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RESEARCH ARTICLE

Empowering Knowledge With Virtual and Augmented Reality

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ABSTRACT Recent global advancements in ICT technologies have motivated our research to assess the impact of Virtual and Augmented Reality on teaching and learning. In particular, we conducted a rigorous study on the effects on learning by subjecting classes of students to an experience of these emerging technologies and measuring their feelings before and after the experiment through questionnaires. We carried out the research involving three high schools and a total of 162 students aged between 15 and 20. During the meetings, we made available two applications that we developed. The first is a Virtual Reality environment that enables the user to explore a room in which the system spawns three-dimensional objects defined by the teacher. The objects may represent mathematical functions, physics simulations, scenes relating to historical re-enactments, etc. The second is an Augmented Reality smartphone application that allows three-dimensional figures to be observed via the smartphone screen by framing a marker printed on paper. Both applications are realised with free software, trying to minimise the technical requirements for their operation and guaranteeing reliability and usability. The work concludes by analysing the results obtained and comparing the effectiveness of the two technologies tested. Results of tests conducted in three Italian schools show that Augmented Reality is seen as a useful tool in education by about 94.43%. Importantly, the use of these technologies requires an inclusive design that involves all students, regardless of their level of familiarity with the technology. The overall analysis reveals that both technologies performed well, and students value them for their intuitiveness and level of immersion. The in presence experience is more effective for using immersive applications fostered by student collaboration.

INDEX TERMS Virtual reality, augmented reality, education, COVID-19.

I. INTRODUCTION

The study of new ways to disseminate knowledge is one of the fascinating sectors in which scientific research can be concentrated [1]. Research into how to apply and exploit new technologies can outline new best practices to enhance students' quality of life [2]. Furthermore, that leads to simplifying the work of teachers while striving to improve the skills of the future generation of adults who will make up the company in the coming years [3]. In recent times, both Virtual Reality and Augmented Reality technologies have undergone constant refinement and advancement, both in graphic quality [4], [5], [6] and in performance [7] for the execution and rendering of three-dimensional objects, thanks to the increased computational power available to modern hardware. The research presented was divided into several phases. In the first phase, two software applications were developed that exploit the technologies mentioned earlier. Then, to test the efficiency of the software in teaching and learning, we organised usability tests with three different classes of high school students, who were given questionnaires to evaluate the experience [8]. Next, the results

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obtained from the questionnaires administered to students of three high schools were analysed.

The software developed is designed to guarantee its execution on low-end hardware that does not require huge expenses for schools or students. The first software is a Web App and runs exclusively in the web browser, without additional software components, and is therefore independent of the operating system of the user device [9]. The second software uses Augmented Reality and has been developed for Android mobile devices.

The questionnaires are made up of various questions to monitor the students' opinions and suggestions and verify whether the proposed approach improves the quality of learning within schools. In total, we collected 173 questionnaires, of which male students produced 110 and 63 by female students. All the students who participated in the questionnaire were enrolled in high schools with scientific specialisations. The schools have different social contexts and are located in various urban areas.

The present work is organised as follows: Section II discusses the most recent works that address teaching and disseminating knowledge through advanced techniques and technologies such as Virtual and Augmented Reality. Section III highlights the findings that appeared in previous related studies related to the empowerment of knowledge with Virtual and Augmented Reality. In Section IV, the architecture of the system and the main algorithms underlying the two software projects are presented. Section V describes the questionnaires and data collection methods. In Section VI, the results of the three usability tests carried out are analysed.

Section VII discusses the conclusions of our research and outlines future developments.

II. RELATED WORKS

Enhancing the knowledge dissemination through sensory engagement makes learning more effective, as our minds benefit from experiencing concepts through multiple sensory levels [10]. For instance, through looking, hearing and contacting, we fabricate a complex reasonable design that bears and reinforces our knowledge [11], [12]. Multisensory learning is valuable in unique situations like autism and dyslexia [13], [14], [15], [16], [17], [18], [19], [20], [21]. An immersive learning environment offers several advantages over traditional methods, providing spatial comprehension of concepts, heightened peripheral awareness, increased bandwidth for information, and reduced data scattering [22].

With the following work, we aim to fill a research gap that currently exists in the literature. This paper aims to provide teachers with open technologies to facilitate the knowledge dissemination of abstract concepts that are difficult to represent on the blackboard or via a slide presentation. Examples of these concepts are mathematical functions and models, chemical reactions, representations of physical phenomena, and so on. We analyse students' perceptions with respect to the same content delivered via Virtual Reality and Augmented Reality to compare the results and understand their advantages and disadvantages.

A few works have been proposed to accomplish the reason, particularly in the natural sciences: chemistry [23], biology [24], [25], physiology [26], physics [27]. Since their origin, Virtual Reality (VR) and Augmented Reality (AR) have been technologies with varying degrees of success, sometimes due to the absence of sufficient low-cost hardware and other times due to the inherent complexity of the technologies used. Their fortunes have drastically changed since the development of mobile technology, and we now have affordable hardware and software solutions that make them broadly useable in many facets of contemporary life. These days, VR and AR are used for various purposes. From the fields of entertainment [28], [28], education [29], [30], [31], [32], tourism [33], [34], [35], [36], [37], [38], networking and communications [39], [40], microelectronic and high-performances hardware industries [41], e-commerce [25], [42], [43], medicine [44], [45], [46], [47], [48]. The thought may be to establish computerised conditions to upgrade abilities, information, and capabilities in mathematics, which can diminish tension and further develop results [49].

III. DISCUSSION

Combining VR and AR technologies in education has made learning and teaching more immersive, which has a favourable impact on both. The applications of these technologies have become increasingly prevalent, especially in response to the challenges posed by the COVID-19 pandemic, including their heterogeneous combinations and varied experiences. It has been proved that in university higher education, such technologies have been very effective, increasing the effectiveness of teaching and learning [50], [51]. However, it is crucial to acknowledge potential drawbacks, such as reported instances of increased mental fatigue and visual exhaustion, which merit consideration in the implementation of these technologies [52].

Research indicates that immersion in a digital environment can enhance education in multiple ways, as it activates various perspectives [53], a valuable asset in all areas of mathematics [54].

