertainment were perceived for the VR-based with $p < 0.01$, while the perceived better immersion was even stronger, reaching $p < 0.001$. These results highlight that the students appreciated the interactivity of the VR environment more, and they particularly appreciated the naturalness of interaction with the elements of the VR room and enjoyed the fun during this learning experience; above all, they felt more immersed in the learning environment. On the contrary, the VR-based learning environment has not provided an adequate environment to take notes on the attended lesson. Indeed, the ease of taking notes was perceived as much better ($p < 0.001$) for the video-based learning experience than the VR-based one. This can be due to the poor optimization of the virtualization of the student's laptop into the virtual environment provided by Horizon Workrooms.

B. Subjective Results

Based on the Kruskal–Wallis test results, we can assume that the subjective ratings were provided for a single test session (rather than five different sessions), including 44 students attending with the VR-based online approach and 163 with the video-based one. Thus, we have computed the MOS with a 95% confidence interval on the ratings provided for all sessions (Avg in the figures). For completeness, we also show in the figures the MOS with a 95% confidence interval computed on the ratings provided for each different test session. Fig. 5 shows the MOS for the overall perceived QoE, which, on average, is slightly greater for the VR-based online learning approach than the video-based one. This means that the overall satisfaction with the attended lesson was improved in the VR-based environment. However, both learning experiences were perceived as more than satisfying

TABLE II
KRUSKAL–WALLIS TEST RESULTS: THE *P*-VALUE ACHIEVED VALUES GREATER THAN THE THRESHOLD (0.05) FOR EACH CONSIDERED EVALUATION METRIC AND BOTH LEARNING EXPERIENCES

Online learning experience	QoE	IMM	USA	NAT	INT	ENT	COM	IntT	IntS	NOT
Video-based	0.80	0.42	0.81	0.98	0.93	0.29	0.86	0.96	0.54	0.76
VR-based	0.26	0.87	0.92	0.63	0.62	0.49	0.93	0.70	0.72	0.75

TABLE III
P-VALUE RESULTS FOR THE WELCH'S TEST BETWEEN THE RATINGS PROVIDED FOR THE VIDEO-BASED AND VR-BASED ONLINE LEARNING EXPERIENCES FOR ALL TEST SESSIONS

QoE	IntT	IntS	NAT	ENT	INT	NOT	USA	IMM	COM
			< 0.01	< 0.01	< 0.05	< 0.001		< 0.001	

If $p > 0.05$, the box is empty.

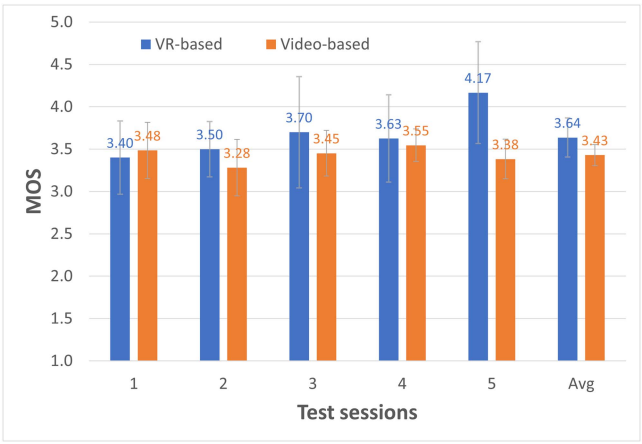


Fig. 5. MOS with 95% confidence interval for the overall perceived QoE.

(MOS about 3.5/5). Fig. 6 summarizes the subjective results concerning the platform-related metrics. As expected, the VR-based environment provided greater immersion to the students (MOS of 4 versus 3.55 for video-based), who perceived themselves as being inside the VR environment. The VR-based platform also provided greater levels of naturalness (MOS of 3.86 versus 3.48), interactivity (MOS of 3.80 versus 3.49), and entertainment (MOS of 3.93 versus 3.50) to the students than the video-based platform, which means that students appreciated using the VR environment. Moreover, the overall usability was rated the same for the two platforms, which means that students perceived the same ease of use, although the VR environment was more novel for them than the traditional video-based platform. However, the negative aspect of the VR-based platform was the comfort, which was rated slightly lower than that for the video-based one (MOS of 3.02 versus 3.28). This was mostly due to the need to wear the HMD, as will be discussed later.

Fig. 7 summarizes the subjective results concerning the interaction between teacher and students, and taking notes. A slightly greater quality of interaction with the teacher and the other students was perceived for the VR-based online learning approach than for the video-based approach. Also, the quality of interaction with the teacher was perceived as better than that with other students. Concerning notes, these were not taken by 43.2% of VR-based students and by 27.6% of video-based students. Of the 72.4% of video-based students who took notes, almost 55% used paper and pen, whereas the rest used the PC. VR-based students who took notes (56.8%) could only use the virtualized PC in the VR class environment. However, the ease of taking notes with this approach achieved negative feedback (MOS of 2.73 versus 3.78 rated for video-based), which highlights the need for improving this platform's features.

Finally, we have computed the results of the questions only directed at students using the VR-based online environment. Fig. 8 shows the results of the multiple-response questions (Q12 and Q13) concerning the willingness to attend lessons using the VR-based learning approach [see Fig. 8(a)] and the occurrence of side effects [see Fig. 8(b)]. Although students appreciated this immersive learning experience, most of them (68%) would only use it occasionally. However, an important part (more than 25%) would be open to using it frequently. These results may be due because only three students have perceived important side effects during this experience, while half of the students have not perceived any side effects, and the rest of the students have perceived some bearable side effects. Probably, the static learning environment helped to minimize typical side effects that can be typically provided by VR-based experiences where people are allowed to move, run, or even fly in the virtual space.

Concerning the two open-ended questions, Q14 and Q15, we have analyzed the students' responses to group them into the three most positive and negative aspects they have encountered during the VR-based online learning experience. The three most positive aspects are as follows.

1) *Immersion:* It is the most rated aspect concerned the fact that the students were immersed in the VR class environment as if they were F2F.
2) *Video and audio quality:* Being in the VR environment, they appreciated the possibility to clearly listen to the teacher's voice and easily read the blackboard and projected slides.
3) *More attention to the class:* Students found this environment to be more stimulating, and they were able to focus more on the class because being immersed in the VR class reduced possible distractions. Also, they highlighted greater interaction with the teacher and the other students.

The three most negative aspects are as follows.

1) *Network-related problems:* Bad network performance can decrease the graphic and audio quality (lower resolution,