In some works, it has been seen that despite the numerical straightforwardness of the idea about a function [55], numerous students think that it is hard to relate its logical structure to the relative diagram. That seems to be as though the intermediate layers existing between the innate idea and the scientific, mathematical one forestalled a reasonable comprehension of the link [56], [57]. It has also been demonstrated that using programming tools prepared to promote the intrinsic logical-mathematical connection in math functions can assist students with fostering a positive mentality towards science [58].

Concerning attitudes, motivation, curiosity, and competence [59], we acknowledge the need for further research to grasp the significant implications fully.

The success of VR and AR in education relies heavily on students' perceptions and the ability of teachers to develop an inclusive design to accommodate students with varying levels of familiarity with technology.

IV. THE ARCHITECTURE OF THE PROPOSED SYSTEM

This section describes the techniques used to create the environments and three-dimensional shapes necessary to design the experience for the students. Two software applications have been developed. The first application performs an Augmented Reality simulation and was developed and compiled for the Android operating system. The second application performs a simulation in Virtual Reality, and it is based on WebGL to make it accessible via a browser. The software adopted for developing the environments are Unity,[1] Blender,[2] and Vuforia.[3]

The first, Unity, allows one to compose scenarios starting from three-dimensional models, insert and implement scripts and animations and finally, allow the programmer to export the project for different platforms and devices. In our case, we exported the project for the Android platform. The license with which this software is made available is bound by the Unity software, which has a proprietary license that allows unrestricted use for all projects with annual earnings of less than 1,000,000 USD.[4] Since our application is intended for scientific and educational uses, it does not exceed this limit. Even Vuforia is subject to similar limitations linked to the number of model targets present in the project, and this limitation does not affect its use in our context. Blender is released under the Open-Source GPL3 licence. In our opinion, this combination of software is optimal in terms of functionality, accessibility and ease of use to develop innovative applications in the Virtual Reality and Augmented Reality field. Unity also permits the export of projects for various platforms, such as Android, iOS, WebGL and others. The second program, Blender, is necessary for creating three-dimensional models that decorate the scene and increase the sense of immersion the user feels.

Finally, Vuforia is a framework for Unity and other platforms that integrates the management of markers used to start the spawn and despawn events of the three-dimensional objects related to the project in Augmented Reality. The Vumarks markers are images with many vertices and edges and are used to identify the various shapes to be displayed uniquely. When the smartphone camera frames them, the Vuforia software identifies them and superimposes the Virtual models in the real world. The generation of the models takes place through two scripts in C#. The first script takes as input a pair of parameters: the resolution of the representation grid and the expression of the functional form.

[1] https://unity.com/
[2] https://www.blender.org/
[3] https://developer.vuforia.com/
[4] https://unity.com/pricing-updates

Through this first phase, the script generates the list of vertices having coordinates (X, Y, Z). Subsequently, the second part of the script processes the list of vertices to calculate the triangles that make up the final figure. The list of triangles and their coordinates is the output. The output is handled by a second script, which takes a generic list of triangles and transforms it into a Game Object.[5] During the Game Objects creation process, it is essential to underline that *the normals* are also calculated, necessary to manage the behaviour of light rays on the surface of the objects. Subsequently, the Game Object is assigned the texture, and the scene is enriched with a Point Light to guarantee the correct lighting. The code just described is the same for both the Augmented Reality project and the Virtual Reality project.

A. AUGMENTED REALITY APP

After the steps just described, the Game Object is ready to be connected to a Vumark-type marker for managing the figures for the Augmented Reality application. We generated the Vumarks through a web app that builds square images composed of lines, vertices and random colours.[6] Once the images have been saved, they must be imported into the Vumark database managed via Vuforia, and finally, the database is inserted into the Unity project. The Vumarks are arranged inside the project scene without worrying about the positioning of the elements; the only important thing is that these are present in the logic of the scenario, as shown in Figure 1.

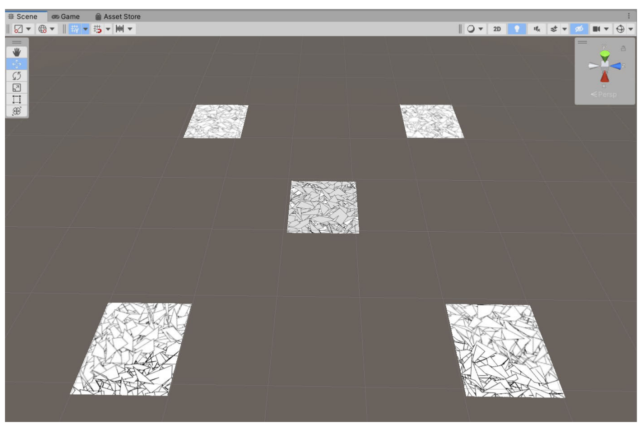


FIGURE 1. The Vumarks arranged in the project scene.

For each Vumark, now treated as a Game Object, a child Game Object is grafted, made up of the 3D representation of the mathematical function, generated using the scripts described above. An example is shown in Figure 2. The developed code that qualifies to generate three-dimensional figures has been published on GitHub.[7] The minimum operating system required to run the application is Android

[5] https://docs.unity3d.com/Manual/GameObjects.html
[6] https://www.brosvision.com/ar-marker-generator/
[7] https://github.com/DamianoP/ReinforcingTeaching

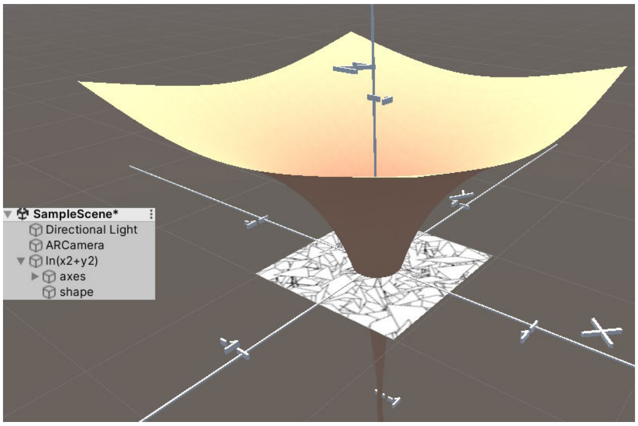


FIGURE 2. The 3D object representing the mathematical function is set as a daughter of the Vumark.

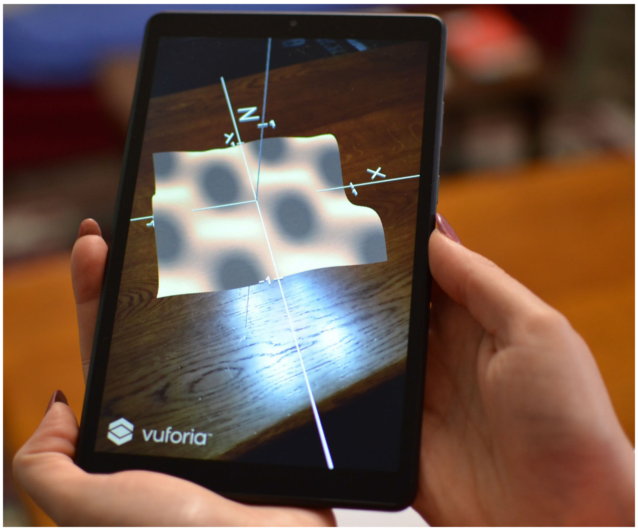


FIGURE 3. Application running on an Android tablet, the function shown is $f(x, y) = \frac{1}{5} sin(5x)cos(5y)$.

4.4, and the final size of the application is 37.2MB. Exporting the project in Augmented Reality produced an *apk* file, which was published on the Google Play Store and made available to users for download. An example of the application in operation is shown in Figure 3.

B. VIRTUAL REALITY APP

The Virtual Reality application is based on an environment that can be explored similarly to what happens in Virtual worlds dedicated to entertainment, such as video games. The scenario was first drawn on paper drafts and then drawn in computer graphics with Blender. The ceiling, the floor, the walls of the room, the doors, and the shape of the lights were modelled. These components have been exported from Blender in FBX format and subsequently imported into the Unity project. We performed the level design and scene composition phase by realistically distributing the elements, i.e., the mathematical functions. A critical aspect of obtaining a good final performance of the project, which requires extreme care, is optimising the various components and processes. In particular, the optimisation concerned two aspects: the graphic quality and the rendering speed. We sought an acceptable compromise to obtain high graphic quality, a low loading time, independence from the user's operating systems [9], and a good rendering speed, even on hardware with little computational power. To ensure acceptable performance, the whole scenario was set up as 'static', and we pre-calculated the lighting. The only objects that will receive real-time lighting are those that are animated or with which the user can interact. We have focused on developing the application as a Web App using WebGL technology to make it independent from the Operating System, and we have optimised the graphics with the following techniques:

- adopting texture streaming, i.e. loading textures only when the system really needs to use them.
- using Occlusion Culling,[8] i.e. the rendering of only the objects that are visible through the camera of the scene.
- using GPU instancing to optimise Draw Calls and render multiple copies of objects with the same mesh and texture in a single Draw Call.

Compression based on the open-source algorithm Brotli [60] was used to reduce the project size. Exporting the project in Virtual Reality generated a series of HTML and JavaScript files, which are made available to users through an Apache web server. Figure 4 shows an example of the Virtual scenario explored by the students.

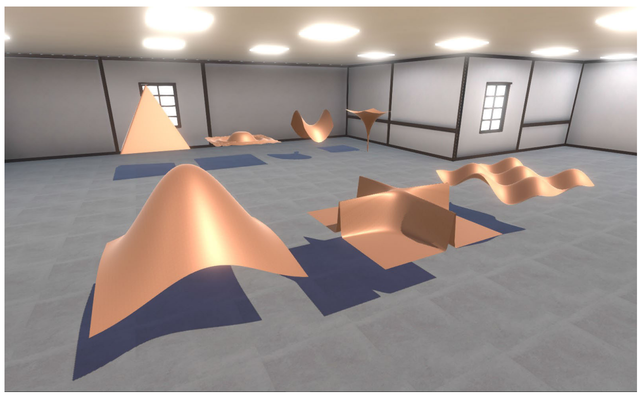


FIGURE 4. Some mathematical functions placed inside the scenario.

V. DESCRIPTION OF QUESTIONNAIRES AND EXPERIENCES

his research aims to determine the students' opinions and understand how these applications can empower students' knowledge. In total, three usability tests were held in three different schools and different periods. Due to the rules governing social distancing after the COVID-19 pandemic,

[8]https://docs.unity3d.com/2021.3/Documentation/Manual/

it was necessary to conduct the meeting with two of these schools remotely.

The usability tests started with an introduction of the concepts related to the Virtual environments, in particular highlighting the peculiarities of Virtual Reality and Augmented Reality, followed by some preliminary instructions on how to conduct the experience and detailing the assigned tasks. In the case of remote tests, we added a calibration and verification phase for the devices and a practical remote demonstration of how the test was to be carried out to avoid problems due to misinterpretation of the instructions provided.

We then provided the Vumark associated with the mathematical functions to be studied and represented as a link to a PDF file in the case of remote tests and printed in the case of in presence tests. Subsequently, the students experienced the Virtual Reality environments using the computer and the Augmented Reality application using their own smartphones.

At the end of all tests, the students answered the questions we proposed with the questionnaire.

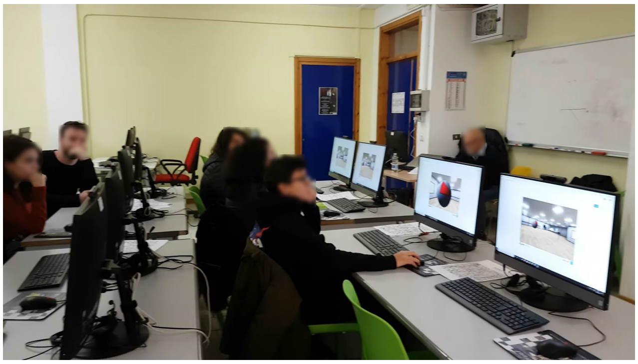
In the questionnaires provided, some questions aimed to analyse the effects of Virtual Reality and Augmented Reality on students. That permits us to understand whether these simple software applications can cause cyber-sickness, i.e. that condition of fatigue caused by immersive systems that leads the user to have any headache, nausea, or other symptoms [61], [62].