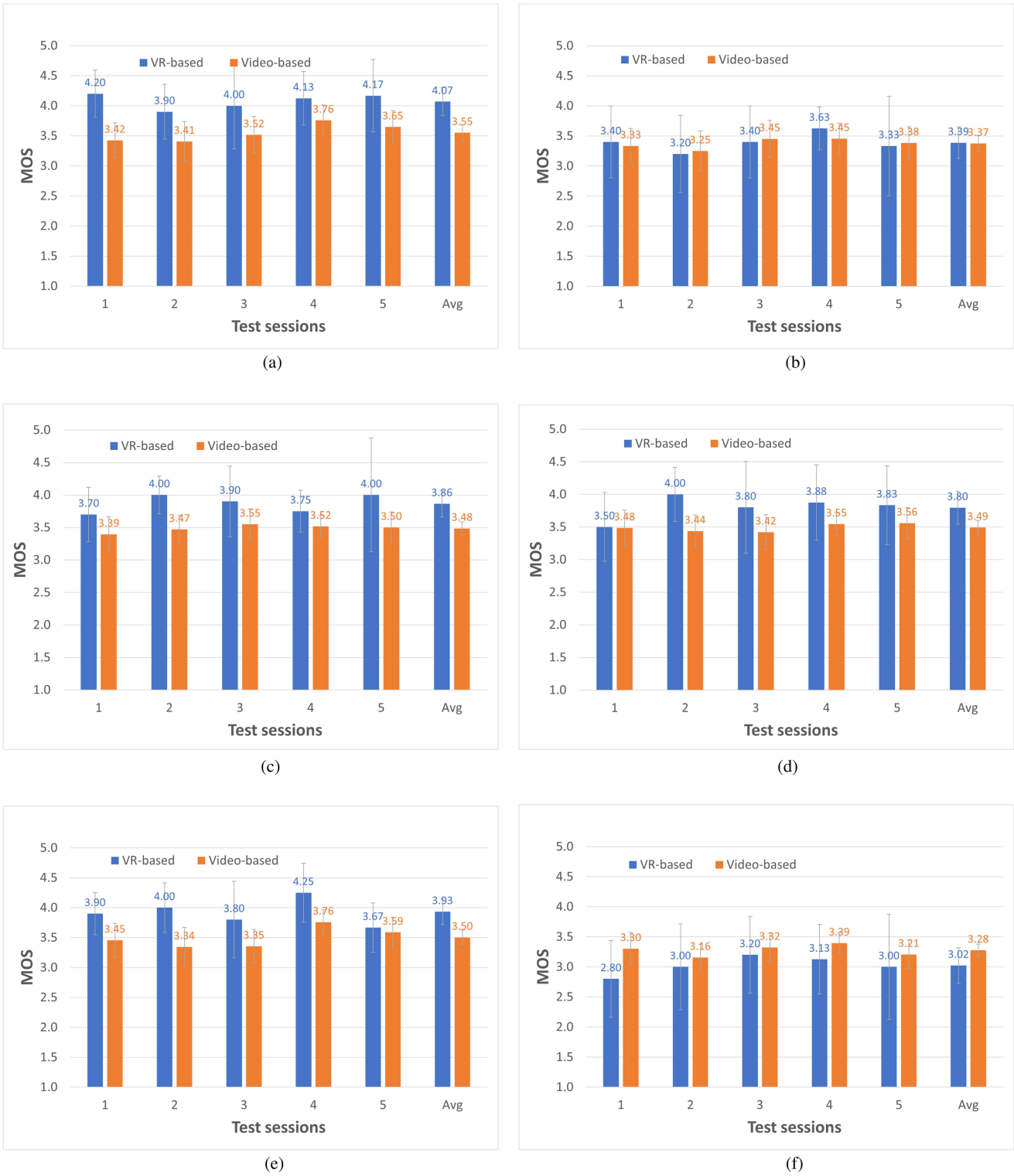
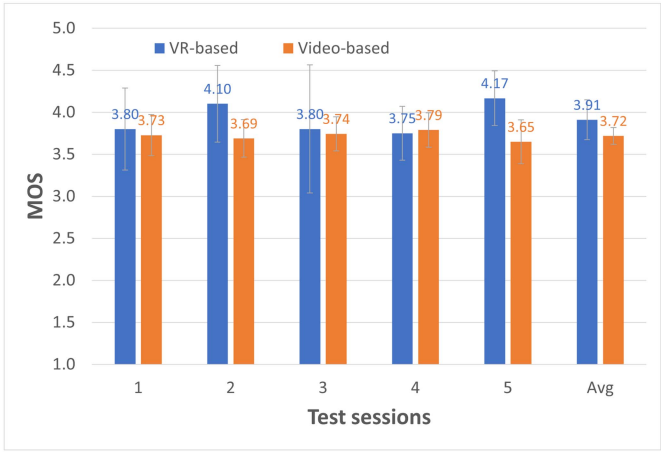


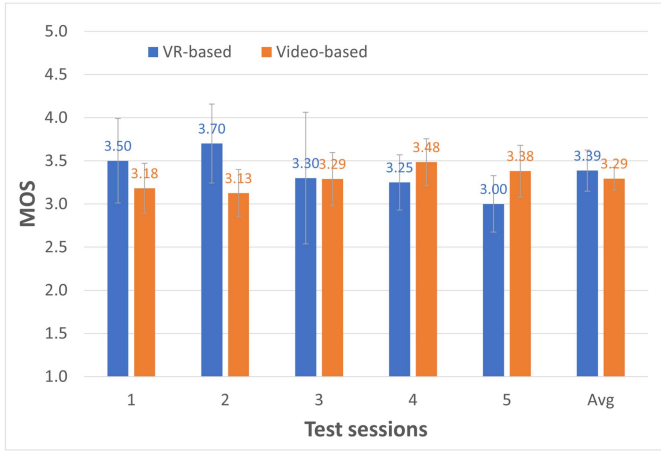
Fig. 6. MOS results with 95% confidence interval for platform-related evaluation metrics, i.e., IMM, USA, NAT, INT, ENT, and COM. (a) IMM—Immersion. (b) USA–Usability. (c) NAT—Naturalness. (d) INT—Interactivity. (e) ENT—Entertainment and fun. (f) COM—Comfort.

lag) of the VR class environment, harming the learning experience.