A. DESCRIPTION OF THE QUESTIONS

For the definition of the questionnaire, we chose a series of questions aimed at understanding the students' perception of the software used, what impression they have of its ease of use, its graphic quality, and its immediacy. The questions are organised into three categories: the first category includes general questions, the second category includes questions related to VR and the third category questions related to AR. AR- and VR-related questions are identical; only the technology they refer to changes. The questionnaire first prompted the personal data indicating age, gender, and class attended, followed by some general questions formulated to understand the degree of knowledge the students had regarding Virtual Reality worlds. In particular, they were asked

- whether they had ever used or experimented with applications using Virtual Reality and Augmented Reality.
- to rate the Ease of use, Ease of installation, User experience, and Graphic quality of the content provided by the Virtual Reality application.
- if the expectations of the Virtual Reality experience were fulfilled.
- to rate the Ease of use, Ease of installation, User experience, and Graphic quality of the content provided by the Augmented Reality application.
- if the expectations of the Augmented Reality experience were fulfilled.
- if the adopted methodology was appropriated.
- if the user experienced any disorientation or vomiting with VR or AR.
- if the user had other complaints.
- if they thought Virtual Reality or Augmented Reality could improve the quality of teaching.
- if the content shown with Virtual and Augmented Reality was already known.

Figure 5a and Figure 5b show two photographs of the experience conducted in presence.



(a) in presence lecture explaining Virtual and Augmented Reality

(b) Students testing the software and carrying out the questionnaire

FIGURE 5. Experience conducted in presence.

B. DESCRIPTION OF THE INVOLVED SCHOOLS

The selection of the schools where the usability tests were to be carried out was mainly driven by logistical reasons and considering the importance of these schools in the area where we operate by carrying out university orientation activities for our department's courses. The schools selected were two 'Liceo Scientifico Statale' in Perugia, Italy and one 'Liceo Scientifico Statale' in Foligno (PG), Italy; the type of institutes and the number of students involved reassured us as to the goodness of the sample selected. Once informed of the type of experience we intended to carry out with the students, the teachers took steps to provide the students with the necessary technical information and to obtain the necessary clearances from the parents of the minor students.

The first school involved was the 'Liceo Scientifico Statale Guglielmo Marconi' in Foligno. The school is located in the central area of Foligno. Foligno is a peripheral city about 40km from Perugia, the capital of the Umbria region. At that time, various restrictions were in force due to the COVID-19 pandemic; therefore, it was decided to proceed with an electronic meeting with the students using a custom platform based on the Open-Source software Jitsi.[9] During the day of the lesson, we had the opportunity to meet 45 fourth-year students aged between 17 (51.11%) and 18 (48.88%) years; 11 students were female (24.44%), while 34 (75.55%) were male.

The second school analysed was the 'Liceo Scientifico Statale Galileo Galilei' in Perugia. The school is located in the provincial capital of Perugia, in a central city area. The meeting with the students took place during the COVID-19 pandemic, using the school's commercial Google Meet platform for online meetings. During the user experience tests, we had the opportunity to meet the fifth-year students. The sample analysed comprises 27 students, of which 11 are male (40.7%) and 16 are female (59.3%).

The third school involved was the 'Liceo Scientifico Statale Giordano Bruno' in Perugia, where the experience was conducted in presence. The school is located in a suburban area of Perugia. The meeting with the students took place when the COVID-19 pandemic was over, and there were no restrictions on freedom of movement or social distancing. In total, 90 students participated in the lesson and questionnaire. The students were partly in the third year (52) and partly in the fourth year (38). The sample examined is divided into 64.4% males (58) and 35.6% females (32).

C. METHODOLOGY USED IN THE STUDY

Data collection was a very delicate procedure as we interacted with human beings. To comply with current regulations and laws, we first provided informed consent explaining that the data collected is completely anonymous and aggregated and does not allow the identification of the person who answered the questionnaire. Students under the age of 18 obtain parental approval, without which they could not participate in the questionnaire. Several factors guarantee anonymity; first of all, the questionnaire was done by computer, and therefore, it is not possible for us to trace who filled in a questionnaire sheet. The data was stored in a database in aggregate form, and there is no way to trace it back to the user who entered the answers. No timestamp was stored for the answers, so it is impossible to identify a person based on the time of submission of the questionnaire. There was no discrimination based on race, gender, religion or other factors, and all interested students could participate in the questionnaire. To ensure the smooth running of the data collection, all local laws were properly adhered to, and we constantly monitored the progress of the experience to ensure the smooth running of the event. The questionnaire, classroom and remote experience, and apps were first validated, tested and approved by the schools' staff.

[9]https://jitsi.org

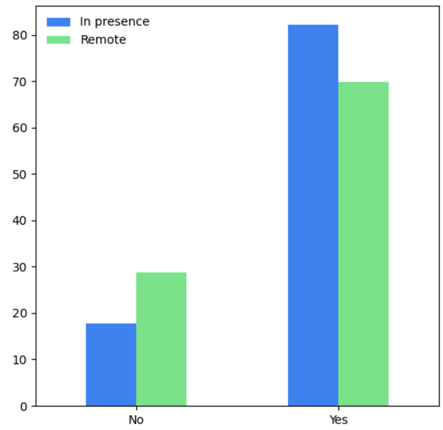


FIGURE 6. Graph related to the question: Have you ever had experience with Virtual Reality?.

VI. RESULTS OF QUESTIONNAIRES

This section describes the results obtained and the questionnaires that the students completed. A total of 162 students participated in the data collection, of which 72 took the questionnaire remotely and 90 took the questionnaire in presence. The purpose of our work is to understand if there are any appreciable differences between the answers given by the students who carried out the usability test during the COVID-19 pandemic period remotely and those who carried out the test in presence. For this reason, all the summary histograms are presented, keeping the two groups of students separate, thus allowing a direct comparison between the population of in presence students, highlighted in green, and that of remote students, highlighted in blue.

The values shown in the graphs are expressed as the percentage with respect to the total instead of the absolute values of the given sample. In all figures related to Lickert-scale graphs, the value for the median X of the corresponding population is also indicated. The median allows us to observe the response that divides the distribution of responses into two equal parts, with 50% of responses above and 50% below this value. The median for research purposes is useful for understanding the central tendency of the data as it is a measure that is less sensitive to extreme values than the mean.

The sample that participated in our study comprised the usability tests carried out at a distance with a prevalence of 18 and 17 years (fifth and fourth year of the school), while the sample that carried out similar tests in the presence, a prevalence of 16 and 17 years (third and fourth year of the school). Furthermore, the population consisted of 65% boys and 35% girls, with no particular differences between the population of the in presence students and that of the remote students. The above results from the first three questions of the questionnaire.

The fourth question shown in Figure 6 asks whether or not the students have experienced Virtual Reality. The two populations have approximately the same behaviour, and in

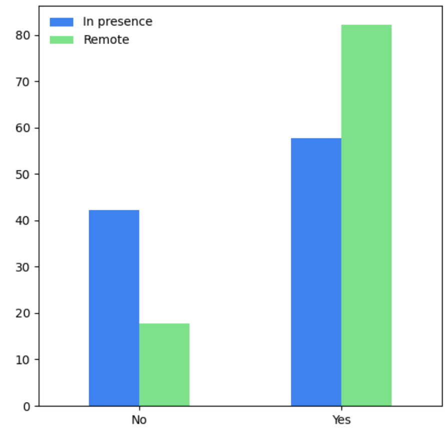


FIGURE 7. Graph related to the question: Have you ever had experience with Augmented Reality?.

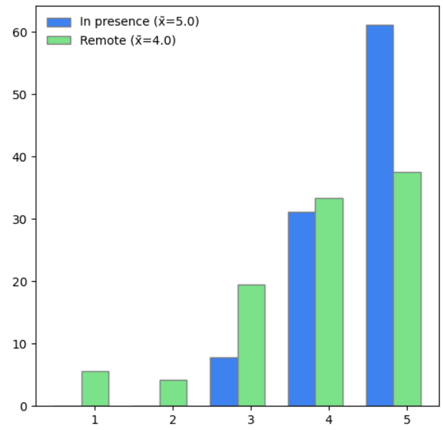


FIGURE 8. Please rate your appreciation of Virtual Reality applied to mathematics [Ease of use]. (Lickert scale, 1=worst, 5=best).

general, they have already used Virtual Reality due to the widespread use of video games among young people.

We asked the students whether they had experienced Augmented Reality. Figure 7 shows the graph related to this question. If we analyse the results, we can see that, again, most of the young people had experience with Augmented Reality, but fewer than those who experienced Virtual Reality. Again, Augmented Reality had been known to them thanks to video games. The students told us they had experience with smartphone games such as Pokémon Go [63], which was famous for offering Augmented Reality gameplay.

The following questions from number 6 to number 15 present questions requiring answers on a scale of one to five, where 1 is a very negative result, and 5 is a very positive result, according to a Lickert scale. We have chosen the Lickert scale for those questions that require positive or negative ratings on specific topics so that the answers can be easily compared. On the legend, next to the description of the sample represented by the associated colour, there will be the median calculated for the population under consideration and for that specific question.

Figure 8 shows the histogram relating to the answers to the sixth question, which asked the students to express the ease of use they found when using the system we presented in relation to their experience with Virtual Reality.

The students who had the opportunity to use the application in person gave higher ratings. This is due to the possibility of comparison that the students had since they could talk to each other and use the application with their peers during the experience. This same possibility was, of course, not possible for the remote students who still gave high evaluations but still lower than those of the students in presence.

Figure 9 shows the graph for question number 7, which asked students to rate the ease of installation of the application. Both populations provided excellent results. In particular, the Virtual Reality application was delivered via a web platform and required students to open a link we provided and output the web page full screen.

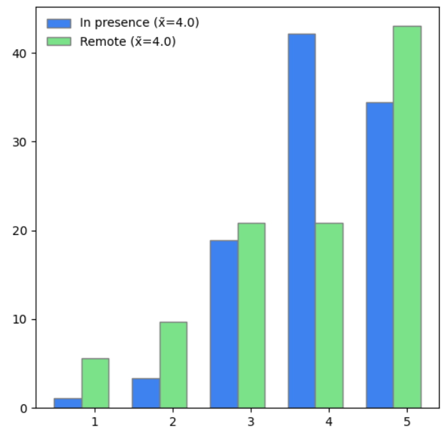


FIGURE 9. Graph related to the question: Please rate your appreciation of the Virtual Reality applied to mathematics [Ease of installation]. (Lickert scale, 1=worst, 5=best).

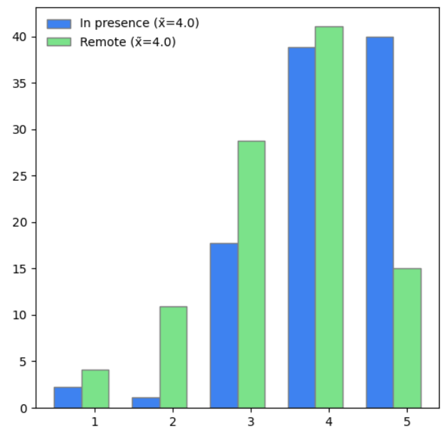


FIGURE 10. Graph related to the question: Please rate your appreciation of the Virtual Reality applied to mathematics [User experience]. (Lickert scale, 1=worst, 5=best).

Figure 10 shows the graph for question number 8, which asked students to rate their user experience during the Virtual

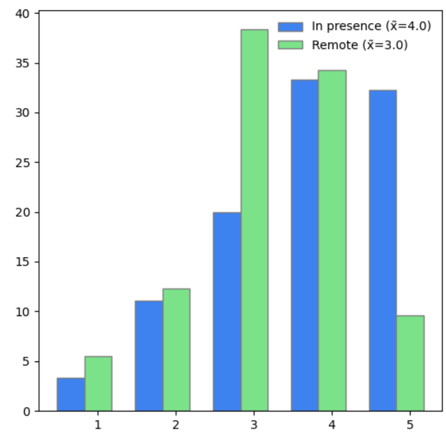


FIGURE 11. **Graph related to the question: Please rate your appreciation of the Virtual Reality applied to mathematics on the following scale [Graphic quality]. (Lickert scale, 1=worst, 5=best).**

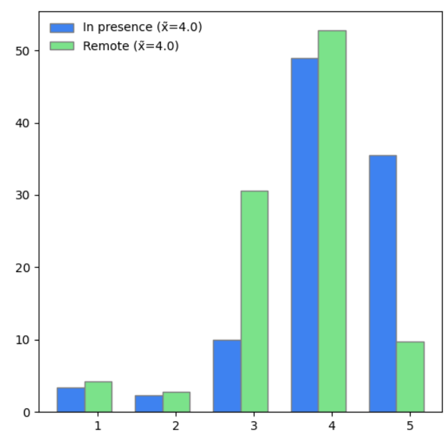


FIGURE 12. **Graph related to the question: Were the expectations you had at the beginning of the Virtual Reality presentation fulfilled? (Lickert scale, 1=worst, 5=best).**