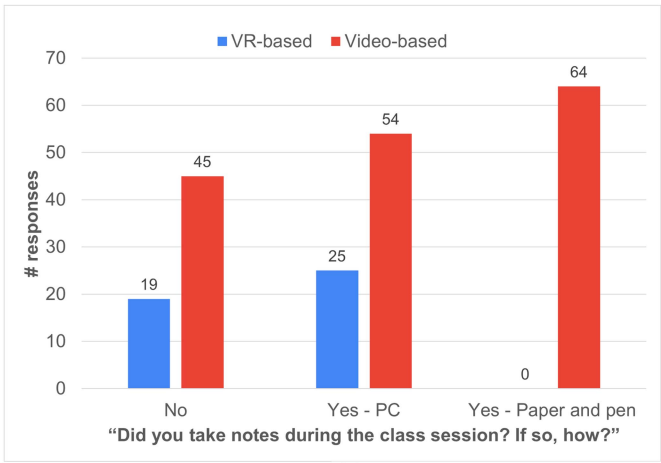
2) *Uncomfortable:* Besides possible side effects, wearing the HMD during the classes was generally uncomfortable (in particular for students wearing glasses), causing pain and discomfort, which increases with the session length.
3) *Configuration:* Setting the HMD and the software needed to participate in the VR class was not found to be easy.



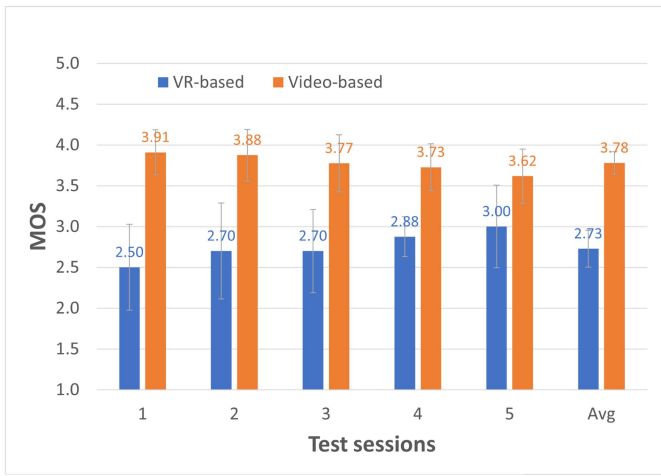
(a)



(b)

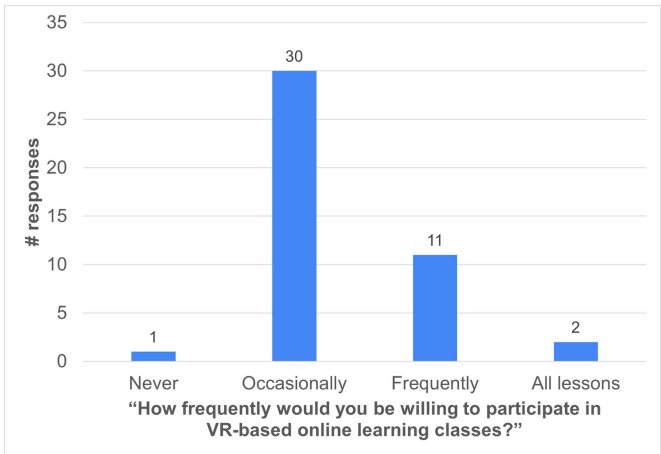


(c)

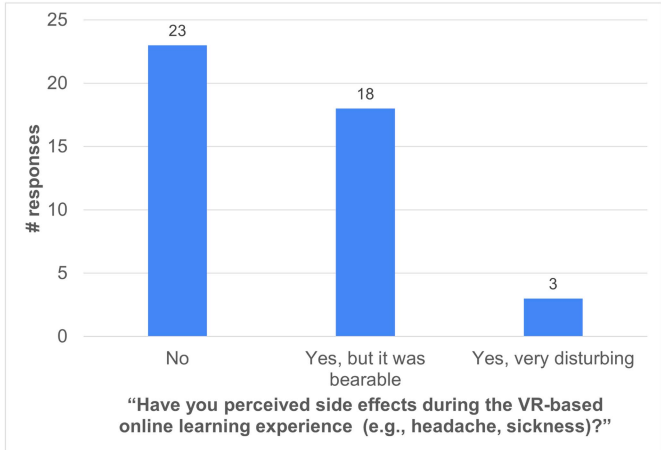


(d)

Fig. 7. MOS results with 95% confidence interval for IntT, IntS, and NOT. (a) IntT—Interaction with the teacher. (b) IntS—Interaction with other students. (c) Quantitative response to the notes question. (d) NOT—Ease of taking notes.



(a)



(b)

Fig. 8. Results of questions concerning the VR-based online learning approach. (a) Willingness to attend VR-based online lessons. (b) Occurrence of side effects during VR-based online lessons.

The same applies to virtualizing the student's PC in the VR environment.