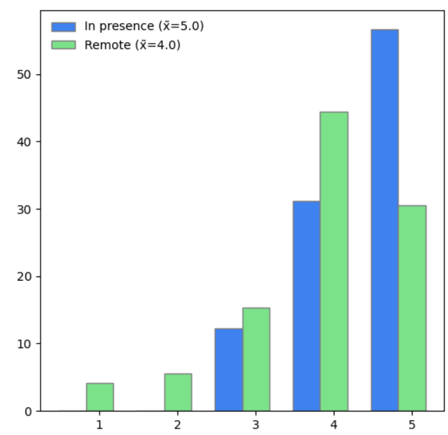


FIGURE 13. **Graph related to the question: Please rate your appreciation of the Augmented Reality applied to mathematics [Ease of use]. (Lickert scale, 1=worst, 5=best).**

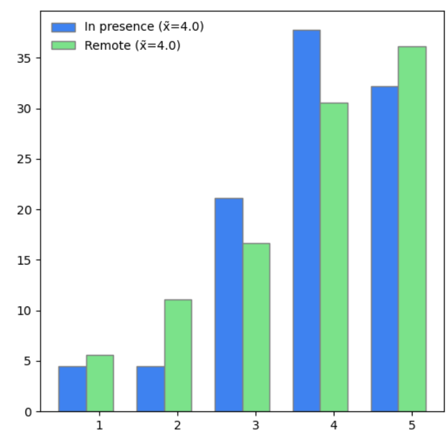


FIGURE 14. **Graph related to the question: Please rate your appreciation of the Augmented Reality applied to mathematics [Ease of installation]. (Lickert scale, 1=worst, 5=best).**

Reality practice. Notably, both populations provided very high values, and about 40 per cent of the in presence students gave a rating of five compared to 15 per cent of the remote students. The difference is significant and shows that working in a group with colleagues and in presence helps improve the perceived quality of Virtual Reality applications.

Question 9, the results of which are shown in Figure 11, asked students to rate the graphical quality of the Virtual Reality application. The results show that the in presence students rated the graphical quality significantly higher than the remote students. In both populations, however, the graphic quality was rated positively.

Question 10 asked the students whether or not their expectations of the Virtual Reality experience were met, and the results are shown in Figure 12. For both populations, we obtained highly positive ratings, which are also confirmed by the warm comments made by the students verbally during the meeting days. We found a significantly higher evaluation for the population of students who participated in presence, with around 35 per cent of the students giving an evaluation of five. The slightly better evaluation of the students who took the in-person practice can be attributed to the more significant interaction between teachers and students in the in-person experience compared to the distance one.

Question number 11, whose results are shown in Figure 13, confirms that the ease of installation of the application was significantly higher during the in presence experience.

Question 12, the results of which are shown in Figure 14, demonstrates that the Augmented Reality application was straightforward to install, with slight variations in the assessment between the two populations. The students have found installation easy thanks to the link provided to the Google Play Store via chat.

Question 13, whose results are shown in Figure 15, reports the students' evaluations of the user experience, showing that almost 40 per cent of the in presence students gave a rating of five out of five against 15 per cent of the remote students, in each case, both populations gave very positive ratings.

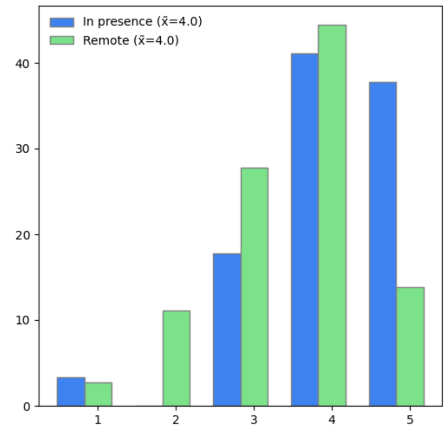


FIGURE 15. Graph related to the question: Please rate your appreciation of the Augmented Reality applied to mathematics [User experience]. (Lickert scale, 1=worst, 5=best).

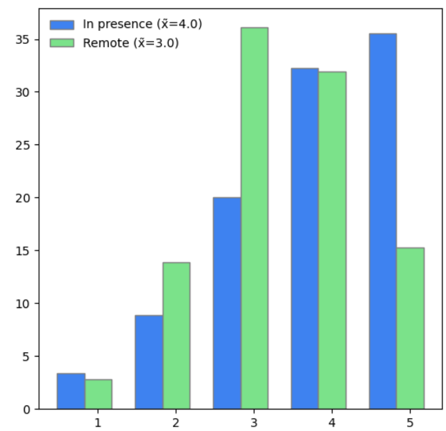


FIGURE 16. Graph related to the question: Please rate your appreciation of the Augmented Reality applied to mathematics [Graphic quality] (Lickert scale, 1=worst, 5=best).

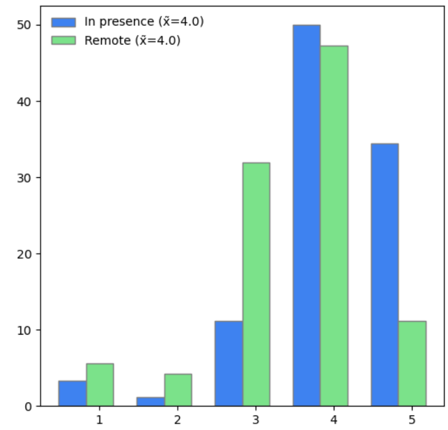


FIGURE 17. Graph related to the question: Were the expectations you had at the beginning of the Augmented Reality presentation fulfilled? (Lickert scale, 1=worst, 5=best).

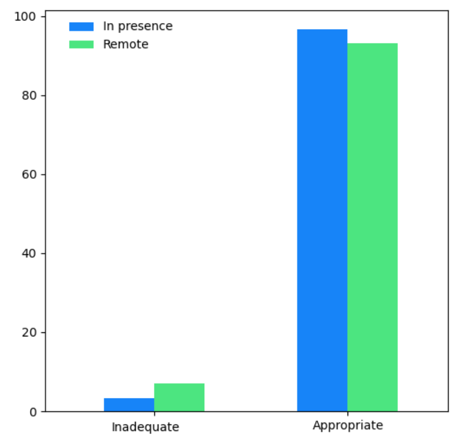


FIGURE 18. Graph related to the question: The methodology used seemed to you Appropriate or Inadequate.

Question number 14, the results of which are shown in Figure 16, illustrates the judgments given by the students regarding the perceived graphic quality. The Augmented Reality application is an Android app and is consequently installed and launched from the student's smartphone. The figures shown, which appear when Vumarks are framed, was assessed positively by the two populations, with higher ratings by the students in presence. This can also be explained by the fact that the students passed each other's smartphones and also viewed several forms at the same time through the use of several mobile phones, working in groups and interacting with each other. This contributed to a significant improvement in the results that were obtained, as is also confirmed by the graph relating to question number 15 shown in Figure 17.

The methodology of working, explaining the functionalities, and using the applications was evaluated as appropriate by the majority of the students, as shown in Figure 18. Both populations gave very similar responses, and there are no significant differences between the two samples analysed.

Some students experienced a sense of disorientation using the Augmented Reality application, as shown by the results of question 17 shown in Figure 19. There are no appreciable differences between the two populations.

This situation was slightly reversed with the Virtual Reality experience. The results of question 18 reported in Figure 20 show that the in presence population experienced less stress with regard to the Virtual Reality practice.

The following two questions ask the students whether they experienced nausea complaints with the use of the Augmented Reality application, the results of which are shown in Figure 21, and Virtual Reality, the results of which are shown in Figure 22, respectively. The results are comparable between the two populations. A total of three students experienced a sense of nausea using these immersive systems. The students also informed us that these problems occurred often using video games. Question 21, the results of which are shown in Figure 23, asked the students if they

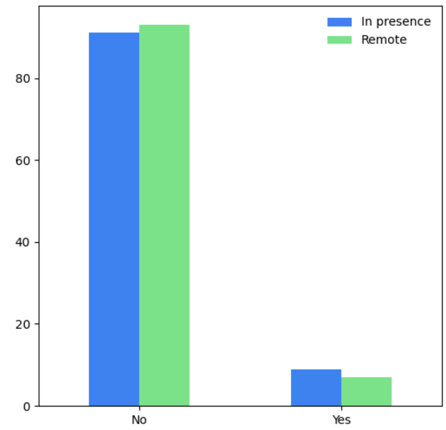


FIGURE 19. Graph related to the question: During the AR/VR experience have you ever experienced disorientation with AR?.

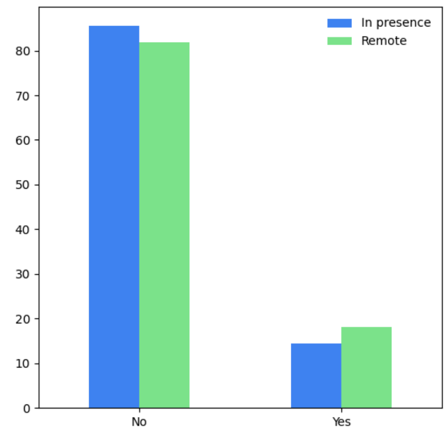


FIGURE 20. Graph related to the question: During the AR/VR experience have you ever experienced disorientation with VR?.

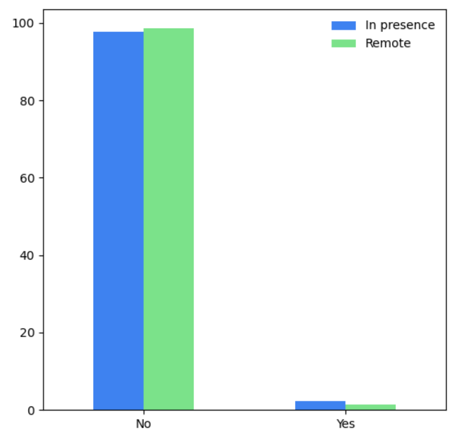


FIGURE 21. Graph related to the question: During the AR/VR experience have you ever experienced vomiting with AR?.

have experienced other problems. Three students reported headaches.

Question 22 asked students whether the application is useful or useless for improving school teaching techniques.

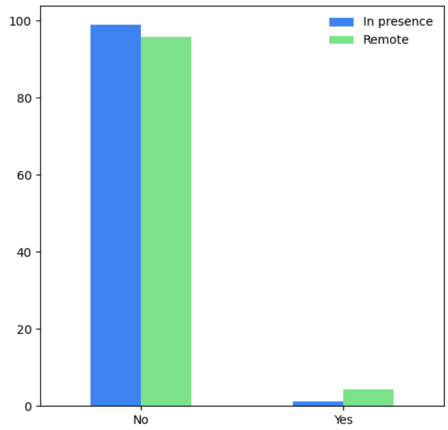


FIGURE 22. Graph related to the question: During your AR/VR experience have you ever experienced vomiting with VR?.

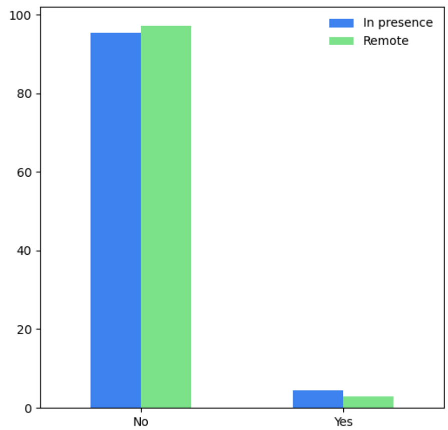


FIGURE 23. Graph related to the question: Have you experienced any other complaints?.

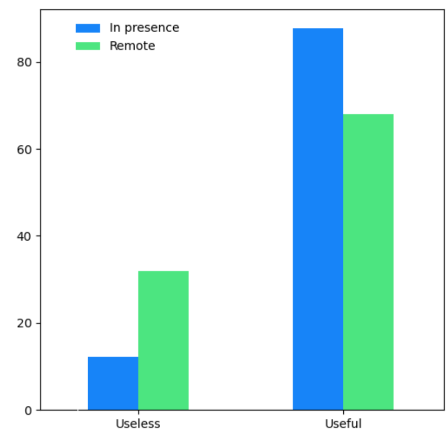


FIGURE 24. Graph related to the question: Do you feel that this type of application for your training is Useless or Useful.

The results are shown in Figure 24. The majority of students appreciated the use of these tools to improve teaching.