V. Discussion

Both video-based and VR-based online learning offer solutions for remote education, yet their respective limitations remain underexplored in the existing literature. Video-based online learning, despite its widespread adoption, faces several challenges. The 2-D nature of video screens fails to provide a sense of presence, potentially reducing attention and engagement. Also, video conferencing platforms often fail to facilitate natural spontaneous interactions among students and with the teacher, limiting the collaborative aspect of learning. Moreover, prolonged screen time can lead to eye fatigue issues, affecting students' attention. Technical issues, such as poor Internet connectivity or hardware limitations, can further negatively impact the learning experience.

On the other hand, VR-based online learning, while promising, also has potential drawbacks. The need for VR headsets can be a significant obstacle to entry due to cost and availability, potentially excluding some students from participating. Extended use of VR headsets may cause physical discomfort, including motion sickness or eye stress, for some users. Both students and educators need time to adapt to the new virtual environment and its controls, creating a learning curve that could initially hinder educational progress. In addition, despite improved immersion, current avatar technology may not fully capture subtle facial expressions and body language, potentially limiting some aspects of nonverbal communication.

By conducting a comparative study between these two online learning approaches, our research addresses a critical gap in understanding how these limitations manifest in real educational settings. In future work, we aim to consider the findings achieved in this study with those of other studies to define hybrid models integrating the strengths of VR-based and video-based online learning, which would be desired to offer practical solutions for a wider range of educational settings.

A. Limitations of the Study

The proposed study was conducted with the primary goal of investigating the potential of VR technologies in the online learning context, in particular when compared with the traditional video conferencing approach. We specifically focused on the subjective point of view of the students concerning the learning experience provided by the learning environment (i.e., a virtual classroom where students can join and attend the class together as if they were in person) and its functionalities, while also considering application-related aspects, such as usability, immersiveness, interactivity, and the ease of taking notes. The lack of consideration of objective learning outcomes related to the content of instruction is a limitation of our study. We aim to conduct further tests in future work to include the measurement of learning outcomes and to observe whether the VR-based experience can enhance this aspect for students.

Another limitation is that the sample considered only includes engineering students, predominantly male participants from a single discipline. This restricts the generalizability of the achieved finding, which may also be affected by the specific background of the students participating in this test. However, we have preliminarily investigated the previous experience with VR-based applications, which was limited for all the students involved. Nonetheless, students of different subjects and schools can be considered in future works to include diverse demographics and educational contexts and to validate and extend the findings achieved in this article.

Moreover, unlike common subjective tests conducted in the laboratory, where each aspect is under the control of the researchers, in the proposed assessment, the students were engaged in real lessons, which introduced a level of unpredictability and variability into the study. In particular, we have not performed any control on the network, and the end devices were connected to the Horizon Workrooms platform through the best-effort Internet. Thus, the network conditions were variable and could not be standardized across all tests. However, to minimize possible effects of network-related issues on the student's experience, the test devices (headsets and laptops) were connected to the learning platform through the Internet connection provided by the University. We have conducted several tests to verify the performance of Internet connectivity, which resulted in an average download speed of 49.65 Mb/s, an average upload speed of 53.19 Mb/s, and an average latency of 21.25 ms.

Finally, the VR technology itself includes some limits, mostly hardware-related, i.e., the HMDs that still fail to be lightweight and comfortable. Further experiments can be conducted by considering recent HMDs, such as the Meta Quest 3 and the Apple Vision Pro. However, the real breakthrough is likely to be achieved when glasses-like VR headsets will be available in the market.

VI. Conclusion

In this article, we presented and discussed the outcomes of a subjective evaluation involving 44 students who participated in actual lessons through either VR-based or video-based online synchronous learning. The obtained results show that the levels of naturalness, entertainment, interactivity, and immersion are significantly higher when using VR technologies for teaching compared to traditional video conferencing platforms, whereas the level of comfort is penalized. The low level of comfort appears to be the reason why most of the students would be keen on using these new immersive technologies only occasionally. From their feedback, it appears that the comfort is mostly affected by the heaviness of the device and the complexity in setting and maintaining the correct configuration, mostly linked to entering the virtual room and keeping the device and PC connected to the virtual environment and to the fact that students were occasionally kicked out from the virtual room.

Despite these challenges, the study paves the way for the future of VR in education by identifying key areas for improvement. The achieved results suggest that further investigations are needed, including extensive tests with different devices and involving experienced users who can better harness the potential of VR technologies. By addressing comfort and technical

issues, VR technologies possess the capabilities to become an integrated and transformative tool for online learning in schools and universities.

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