Question 23, which concludes the questionnaire and whose results are shown in Figure 25, asked students to express on a

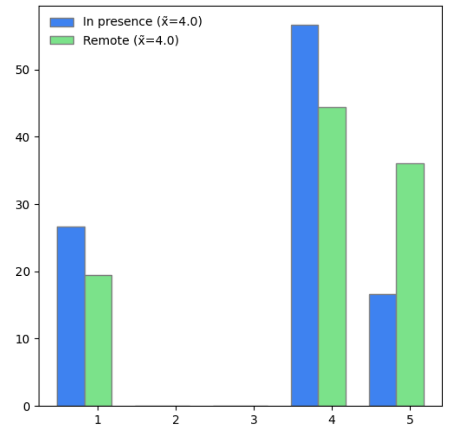


FIGURE 25. Graph related to the question: Express the knowledge of the shape of the functions in a scale of 1 to 5.

scale of one to five whether or not the mathematical geometric figures shown were known to them. Both populations affirmed that the figures were known to them.

VII. CONCLUSION AND FUTURE WORK

Our work analysed the effects on two student populations of introducing Augmented Reality and Virtual Reality to convey understanding of abstract concepts. Through a questionnaire administered to the students, a thorough analysis was conducted that leads us to affirm a positive evaluation by the students on the use of these tools and the user experience.

Two software applications have been developed. The first is based on Virtual Reality technologies and can be accessed using a web browser. It aims to immerse students in a realistic world where the teacher can create three-dimensional structures. These can help learners study concepts that would otherwise be difficult to represent on a blackboard or a two-dimensional projector sheet. Another strong point is the possibility of interacting with the scenario, moving freely within it, and managing and governing the scene's framing independently. This application is also independent of the operating system as it uses WebGL technology and so can run in any browser via a computer, tablet or smartphone. The second application is instead based on Augmented Reality technologies, and it was developed for Android operating system. It allows the teacher to create special markers that can be printed and provided to the class. When the markers are framed by the app the corresponding trimensional objects will appear above them. These objects can represent mathematical functions, simulations of physical objects, artistic paintings, simulations of chemical reactions, etc. The student can then move the smartphone or the paper, and consequently, the three-dimensional object will change its position in the 3D environment. It can be enlarged or reduced by moving the smartphone closer or further away.

This type of application can empower knowledge as proved by the conducted usability tests involving three Italian schools and carrying out the experiences on two populations, one in presence and one remotely. The students were able to personally try out these new teaching methods and answered the questionnaire by providing anonymous answers, expressing personal evaluations and opinions. About 94.43% of the students who participated in the survey believe Augmented Reality is a helpful tool that should be used in education. A comparable value was found for Virtual Reality, which was approved by 93.81% of the students.

Introducing advanced digital instruments and updating school systems can be facilitated by these technologies. We have observed that not all youths have the same immediacy with information technology. It is necessary to create inclusive systems that involve all learners regardless of their experience. Both technologies have achieved excellent results. Regarding user experience, Virtual Reality scored slightly better, as young people see this type of teaching as futuristic and fun. The cost-benefit ratio of the two technologies benefits Augmented Reality. The result obtained on intuitiveness and immediacy are very similar to those of Virtual Reality. However, the costs necessary to create classrooms and infrastructures suitable for exploiting Augmented Reality environments are much lower. Indeed, it is sufficient to have a smartphone or a tablet at least every two students to allow him to observe and visualise the three-dimensional models autonomously.

We then analysed the results obtained from the two populations of students: those who participated in the experience and answered the questionnaire remotely during the COVID-19 pandemic and those who participated in the in presence experience following the COVID-19. The comparison of the two questionnaires showed some differences between the two populations. We have seen that immersive applications perform better and are more appreciated when the student and teacher are in presence. Remotely, the teacher could experience some difficulties communicating the steps and operations to be done to the students because one is limited by only sharing the screen and has little interactivity with the student's device. The student himself can be more easily distracted and lose track of the steps, which, although few, are essential in order to achieve the result. The purpose is to immerse oneself within Virtual worlds in the case of Virtual Reality or correctly view three-dimensional figures and shapes via the smartphone in the case of Augmented Reality. Another significant difference that we could see was that group work was beneficial in the case of the face-to-face experience, as boys and girls who were more accustomed to using technology could help those less adept at it. This form of live interaction contributed to improving the quality of the experience to create a more cohesive group of students, as confirmed by the graph shown in Figure 24. The technologies we have developed and released with open-source code via GitHub can be used by anyone to make such Computer Graphic representations to explain abstract concepts effectively. As future work, we are working to create a public repository where user-created work can be uploaded.

This study method could also be used at home without buying Virtual Reality viewers, which currently have high acquisition costs. The future work we intend to undertake concerns optimising the interaction between the teacher and the students.

The goal will be to allow the teacher to customise the 3D shapes as straightforwardly as possible. That can be achieved by inserting 3D models using an Open-Source web environment and integrating a QR code within the Vumark. The advantage of using a QR code within the Vumark is to simplify the visualization of different content, which is delivered from the website referenced by the QR code and displayed via Vuforia with the same Vumark. A single Vumark will thus display variable content according to a different QR code.

ABBREVIATIONS

The following abbreviations are used in this manuscript:

APK	Android Package
AR	Augmented Reality
FBX	Filmbox
GPU	Graphics Processing Unit
HTML	HyperText Markup Language
ICT	Information and Communication Technologies
JS	JavaScript
MB	MegaBytes
URL	Uniform Resource Locator
VR	Virtual Reality

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AUTHOR CONTRIBUTIONS

Conceptualization, Osvaldo Gervasi, Damiano Perri, and Marco Simonetti; Software, Damiano Perri; Data curation, Osvaldo Gervasi and Damiano Perri; Investigation, Osvaldo Gervasi, Damiano Perri, and Marco Simonetti; Methodology, Osvaldo Gervasi, Damiano Perri, and Marco Simonetti; Supervision, Osvaldo Gervasi; Validation, Osvaldo Gervasi, Damiano Perri, and Marco Simonetti; Writing—original draft, Damiano Perri; and Writing—review and editing, Damiano Perri, Osvaldo Gervasi, and Marco Simonetti.

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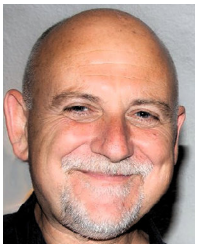

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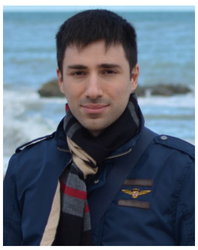

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